AQUACULTURE
AN INTRODUCTORY TEXT

4th Edition

ROBERT R. STICKNEY AND DELBERT M. GATLIN III

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CABI is a trading name of CAB International

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A catalogue record for this book is available from the British Library, London, UK.

Library of Congress Cataloging-in-Publication Data

Names: Stickney, Robert R., author. | Gatlin, Delbert M., 1958- author.
Title: Aquaculture : an introductory text / Robert R. Stickney, Professor Emeritus, Texas A&M University, College Station, Texas, USA and Delbert M. Gatlin III, Regents Professor, Texas A&M University, College Station, Texas, USA.
Description: 4th edition. | Wallingford, Oxfordshire ; Boston, MA : CAB International, 2022. | Includes bibliographical references and index. | Summary: "This new edition covers sustainable aquaculture development, culture systems, hatchery methods, reproductive strategies, harvesting and many other topics. Fully updated and revised, it includes more information on open ocean cage culture, diseases and parasites, nutrition, biofloc technology, climate change, probiotics, and the impact of COVID-19"-- Provided by publisher.
Identifiers: LCCN 2021057926 (print) | LCCN 2021057927 (ebook) | ISBN 9781800621114 (hardback) | ISBN 9781800621121 (paperback) | ISBN 9781800621138 (ebook) | ISBN 9781800621145 (epub)
Subjects: LCSH: Aquaculture.
Classification: LCC SH135 .S736 2022 (print) | LCC SH135 (ebook) | DDC 639.8--dc23/eng/20211202
LC record available at https://lccn.loc.gov/2021057926
LC ebook record available at https://lccn.loc.gov/2021057927

References to Internet websites (URLs) were accurate at the time of writing.

ISBN-13: 9781800621114 (hardback)
9781800621121 (paperback)
9781800621138 (ePDF)
9781800621145 (ePub)
DOI: 10.1079/9781800621145.0000

Commissioning Editor: Alex Lainsbury
Editorial Assistant: Kate Hill
Production Editor: Shankari Wilford

Typeset by SPi, Pondicherry, India
Printed and bound in the UK by Severn, Gloucester

Contents

Preface

The primary target audience for this book is undergraduate students and individuals or lay groups who might be interested in learning more about the topic before deciding to take the leap into some component of the aquaculture production sector. The book is also designed for graduate students who may be interested in conducting research associated with some aspect of aquaculture (e.g. fish nutrition or disease) but have taken a course on aquaculture. The books listed at the end of the chapters provide readers with the sources of more detailed information. A large number of journals, websites, published abstracts from scientific meetings and a few magazines are devoted to aquaculture, or at least publish some information on the subject. Among the journals devoted exclusively or largely to aquaculture are:

- *Aquaculture;*
- *Aquaculture International*;
- *Aquaculture Economics and Management*;
- *Bamidgeh* (*The Israeli Journal of Aquaculture*);
- *Journal of Applied Aquaculture*;
- *Journal of Fisheries and Aquatic Science*;
- *Journal of the World Aquaculture Society*;
- *North American Journal of Aquaculture*;
- *The Journal of Shellfisheries Research*;
- *Reviews in Aquaculture*;
- *Reviews in Fisheries Science*;
- *Reviews in Fisheries Science and Aquaculture*; also
- *World Aquaculture Magazine* (a quarterly, published by the World Aquaculture Society, that provides up-to-date information on the aquaculture industry, research, society meetings, regional activities of affiliated societies and sections of the World Aquaculture Society, and editorial comments on the subject).

We are concerned that the results of studies published in journals and other aquaculture publications involve experiments that are very similar, or perhaps identical, to previously published information, without attribution of previously published studies. This can be blamed to some extent on the Internet and, perhaps, laziness. In many instances, earlier research may not be available in e-journals, either because similar studies were published before the advent of the Internet, or the author(s) only looked at recent literature (perhaps only going back a few years). To avoid the problem, which is a form of plagiarism, though it is usually not intentional, authors should review the most recent published literature on the subject of interest, look at the literature cited section and then proceed to examine each article to determine if similar information had previously been published (secondary level of investigation). Third, fourth or more levels of investigation may be required to ensure the information had not previously been published and, as an additional benefit, may reveal questionable conclusions of previous studies, which could lead to additional research.

Since the third edition of this book was published, the world has been faced since 2020 with a pandemic associated with the COVID-19 virus. While the situation has been ameliorated due to the rapid development of highly effective vaccines, millions have died and there have been significant negative impacts on the global economy, education, and research (including aquaculture research). Numerous universities and research agencies around the world were required to suspend research activities and close their facilities during the pandemic. Some facilities were not allowed to resume research activities until after over one year of closure. Fortunately, the aquacultural research and educational activities conducted at Texas A&M University were considered essential and thus were allowed to continue throughout the pandemic.

Please note that unless indicated otherwise in the captions, all the photos in this book were taken by the authors, and all tables are the authors' own.

Also included at the end of each chapter is a list of references for additional reading. We also have included the URL of a website supported by the Southern Regional Aquaculture Center which maintains fact sheets on various topics related to different aspects of aquaculture. This site can be found at: https://srac.tamu.edu/ (accessed 17 December 2021). Additional information about the site is provided below.

The Southern Regional Aquaculture Center is sponsored by the USDA National Institute of Food and Agriculture (NIFA).

The Fact Sheets on this site provide information on important species of fish and shellfish produced in the Southern Region. These fact sheets are reviewed annually by the Publications, Videos, and Computer Software Steering Committee and are revised when significant new information becomes available on the subject. Any that have not been revised are considered to represent the essential state of available knowledge.

1 General Overview of Aquaculture

Definitions

What is aquaculture?

Aquaculture can be defined in a number of ways. The one we have chosen is: *aquaculture is the rearing of aquatic organisms under controlled or semi-controlled conditions*. That is a fairly simple, but comprehensive definition. An abbreviated definition is that aquaculture is: *underwater agriculture*. The longer of the two definitions can be broken down into three major components:

- Aquatic refers to a variety of environments, including fresh, brackish, marine and hypersaline waters. Each environment is defined on the basis of its salinity (most simply the amount of salt that is dissolved in the water). Salinity is discussed in some detail in Chapter 4.
- Aquatic organisms are any organisms that live or can live in water. A branch of aquaculture called mariculture is reserved for aquatic organisms reared in saltwater (which can range from low salinity to hypersaline). Aquaculture organisms of interest with regard to human food include a wide variety of plants, invertebrates and vertebrates. In the plant kingdom, we include algae along with higher plants and, in some cases, terrestrial plants that are grown using a method called hydroponics or aquaponics (discussed in Chapter 9).
- Controlled or semi-controlled refers to the fact that the aquaculturist is growing one or more types of aquatic organisms in an environment that has been altered to a greater or lesser extent from the environment in which the species is normally found. The amount of control that is exerted by the aquaculturist can vary significantly. Spreading oyster shell on the bottom of a bay to provide a surface for settlement of larval oysters is at one extreme, while operation of an indoor hatchery that incorporates a water-reuse system for early life stage rearing, and in many cases growout to harvest, is at the other (see Chapter 3).

The oyster example would fit the definition of extensive aquaculture where the culturist has little control over the system but merely provides a more suitable habitat for the settling oyster larvae (spat) on a hard surface until growout and harvest. The larval oysters may come from natural spawning, or they may be produced and settled on oyster shell (cultch) in a hatchery, which increases the level of interaction between the culturist and the target species and thus modifies (increases) the level of intensity in the overall production process.

When operating a recirculating system, the aquaculturist exerts a high level of control and the system is called intensive. Even just placing a culture unit in the aquatic environment represents a means of controlling the animals that are being reared. Cages and net pens are examples (see Chapter 3). There are a number of other approaches that lie somewhere between the extremes of extensive and intensive. Those are often referred to as semi-intensive systems. Systems that go beyond intensive are called hyper-intensive; thus we can view aquaculture approaches as ranging broadly from very simple to highly complex, or – perhaps more precisely – as ranging from systems that employ little technology to those that rely heavily upon technology. It can be argued that as the amount of technology involved in the culture system increases, so does the amount of control that the culturist has over the system. One can also argue that as production intensity and the level of technology employed increase, so does the probability of system failure, because there are more things that can and often will go wrong as you add complicated mechanics, work in harsher and harsher environments (like in the open ocean) and add automation (automatic feeders, water quality monitors, alarm systems, computer data collection,

DOI: 10.1079/9781800621145.0001

etc., as discussed later in this volume). Persons who engage in aquaculture may be called *aquaculturists*, independent of the type of water system that is employed, or *mariculturists*, who work with aquatic species in saline environments (from low-salinity to hypersaline waters). Depending upon the type of organism(s) being reared, the culturist may also be referred to as a *fish farmer*, *shrimp farmer*, *clam farmer*, etc., or by an even more limited restrictive title, such as *rainbow trout producer*, *catfish farmer*, *Atlantic halibut farmer*, etc.

As you read this book, you will run into the word *seafood* periodically. When we use that word, you need to think in terms of all edible aquatic species, not just those that are captured from, or cultured in, saltwater. When you think about it, seafood restaurants usually serve both marine and freshwater species. There are exceptions, of course, but in general a mixture of marine and freshwater species is typical. *Seafood* includes finfish, invertebrates and often algae (such as in sushi wrappers, salads and various other dishes).

While the above definitions are fairly simple, they embrace an extremely broad and complex topic that involves a broad array of scientific disciplines and business management, along with engineering, economics, accounting and trade skills. A serious student of aquaculture should have experience (and preferably have taken formal courses) in mathematics, chemistry (through at least organic), physics, biology, business management and economics, and, if possible, some basic engineering. Mechanical engineering is certainly beneficial and courses in such subjects as hydrology and sanitary engineering can be useful. For many practising aquaculturists, including those involved in certain types of research, the ability to drive trucks and tractors and having some skills in association with plumbing, electrical wiring, welding, painting and carpentry are beneficial, if not required. Experience pouring concrete will also often come in handy. A list of skills and disciplines which are often useful to aquaculturists and that reiterates what you have just read is provided in Box 1.1. A high level of expertise in each of the items on the list is not required, though familiarity with the majority of them will certainly be of value. You probably will not be able to begin a career in aquaculture having had all the background you will ultimately need, but you will quickly acquire the knowledge and/or skills you need yourself or you will surround yourself with a complement of people who have the skills you lack. If you do not, it could be a difficult uphill battle to become successful. One thing you should take away from this book is that aquaculture is not a science or a discipline that stands on its own. It is made up of many disciplines that come together and are required if a venture is to become economically viable. An important

Box 1.1. A sampling of the skills and disciplines that are often of considerable value to the aquaculturist.

Skills:
- Plumbing
- Carpentry
- Welding
- Electrical wiring
- Computer skills (word processing, spreadsheets, control systems)
- Painting
- Concrete pouring and finishing
- Operating equipment such as tractors, backhoes, bulldozers
- Truck driving (pickup trucks and larger)

Courses:
- Business management (bookkeeping, accounting, marketing)
- Basic economics
- Chemistry (particularly water chemistry and organic chemistry)
- Biology (ichthyology, invertebrate zoology, physiology)
- Physics
- Geology (particularly marine, as appropriate to the species produced)
- Limnology and/or oceanography
- Nutrition (animal)
- Aquatic animal disease
- Basic engineering principles
- Hydrology

attribute of the successful aquaculturist is also a high level of common sense.

What is involved?

The aquaculturist is often faced with making on-the-spot decisions. Example: *The fish are at the surface looking like they are gasping for air! What should I do?* This is where common sense comes into play. There is no time to call in an expert and, if there were, what type of expert would you call? If you know who to call, do you know how to describe the problem in sufficient detail so that the person can provide a reasonable solution for you? Questions that you may be asked by the person you call are: Is there the possibility of a chemical in the water such as a pesticide that is causing the problem? Can you tell if your animals have a disease? You also do not have time to study the situation. You have to take action based upon your knowledge and, again, a good measure of common sense. As you will see in Chapter 4, the described behaviour is most commonly associated with oxygen depletion, so you would immediately take steps to increase the dissolved oxygen (DO) level in the pond. To do that, you need to not only know how to accomplish the task, but also must have the proper means of doing so quickly and efficiently.

In this book, the focus is on aquaculture that is typically of a commercial nature. While that may involve raising aquatic species as bait or for the ornamental trade, the focus here is on production of aquatic species that will be marketed as human food. Having said that, it has been reported that over 1 billion ornamental fish are traded around the world each year. At least several hundred freshwater species and fewer, but increasing numbers, of marine species are involved. Many of the freshwater species have been and are being produced by aquaculturists, but far fewer marine species are being commercially cultured, though their numbers seem to be increasing. Marine ornamentals involve not only finfish but also a wide variety of invertebrates. Interest is increasing within the scientific community to address the issue of culturing marine ornamentals, and some breakthroughs have been made. Prior to a few years ago when interest by the scientific community began to increase, the majority of the breakthroughs in ornamental aquaculture were made by hobbyists and commercial producers who began working to develop culture methods for species that could not be taken through their entire life cycle in captivity but had to be captured from the wild. The techniques often appeared in aquarium magazines or, when developed by a commercial ornamental species producer, were not revealed so that the person or company would, at least for a time, have a monopoly on the methodology. You can be sure that if one person figures out/solves a problem, such as how to breed a particular species of cleaner shrimp, someone else will also figure it out. In addition, researchers have increasingly been interested in how to spawn and rear ornamental marine fish, and those researchers are happy to publish the details.

Another interest of aquaculturists is production of non-food and non-ornamental species that have commercial value. Those include pearl oysters (marine) and freshwater pearl mussels. Aquaculturists are also raising bath sponges, live rock and corals. Live rock is produced by placing terrestrial rocks, such as limestone, in the marine environment and leaving them until they become colonized with various benthic organisms. Then the rocks can be sold into the marine aquarium trade. As in the case of fingerprints, no two live rocks are the same. They vary in terms of the species present and the densities of each. Coral culture is similar except that a suitable substrate, perhaps limestone again, is placed in a location in the vicinity of a living coral reef where naturally produced coral larvae can settle on the substrate and grow. The substrate is allowed to remain in place until the corals that colonize it reach sizes where the rock can be sold. People who purchase live coral need to buy from reputable dealers who do not obtain their coral by extracting pieces from natural reefs. Coral reefs are protected from poaching in many parts of the world, and there has been a major decline in living corals due to what is known as coral bleaching, largely attributed to climate change. However, it is difficult, if not impossible, to stop the practice of taking pieces from living reefs for marketing purposes by those who ignore laws and regulations.

There is also the need, in some cases, for aquaculturists to raise live food, particularly for feeding the early life stages of species that ultimately are marketed. Some aquaculturists grow algae intended for the production of nutritional supplements for humans and/or for inclusion in aquaculture feeds (e.g. spirulina, which includes *Arthrospira platensis*, *Arthrospira maxima* and *Arthrospira fusiformis*) and to produce biodiesel fuel (though biodiesel production from algae is not significant at this time).

There are also ornamental and other species that require zooplankton (small, often microscopic animals that drift in the water column in fresh or marine waters) for food, especially during the early phases of the life cycles of fish and invertebrates, though in some cases throughout their life cycles.

Some people enjoy so-called backyard aquaculture, usually with the aim of producing a crop for their own use. The approach can be accommodated by developing a small-scale water system using some of the information presented in Chapter 3. A considerable portion of the aquaculture production in many developing nations is artisanal; that is, small-scale individual farmer or family operations designed to either provide the family with food or, through local sales, generate a modest amount of income. Artisanal farm production most commonly is practised using small ponds, often with no feeding, though inorganic or organic fertilizers are often applied (see Chapter 4). Such artisanal approaches typically mean that the culturist has to learn on the job, though some training may be available from other local producers or through government extension programmes and written information.

Large commercial operations will employ skilled professional aquaculturists who have credentials in one or more specific areas of expertise and familiarity with others. Examples of the types of expertise that are often required are presented in Box 1.1. Professional aquaculturists, along with skilled labourers, will have at their fingertips most, if not all, of the knowledge required to make an operation successful. That does not mean that there will not be occasions when outside expertise is needed. For example, a disease may break out on a facility that is not recognized by the staff. An aquaculture veterinarian or fish pathologist may have to be consulted to determine what the pathogen is and what, if any, treatment might be effective against that pathogen. The problem is that there are very few veterinarians who specialize or even have any knowledge of aquatic animal diseases unless the veterinarian is operating in an area where large numbers of culture facilities are located (e.g. the Hagerman Valley in Idaho, which is the major rainbow-trout-growing area in the USA, and the catfish-growing regions in Mississippi and various other US states). Some universities provide diagnostic services to aquaculturists, though having the facility where a problem is recognized near one of those universities is a distinct advantage.

Parsing the discipline by temperature

Aquaculture species tend to be classified as having a preference for warm, cool or cold water. That relationship applies to both plants and animals, though when we think about temperature requirements we often think in terms of the culture of animals, not plants, which makes sense as although the culture of aquatic plants is significant, it is mostly confined to fewer countries and areas than is true of cultured animals.

While not absolute, warmwater species tend to grow optimally at or above 25°C (usually within the range of 25 to 30°C), while coldwater species exhibit optimum growth at temperatures at or below 20°C. Coolwater species typically grow best at temperatures between 20 and 25°C (see Box 1.2). Most commercially cultured species are either of the warmwater or coldwater variety. Some popular species that are primarily cultured with the objective of stocking to support recreational fisheries are of the coolwater variety. The designation of warmwater, coolwater or coldwater does not mean the species will die if the water temperature moves out of the optimal range, as may happen seasonally. The optimal temperature range is an indicator of when growth is usually best. Many species of finfish can survive temperatures as low as 4°C, and some will even eat when the water is that cold – otherwise there would not be any interest in ice fishing. Many fish can tolerate temperatures of about 30°C, though protein coagulates at 40°C, so there is a definite upper limit. Commercial tilapia species can tolerate temperatures at least as high as 34°C, for example.

Box 1.2.

A few examples of warmwater, coolwater and coldwater fish species.

Warmwater: Channel catfish (*Ictalurus punctatus*)
Tilapia (*Oreochromis* spp., *Tilapia* spp.)
Coolwater: Walleye (*Stizostedion vitreum vitreum*)
Northern pike (*Esox lucius*)
Coldwater: Rainbow trout (*Oncorhynchus mykiss*)
Atlantic salmon (*Salmo salar*)
Atlantic halibut (*Hippoglossus hippoglossus*)

One species or more?

Culture systems may involve the production of one species (monoculture) or two or more species (polyculture, also called co-culture), which would include the culture of plants and animals in the same culture system. Polyculture is exemplified by Chinese carp culture in which several species of carp are grown together in the same pond, with each species using a different food source. Grass carp (*Ctenopharyngodon idella*) eat higher plants, while silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*Aristichthys nobilis*) consume plankton. Mud carp (*Cirrhinus molitorella*) consume benthic organisms and common carp (*Cyprinus carpio*) are omnivorous. Other species, such as tilapia (Box 1.3), are often added to the mix or are used as substitutes for one or more of the traditional species. Carp farmers generally fertilize their ponds, but in many instances they also provide supplemental feed of various types (see supplemental feed in Chapter 8). Hydroponic or aquaponic systems (detailed in Chapter 9) often pair terrestrial or aquatic plant culture with the culture of aquatic animals, in which case that would also be a form of polyculture.

Integrated multi-trophic aquaculture (IMTA) is a term that has been coined in recent years to describe polyculture systems that use secondary species of plants and/or animals to produce additional marketable crops and also reduce the environmental impacts from the primary culture species. An excellent example is the culture of salmon (primary species) with some type of mollusc (to remove particulate organic compounds) and seaweed (to remove dissolved nutrients from the system). Similarly, integrating seaweed with the culture of at least one species of shrimp has been shown to improve water quality in mariculture systems.

Box 1.3.

When I (R.R.S.) took a position on the faculty of the Department of Wildlife and Fisheries Sciences at Texas A&M University in the state of Texas, USA in 1975, my primary expertise in aquaculture involved research on aquaculture from a summer spent in 1968 at the Fish Farming Experimental Station in Stuttgart, Arkansas (catfish) and the five years I spent at the Skidaway Institute of Oceanography in Georgia, where I conducted research on the nutritional requirements of channel catfish and on the environmental and nutritional requirements of flounders, among other topics not directly related to aquaculture.

I had been in Texas for only a few months when I heard about a fish called tilapia which had arrived in the state from an unknown source and had developed significant populations in a few electric power plant cooling reservoirs. In looking into information on tilapia I learned that they have limited ability to survive at low temperatures, but by moving into the discharge canals of power plants during the winter they were able to find temperatures supportive of their survival. I also learned that various species of tilapia (then *Tilapia* spp., now *Oreochromis* spp.) were being cultured in some parts of the world (primarily the Middle East and Asia at the time) and that they had only been imported to the USA in the 1960s by researchers at Auburn University in Alabama. That university was working with aquaculture development in tropical Asia and South America to help provide animal protein in the diets of people in those areas. Insofar as I could tell, there had been no attempts to stock tilapia in public waters in the USA, so how the fish got into power plant reservoirs in Texas was a mystery.

I collected some blue tilapia (*O. aureus*) from a power plant reservoir population and later, working with one of my graduate students, collected other species (interestingly, from the San Antonio Zoo). Various studies on nutrition, water quality requirements, polyculture with freshwater shrimp and so forth were conducted with my graduate students, though tilapia continued to be virtually unknown to the general public until some years after we had become involved with research on them. Today, tilapia is a staple on the menu in US seafood restaurants (often kept live in tanks, particularly in Asian seafood restaurants) and commonly found in grocery stores. It was interesting to see the development of a significant aquaculture industry with a species that was virtually unknown in the USA to become a popular food fish over a period of only a couple of decades.

Globally, tilapia culture also expanded greatly during the 1980s and 1990s, primarily in tropical areas, but even in temperate regions where geothermal or other sources of warm water were available to provide temperatures suitable for overwintering. One example was a large culture operation using geothermal water in the state of Idaho where winter water temperatures fall well below 0°C, yet the outdoor culture system had year-round production.

Addressing Declining Capture Fisheries

In the 1950s, a renowned oceanographer, John Ryther, estimated that the maximum amount of seafood that could be harvested annually from the world's oceans was about 100 million tonnes. His prediction was high for the oceans, which peaked at about 85 million tons in the 1990s and has fluctuated ever since, with some increases, as mentioned below, being contributed by new target species, and perhaps controlled harvests by government fisheries management agencies to manage harvest levels with the intention of allowing overfished populations to recover. There may also have been some increase due to enhancement (stocking hatchery-produced fish in the oceans with the intent they would increase the harvest level when they recruited to the fisheries). The positive impact of enhancement is probably best associated with Atlantic, and particularly Pacific, salmon species.

Total annual fishery production figures include species for direct human consumption and for non-human consumption (e.g. species that are rendered for fishmeal, which is used in terrestrial and aquatic animal feeds, and fish oil, which is used in aquatic animal feeds and in margarine in some countries). The 85 million tonnes total from the marine environment also excluded plants, which would involve phytoplankton (usually single-cell, often microscopic, algal species that grow suspended in the water column in both freshwater and saltwater) and seaweeds (also algae).

Many commercial fisheries have declined significantly or have even collapsed in the past few decades. The cod (*Gadus morhua*) fishery in the North Atlantic off the east coast of North America is an example of a fishery that collapsed. The cod fishery off northern Europe has also been in severe decline. Fisheries management agencies have implemented plans with the intent of restricting or outlawing commercial fishing on stocks that have collapsed, with the intention of promoting the recovery of those stocks. Of interest is the fact that due to the demand for shark fin soup, primarily in Asia, many shark species are now listed as threatened or endangered and are being protected or under quotas by some nations.

New or expanded fisheries, such as those for squid and mussels, have helped maintain the total harvest and as 2020, the 100 million tonne ceiling is being approached: inland aquaculture, 51.3 million tonnes; marine aquaculture, 30.8 million tonnes; for a total of 82.1 million tonnes according to the Food and Agriculture Organization of the United Nations (FAO), which publishes periodic reports on the subject. The 2020 totals do not include aquatic animals such as alligators, crocodiles, caimans, seaweeds and other aquatic plants.

Squid, sold as calamari, are popular today, but were largely unavailable as a result of low consumer demand in many western hemisphere markets until about the 1980s. Mussels were also thought to be inferior foods in some western markets, particularly in inland areas where there was little or no familiarity with them. Those species, along with squid and octopus, became popular as demand was created when Chinese and other speciality restaurants added them to their menus.

There continues to be limited aquaculture production with respect to squid, octopus, lobsters and various other species now in high demand. Some progress has been achieved, and research continues to produce information on further methods of increasing their commercial production.

As indicated above, the FAO does not provide statistics on alligator culture, though there is a significant production, particularly in the USA as a source of leather from its hides, and the meat is also popular in some areas. In the USA, alligators were listed as endangered for decades, but in recent years alligator production has been approved for captive rearing and sale.

In order to stop the decline and, if possible, promote the recovery of overfished wild populations, fishery management organizations in many nations have placed strict quotas on catches, and in some instances have closed fisheries entirely. For fishes that occur in international waters or off the coasts of neighbouring nations, international management agencies often exist. Examples are the International Pacific Halibut Commission that is a partnership between the USA and Canada, and the Inter-American Tropical Tuna Commission with 16 member nations.

Today, we are in a situation where the capture fisheries, not only in the oceans, but also in freshwater, are being fully exploited or overharvested in nearly every case, yet the demand for seafood continues to rise. That increase in demand is fuelled in part by the increasing human population but also by the rising per capita consumption of seafood. On the plus side, due to the protection of some species from harvest, such as many types of whales, many populations have grown significantly, achieving or approaching recovery.

Overfishing of aquatic species in the face of increasing demand has been, in part, addressed through the explosion in interest in worldwide aquaculture. Not only are large numbers of species being produced through aquaculture and expanding in many nations (both in species numbers and total biomass), but also interest in the culture of many of those species is being expressed in regions where such species were formerly literally unknown (see Box 1.3).

Many scientific studies have shown certain health benefits from eating fish. One recommendation is that everyone should eat at least two fish meals a week. Thus, demand increased, while supplies from the capture fisheries continued to fall short of the predicted 100 million tonnes a year, even though new wild captured species continued to enter the markets. Often those species became overexploited within a few years – one of many examples being the orange roughy (*Hoplostethus atlanticus*). That species is found primarily on the tops of seamounts in the South Pacific Ocean. Major trawl fisheries were established after high concentrations of the fish were found in the deep ocean waters off New Zealand and Australia. The fish became popular and was widely exported in the form of frozen fillets around the world. What the fishery biologists didn't know was that the orange roughy being harvested were very old (reportedly the species can live for over 100 years), didn't mature until they were some decades of age, and the young fish didn't recruit into the fishery for many years after being produced. Thus, what had apparently been reliable sources of fish became, to put it mildly, overfished. Fishing is greatly restricted now, but recovery may take decades or centuries. Availability of orange roughy in most markets no longer exists.

Developing or former developing nations that have been exporters of aquaculture products to developed nations, largely in North America and Europe, have increasingly large proportions of their own populations with the ability and desire to purchase locally produced aquaculture products. China, India and other Asian nations, plus several in Latin America, are among those in which increasing percentages of aquaculture production are being consumed domestically. As the trend continues, the traditional importing nations may either have to reduce their consumption of aquacultured products or expand their own levels of production.

There is also this question: at what point do the resources necessary for producing the aquaculture products demanded by the world's human population reach their limit? Available amounts of water and space could, at some point, preclude further development of aquaculture on land. Competition for (and the price of) land, and in particular coastal land, will eventually stop further development of aquaculture in many of the world's coastal regions. Competition for water by various users is already having an impact on the further expansion of freshwater aquaculture in some regions. The open ocean is virtually limitless but, at some point, there may not be enough resources (such as supplies of certain feed ingredients) or proximity to land (offshore operations located far from land may be too expensive to produce a product that can be sold at a profit) to allow continued expansion.

History of Aquaculture

Aquaculture is not new. In fact, it has been practised for millennia. Its origins appear to be rooted in China, perhaps as long ago as 2000 years BC. The first known written record describing aquaculture and its benefits was a very short book in Chinese written by Fan Li in 460 BC. By the time of that writing it is likely that aquaculture was already well established. The Japanese reportedly began farming oysters intertidally about 3000 years ago, and a bas-relief from the period of the Pharaohs of Egypt shows people fishing for tilapia in what appear to be culture ponds. Oysters were apparently cultured by the Romans nearly 2000 years ago. Preceding that by a few hundred years was prototype aquaculture associated with the Etruscans, who managed coastal ponds for fish production. Seaweed culture in Korea apparently dates back to the 15th century. Bath sponge culture in China also appears to have a history of several hundred years.

Native Hawaiians constructed hundreds of coastal ponds that were flooded by the tides as a means of stocking them with marine organisms. The animals were then allowed to grow to harvest size. Pond construction preceded the discovery of the Hawaiian Islands by Captain Cook in 1778 by perhaps 500 years.

For literally thousands of years, aquaculture was practised as an extensive form of agriculture by fish and shellfish farmers who shared techniques among themselves and also by others who developed techniques through trial and error. In the late 19th century, advances in aquaculture began to be associated with the development of new technology by naturalists and others who brought more scientific approaches to the discipline. The first examples of science being applied to aquaculture can be attributed to investigators in Europe and North America.

In 1871, Spencer F. Baird (Fig. 1.1), then Smithsonian Institution Secretary in Washington, District of Columbia, USA, convinced the US Congress that an agency was needed to develop methods to increase the supply of fish in the nation's waters. Some aquatic animal populations were already in decline due, in part, to overfishing. One of the first things Baird did, once the Commission was established within a year of his floating the idea, was to hire fish culturists to develop the technology required to mass produce, transport and stock various marine and freshwater fishes and shellfishes in the nation's waters.

Several of the very few fish culturists of the time, including men like Seth Green, Charles Adkins and Livingston Stone, were recruited to work for the Commission. As a result of the activities of those men and their colleagues in the USA and abroad, particularly in Europe, much of the basic technology associated with modern fish culture was developed. In fact, if those early fish culturists were to come back today, they would immediately recognize such a culture system feature as raceways (Fig. 1.2).

As the 20th century dawned, fish and shellfish were being stocked by the hundreds of millions in the USA and other countries. European brown trout (*Salmo trutta*) were introduced to North America, while North American rainbow trout (*Oncorhynchus mykiss*) were distributed throughout much of Europe and even as far away as New Zealand. New Zealand also obtained chinook salmon (*Oncorhynchus tshawytscha* – please do not ask us how to pronounce

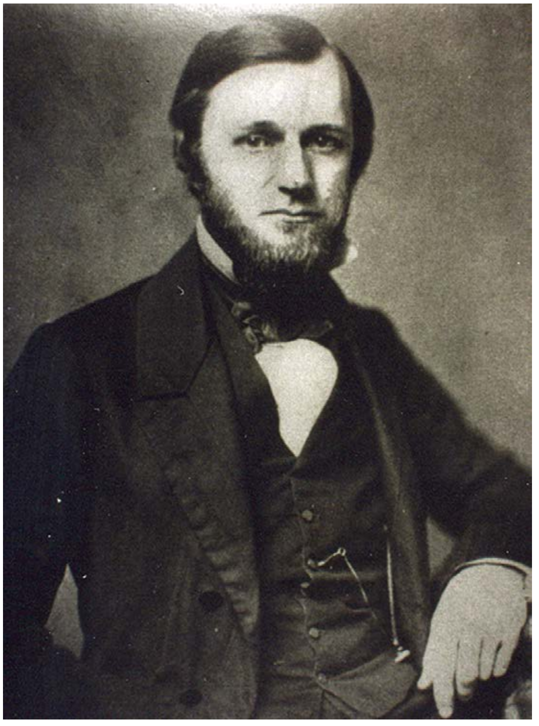

Fig. 1.1. Spencer F. Baird, the first Commissioner of Fish and Fisheries.

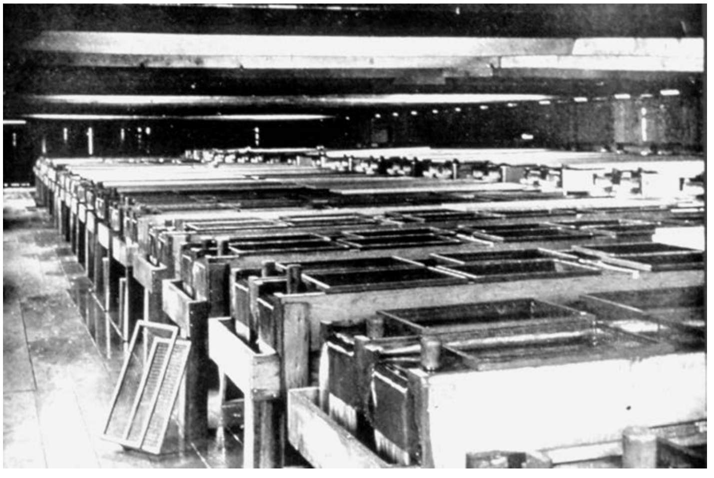

Fig. 1.2. Wooden raceways at a salmon hatchery in the late 19th century were similar to modern hatchery raceways except for the material used in construction.

the species name) from North America. A reproducing population of chinook salmon became established in New Zealand and a fishery for that species has been in place for well over a century. In New Zealand, chinook salmon are known by their Native American name: Quinnat salmon.

The fish culturists of the late 19th century, again in Europe and North America (though there was a lot of activity in Asia that is not too well documented, at least in the English literature), developed many of the techniques that exist today. Species with large eggs, such as trout and salmon, could be fed in the hatchery, but those with small eggs, which represent the majority, could not. Larval salmonids were often fed boiled poultry egg yolk, while older fish were often fed meat from terrestrial animals (e.g. ground horse meat), and it was not until the 1950s that feeds formulated to meet fish nutritional requirements began to be developed. John Halver, then an employee of the US Fish and Wildlife Service, can be credited with determining many of the salmonid nutritional requirements in that decade and continued to contribute to the science of fish nutrition until his death in 2012.

In the 19th century, while billions of eggs and larvae could be produced – often from species for which the original techniques were lost and had to be redeveloped in modern times – there was no way to feed the young animals of many highly fecund animals, for example, so they were released into the wild at hatching with the hope that some would survive. In point of fact, it is likely that the vast majority of the larval fish released from hatcheries (or in some cases, as eggs) became food for other species or perished and decomposed.

Establishment of species outside their native regions of occurrence was rare, again largely because they were stocked at very early stages of development and extremely small sizes, thus having little chance for survival. Transporting them long distances to introduce them to new areas was usually not a reasonable approach. There were a few exceptions, such as the establishment of striped bass (*Morone saxatilis*), which is native to the east coast region of the USA, to California, and the establishment of common carp (*C. carpio*) throughout much of North America after their importation from Europe. Atlantic salmon (*Salmo salar*) eggs and fry were shipped to the west coast of the USA by the millions in the late 1800s and early 1900s, where they were ultimately released, never to be seen again. Pacific salmon eggs (*Oncorhynchus* spp.) were shipped east, put in hatcheries and ultimately released to augment Atlantic salmon stocks. Again, there is no record of survival of Pacific salmon on the eastern seaboard of North America.

Pacific salmon, however, were established in the US Great Lakes in the 1960s. Lauren Donaldson, who began working with salmon culture at the University of Washington in the 1930s, provided salmon for stocking in the Great Lakes, creating what is now at least a US$4 billion annual recreational fishery. Donaldson is also famous for constructing a return pond on the campus of the University of Washington in 1949 to which salmon returned annually. The pond gave students the opportunity to allow the salmon to return virtually to the classroom, where they were stripped of their eggs, which were fertilized, incubated, hatched, reared to smolt size and released, after which some could be relied upon to return to the pond as adults. It is unfortunate that the return pond, and the important opportunity for students to learn about salmon hatchery management that it provided, were eliminated by the university after some 60 years.

I (R.R.S.) was privileged to have had the opportunity to get to know 'Doc' Donaldson when I was affiliated with the University of Washington from 1985 to 1996. He continued to spend time in his office at the university long after his official retirement in the 1970s, counselling graduate students. He also maintained a small flower garden by the fisheries building and delivered blooms to the secretaries in the departmental offices once a week when flowers were available for harvest.

While the fish culturists of the latter part of the 19th century would not have even dreamed of computer-controlled water systems, fibreglass culture tanks or polyvinyl chloride (PVC) plumbing, the modern fish hatchery would look somewhat familiar to the pioneer culturists, who had very primitive facilities. It is likely that, if those early fish culturists were alive today, they would be able to walk into a modern hatchery and recognize much of what they saw.

In the early years, glass jars were used to incubate fish eggs, after which hatched fry were reared in linear raceways (see Chapter 3, for a discussion on raceways and various species that were transported live around the world).

In Europe and North America, much of the aquaculture that was being conducted prior to the middle of the 20th century was in association with government hatcheries and a few private farms that often focused on the production of recreational species. Shellfish, particularly oysters, were an exception in that they were being actively cultured in many nations for human food, as well as pearls. China, of course, continued the practice of carp polyculture that had been developed millennia earlier. A few commercial trout farms were in existence in the USA during the first half of the 20th century and farmers in some areas of the southern USA were looking at buffalo fish (*Ictiobus* spp.) as a possible cash crop. By around 1960, those farmers had moved away from buffalo fish and were establishing the channel catfish (*Ictalurus punctatus*) industry.

During the 1930s, tilapia (primarily *Oreochromis* spp.) were introduced from their native Africa and the Middle East to tropical Asia where they quickly became established. The average Filipino, Malaysian or Indonesian of today does not recognize tilapia as being an exotic species since the majority of their populations grew up consuming locally caught or cultured tilapia.

The decade of the 1960s represents the period when aquaculture began to capture the attention of entrepreneurs, university researchers and the public in the developed world. Trout farming – particularly of rainbow trout (*O. mykiss*) – was expanding in the USA; research in Great Britain on plaice (*Pleuronectes platessa*) was under way; the channel catfish (*I. punctatus*) industry was developing rapidly, first in Alabama and Arkansas and later in Mississippi, which is now the dominant state in terms of production, though several other states have catfish farms; research on tilapia (*Oreochromis* spp. and *Tilapia* spp.) had begun in various nations; tilapia were introduced to the Americas; and interest among researchers to develop even more cultured species around the world began to blossom.

This is not to say that aquaculture was not a prominent activity in some locations and with other species by the 1960s. In their landmark 1972 treatise on aquaculture, John Bardach, John Ryther and William McLarney (see the reference in the 'Additional Reading' section at the end of this chapter) chronicled the global state of affairs and presented detailed information on the methods used to produce a variety of seaweeds, fishes and shellfish. At that time production was largely for domestic consumption and was centred in Asia. International trade in aquaculture products had yet to be developed. Bardach *et al.* described techniques associated with the production of common carp, Chinese carp, Indian carp, catfish, tilapia, milkfish, eels, trout, salmon, striped bass, yellowtail, flatfishes, shrimp, crayfish, crabs, oysters, clams, cockles, scallops, mussels, seaweeds and others, including species of primarily recreational fishing interest which were covered in their book. See Table 1.1 for the common and scientific names of species currently being cultured. The list has expanded significantly not only since 1972, but also since the 3rd edition of this book was published. It is doubtful that the list in Table 1.1 is complete, as it is based on species for which research results have been published. By 1972, some species were of only local interest, like yellowtail (*Seriola quinqueradiata*) in Japan, while others, such as common carp (*C. carpio*), were being cultured in many nations. Carp culture was occurring in Europe (including Eastern Europe) and had been for centuries. Other carp-producing countries were Haiti, India, Israel, Indonesia, Japan, Nigeria, the Philippines, the United Arab Emirates and the USSR. In the USA, the channel catfish industry was growing rapidly but had been in existence only a little over a decade by 1972. Today, a large number of nations produce a wide variety of aquaculture species or are in the process of developing the techniques required to develop additional species.

There was some interest by 1972 in developing economically viable culture techniques for such difficult-to-rear species as Florida pompano (*Trachinotus carolinus*) and American lobster (*Homarus americanus*), but aquaculture of many species, particularly in the tropics, was largely a subsistence activity. That is, aquaculture species were being cultured by small farmers primarily for home or local consumption.

Compared with production levels today, those of the 1960s tended to be very low. For example, channel catfish farmers in the USA produced from 225 to 500 kg/ha in their ponds, compared with up to many times those levels today. Feeds were primitive, diseases and their treatment were not well understood or could not be controlled, and water quality requirements had not been well defined. Those problems, which were certainly not limited to the catfish industry but affected virtually all aquaculturists regardless of what they were raising, became topics of interest for a growing cadre of aquaculture scientists during the 1970s and progress was rapid. There was a great deal of optimism surrounding the notion that aquaculture could fill

Table 1.1. Edible plants, invertebrates and vertebrates that are commercially cultured, under development, or considered as good candidates for culture.

Taxonomic group	Common name	Scientific name
Algae (seaweeds)	Bangia	*Bangia fuscopurpurea*
	Eucheuma	*Eucheuma* sp., *Kappaphycus alvarezii*
	Gracilaria	*Gracilaria* spp.
Kelp	Laminaria	*Laminaria* spp.
	Nori	*Porphyra* spp.
	Laver	*Porphyra yezoensis*
	Wakame	*Undaria pinnatifida*
Macrophytes	Chinese water chestnut	*Eleocharis dulcis*
	Watercress	*Nasturtium* spp.
Echinoderms	Sea cucumbers	
	Black	*Holothuria leucospilota*
	Brown	*Australostichopus mollis* and *Stichopus mollis*
	Brown sandfish	*Holothuria spinifera*
	California	*Parastichopus californicus*
	Curry fish	*Stichopus horrens*
	Japanese	*Apostichopus japonicus*
	Sandfish	*Holothuria scabra*
	White spot	*Holothuria polli*
	No common name found	*Holothuria arguinensis*
	Sea urchins	
	Chilean	*Lytechinus variegatus*
	Collector	*Tripnewutes gratilla*
	Green	*Strongylocentrotus droebachiensis*
	Green or shore	*Psammechinus miliaris*
	Kina	*Evechinus chloroticus*
	Purple	*Anthocidaris crassispina*, *Paracentrotus lividus*, *Strongylocentrotus purpuratus*
	Red	*Mesocentrotus franciscanus*
	No common name found	*Strongylocentrotus intermedius*, *Strongylocentrotus nudus*
Molluscs	Abalone	
	Black lip	*Haliotis rubra*
	Disc (Ezo)	*Haliotis discus discus*
	Donkey's ear	*Haliotis asinine*
	European edible	*Haliotis tuberculata*
	Ezo	*Haliotis discus hannai*
	Giant	*Haliotis gigantean*, *Haliotis madaka*
	Green	*Haliotis fulgens philippi*
	Green lip	*Haliotis laevigata*
	Japanese	*Haliotis diversicolor*
	Northern (Pinto)	*Haliotis kamtschatkana*
	Paua (Blackfoot)	*Haliotis iris*
	Paua (Virgin)	*Haliotis virginea*
	Paua (Queen)	*Haliotis australis*
	Red	*Haliotis rufescens*
	South African	*Haliotis midae*
	Taiwan	*Haliotis diversicolor*

Continued

Table 1.1. Continued.

Taxonomic group	Common name	Scientific name
	Arkshell	*Anadaria* spp., *Scapharca subcrenata*
	Clam	
	Asian hard	*Meretrix meretrix*
	Black	*Chione fluctifraga*
	Blood cockle (mud clam)	*Tegillarca* (*Anadara*) *granosa*
	Boring giant	*Tridacna crocea*
	Carpet shell	*Ruditapes decussatus*
	Hard	*Meretrix lusoria*
	Geoduck	*Panopea abrupta*, *Panopea generosa*, *Panopea globsa*, *Panopea zelandica*, *Panopea japonica* and hybrids
	Giant	*Tridacna noae*
	Manila	*Ruditapes philippinarum*
	Northern quahog	*Mercenaria mercenaria*
	Pullet carpet shell	*Venerupis pullastra*
	Razor	*Ensis arcuatus*, *Ensis siliqua*, *Solen marginatus*
	Short neck (False)	*Paphia malabarica*
	Southern quahog	*Mercenaria campechiensis*
	Spotted hard	*Meretrix petechialis*
	Sunray venus	*Macrocallista nimbosa*
	Surf	*Spisula solidissima*
	Timid venus	*Gafarium tumidum*
	Undulated surf	*Paphia undulata*
	White	*Spisula solida*
	Xishishe	*Coelomactra antiquata*
	Cockle	
	Basket	*Clinocardium nuttallii*
	Blood	*Anadaria granosa*
	Common	*Cerastoderma edule*
	Conch, Queen	*Strombus gigas*
	Cuttlefish	*Sepia lycidas*, *Sepia pharaonus*
	Mussel	
	Blue	*Mytilus edulis*
	Bay	*Mytilus trossulus*
	Brown[a]	*Perna perna*
	Blue-lipped	*Perna viridis*
	Chilean blue	*Mytilus chilensis*
	Cholga	*Aulacomya ater*
	Green	*Perna viridis*
	Green-lipped	*Perna canaliculus*
	Horse-bearded	*Modiolus barbatus*
	Korean	*Mytilus coruscus*
	Mediterranean	*Mytilus galloprovincialis*
	Pearl	*Chamberlania hainesiana*
	Rainbow mussel	*Villosa iris*
	Octopus	
	Common	*Octopus vulgaris*
	Gould	*Octopus mimusa*
	Mexican four-eyed	*Octopus maya*
	Patagonian red	*Enteroctopus megalocyathus*
	No common name?	*Robsonella fontaniana*

Continued

Table 1.1. Continued.

Taxonomic group	Common name	Scientific name
	Oyster	
	American	*Crassostrea virginica*
	European flat	*Ostrea edulis*
	Fujan	*Crassostrea angulata*
	Indian back-water	*Crassostrea madrasensis*
	Cortez	*Crassostrea corteziensis*
	Mangrove	*Crassostrea gasar*
	Pacific	*Crassostrea gigas*
	Slipper cupped	*Crassostrea iredalei*
	Suminoe or Asian	*Crassostrea ariakensis*
	Sydney rock	*Saccostrea glomerata*
	Penshell	*Atrina maura*
	Scallop	
	Bay	*Argopecten irradians*
	Caribbean	*Argopecten nucleus*
	Catarina	*Argopecten circularis*, *Argopecten ventricosus*
	Giant	*Placopecten magellanicus*
	Huaguizhikong	*Chlamys nobilis*
	Japanese or Yesso	*Patinopecten yessoensis*
	King	*Pecten maximus*
	Noble	*Chamys nobilis*
	Northern	*Argopecten purpuratus*
	Lion's paw	*Nodipecten subnodosus*
	Nucleus	*Agropecten nucleus*
	Purple	*Argopecten purpuratus*
	Queen	*Chlamys opercularis*
	Sea	*Placopecten magellanicus*
	Spiny rock	*Spondylus limbatus*
	Zhikong	*Chlamys farreri*
	Whelk	*Dicathais orbita*, *Hemifusus ternatanus*
Crustaceans	Crab	
	Blue (Soft-shell)	*Callinectes sapidus*
	Blue swimmer	*Portunus pelagicus*
	Chinese mitten	*Eriocheir sinensis*
	Flower	*Portunus pelagicus*
	Mud	*Scylla paramosain*, *Scylla serrata*
	Red	*Charbdis feriatus*, *Scylla tranquebarica*
	Southern king	*Lithodes santolla*
	Spider	*Maja brachydactyla*, *Maja squinado*
	Swimming	*Portunus trituberculatus*
	Tiger	*Orithyia sinica*
	Crayfish (Crawfish)	
	Marron	*Cherax tenuimanus*
	Narrow clawed	*Astacus leptodactylus*
	Noble	*Astacus atacus*
	Red claw	*Cherax quadricarinatus*
	Reculilla	*Procambarus acanthophorus*
	Red swamp	*Procambarus clarkii*
	Signal	*Pacifastacus leniusculus*
	White river	*Procambarus acutus*
	Yabby	*Cherax destructor*

Continued

Table 1.1. Continued.

Taxonomic group	Common name	Scientific name
	Lobster	
	American	*Homarus americanus*
	Bay	*Thenus* spp.
	East coast rock	*Panulirus homarus rubellus*
	Eastern spiny	*Sagmariasus verreauxi*
	European	*Homarus grammarus*
	Florida	*Panulirus argus*
	Green rock	*Sagmariasus verreauxi*
	Japanese spiny	*Panulirus japonicus*
	Ornate rock	*Panulirus ornatus*
	Southern rock	*Janus edwardsii*
	Spiny	*Panulirus argus*
	Spiny red rock	*Janus edwardsii*
	Western rock	*Panulirus cygnus*
	Shrimp	
	Amazon river prawn	*Macrobrachium amazonicum*
	Banana	*Penaeus merguiensis*
	Black tiger	*Penaeus monodon*
	Blue	*Litopenaeus stylirostris*
	Brazilian pink	*Farfantepenaeus paulensis*
	Cauque	*Macbrachium americanum*
	Chinese	*Fenneropenaeus chinensis*
	Freshwater	*Macrobrachium nipponense*
	Indian river	*Macrobrachium malcolmsonii*
	Indian white	*Fenneropenaeus indicus*
	Japanese freshwater	*Macrobrachium nipponense*
	Kuruma	*Marsupenaeus japonicus*
	Longarm river prawn	*Macrobrachium tenellum*
	Malaysian giant freshwater	*Macrobrachium rosenbergii*
	Monkey River	*Macrobrachium lar*
	Pacific white	*Litopenaeus vannamei*
	Pink	*Penaeus paulensis*
	Ridgetail white	*Exopalaemon carinicauda*
	Southern brown	*Farfantepenaeus subtilis*
	Southern white	*Litopenaeus schmitt*
	Western king	*Penaeus latisulcatus*
	Western school	*Metapenaeus dalli*
Gastropods	Apple snail	*Pomacea patula*
	Loco	*Concholepas concholepas*
	Snail	*Semisulcospira gottschei*
	Spotted Babylon	*Babylonia areolata*
	Turban snail	*Lithopoma undosa*
Finfish	African bony tongue	*Heterotis niloticus*
	Amazon catfish hybrid	*Leiairus momoatum* × *Pseudoplatsoma reticulatum*
	Amberjack	*Seriola rivoliana*
	Greater	*Seriola dumerili*
	Anchovy, European	*Engraulis encrasicolus*
	Arapaima (Pirarucu, Paiche)	*Arapaima gigas*
	Asian arowana	*Scleropages formusus*
	Asian swamp eel	*Monopterus albus*

Continued

Table 1.1. Continued.

Taxonomic group	Common name	Scientific name
	Asp	*Aspius aspius*
	Atlantic spadefish	*Chaetodipterus faber*
	Ayu	*Plecoglossus altivelis*
	Ballan wrasse (cleaner fish)	*Labrus bergylta*
	Barb	
	Olive	*Puntius sarana*
	Silver	*Puntius* (*Barbonymus*) *gonionotus*
	Barramundi	*Lates calcarifer*
	Bass	
	Palmetto	*Morone chrysops* × *Morone saxatilis*
	Striped	*Morone saxatilis*
	Sunshine	*Morone saxatilis* × *Morone chrysops* hybrids
	Beakfish, Pacific (San Pedro)	*Oplegnathus insignis*
	Bream	
	Oriental	*Abramis brama orientalis*
	Blunt nose black (aka Wuchang)	*Megalobrama amblycephala*
	Triangular	*Megalobrama undulata*
	Brill	*Scophthalmus rhombus*
	Burbot	*Lota lota*
	Butterfly peacock bass	*Cichla ocellaris*
	Catfish	
	African (Vandu)	*Heterobranchus longifilis*
	Australian	*Tandanus tandanus*
	Bagrid (Mahanadi rita)	*Rita chrysea*
	Barred (Surobim)	*Pseudoplatystoma punctifer*
	Basa (Mekong)	*Pangasius bocourti*
	Blue	*Ictalurus furcatus*
	Butter	*Ompok bimaculatus*
	Cachara (Striped surubim)	*Pseudoplatystoma reticulatum*
	Cachapinta	*Pseudoplatystoma reticulatum* × *Pseudoplatystoma corruscans*
	Channel	*Ictalurus punctatus* and hybrids
	Chinese longsnout	*Leiocassis longirostris*
	Darkbarbel	*Pelteobagrus vachelli*
	Far eastern (Korean)	*Silurus asotus*
	Fat greenling	*Hexagrammos otakii*
	Filefish	*Stephanolepis cirrhifer*
	Giant river	*Sperata seenghala*
	Green (River)	*Mystus nemurus*
	Hybrid surubim	*Pseudoplatystoma punctifer* × *Pseudoplatystoma fasciatum*
	Indian	*Clarias batrachus*
	Indian walking	*Clarias magur*
	Jundiá or Silverinese tounge	*Rhamdia quelen*
	Neotropical	*Lophiosilurus alexandri*
	Orinoco striped	*Pseudoplatystoma orinocoense*
	Pacman	*Lophiosilurus alexandri*
	Pangus	*Pangasius hypophthalmus*
	Pengba	*Osteobrama belangeri*
	Pintado	*Pseudoplatystoma horruscans*
	Sampa or Vundu	*Heterobranchus longifilis*

Continued

Table 1.1. Continued.

Taxonomic group	Common name	Scientific name
	Sharptooth	*Clarias gariepinus*
	Silver	*Rhamdia quelen* and *Chrysichys nigrodigitatus*
	Stinging (Singhi)	*Heteropneustes fossilis*
	Striped	*Pangasianodon hypopthalmus*
	Tra (Striped, Sutchi)	*Pangasius* (*Pangasianodon*) *hypophthalmus*
	Trey pra	*Pangasius djambal*
	Ussuri	*Pseudobagrus ussuriensis*
	Wels	*Silurus glanis*
	Yellow	*Pelteobagrus fulvidraco*
	Charr	
	Arctic	*Salvelinus alpinus* and hybrids
	Dolly Varden	*Salvelinus malma*
	Chinese fish (no common name in English)	*Schizothorax davidi*
	Chinese perch (Mandarin fish)	*Siniperca chuatsi* and *Siniperca scherzeri*
	Clariothalmus and Pangapinus	*Clarias garepinus* × *Pangasianodon hypopthalmus*
	Cobia	*Rachycentron canadum*
	Cod	
	Atlantic	*Gadus morhua*
	Murray	*Maccullochella peelii*
	Croaker	
	Atlantic	*Micropogonias undulatus*
	Japanese	*Nibea japonica*
	Large yellow	*Pseudosciaena crocra*
	Miiuy	*Miichthys miiuy*
	Nibe	*Nibea mitsukuri*i
	Whitemouth	*Micropogonias furnieri*
	Culter	
	Mongolicus	*Culter mongolicus*
	Topmouth	Culter *alburnus*
	Curimba	*Prochilodus lineatus*
	Cyprinids	
	African carp	*Labeo parvus*
	Bata	*Labeo bata*
	Bighead carp	*Aristichthys nobilis*
	Catla	*Catla catla*
	Chinese longsnout carp	*Leiocassis longirostris*
	Common carp	*Cyprinus carpio*
	Gibel carp	*Carassius auratus gibelio*
	Grass carp	*Ctenopharyngodon idella* and *Clarias magur*
	Kuria labeo	*Labeo gonius*
	Mahseer	*Tor douronensis*, *Tor tambroides*
	Mrigal	*Cirrhinus mrigala*
	Mud carp	*Cirrhina molitorella*
	Orangefin labeo	*Labeo calbasu*
	Pengze Crucian	*Carrassius auratus* var. Pengze
	Rock carp	*Procypris rabaudi*
	Rohu	*Labeo rohita*
	Sahar	*Tor putitora*
	Scaleless carp	*Gymnocypris przewalskii*
	Silver carp	*Hypophthalmichthys molitrix*
	Snowtrout	*Schizothorax richardsonii*
	Yellow River	*Cyprinus carpio haematoperus*

Continued

Table 1.1. Continued.

Taxonomic group	Common name	Scientific name
	Dentax	
	Common	*Dentax dentax*
	Pink	*Dentax gibbosus*
	Dourado	*Salminus brasiliensis*
	Drum	
	Cuneate	*Nibea miitchthiodes*
	Red	*Sciaenops ocellatus*
	Shi	*Umbrina cirrosa*
	Yellow	*Nibea albiflora*
	Eel	
	American	*Anguilla rostrata*
	European	*Anguilla anguilla*
	Japanese	*Anguilla japonica*
	Marbled	*Anguilla marmorata*
	New Zealand shortfin	*Anguilla australis*
	New Zealand longfin	*Anguilla dieffenbachia*
	Rice field (Asian swamp)	*Monopterus albus*
	Shortfin	*Anguilla bicolor*
	Whitespotted conger	*Conger myriaste*r
	Flounder	
	Barfin	*Verasper moseri*
	Black	*Paralichthys orbignyanus*
	Brazilian	*Paralichthys orbignyanus*
	Cortez	*Paralichthys aestuarius*
	Fine	*Paralichthys adspersus*
	Olive	*Paralichthys olivaceus*
	Southern	*Paralichthys lethostigma*
	Stone	*Kareius bicoloratus*
	Summer	*Paralichthys dentatu*s
	Winter	*Pseudopleuronectes americanus*
	Yellowtail	*Pleuronectes ferrugineus*
	Fugu	*Takifugu rubripes*
	Giant gourami	*Osphronemus gorami*
	Goby, Marble	*Oxyeleotris marmorata*
	Golden trevally	*Gnathanodon speciosus*
	Golden mandarin	*Siniperca sherzeri*
	Golden mahseer	*Tor putitora*
	Grayling, European	*Thymallus thymallus*
	Grouper	
	Brown-marbled (Tiger)	*Epinephelus fuscogutattus*
	Dusky	*Epinephelus marginatus*
	Giant	*Epinephelus lanceolatus*
	Humpback	*Cromileptes altivelis*
	Kelp	*Epinephelus bruneus*
	Leopard	*Mycteroperca rosacea*
	Leopard coral	*Plectropomus leopardus*
	Longtooth	*Epinephelus bruneus*
	Orange spotted	*Epinephelus coioides* and hybrids
	Malabar	*Epinephelus malabaricus*
	Sevenband	*Epinephelus septemfasciatus*
	White	*Epinephalus aeneus*

Continued

Table 1.1. Continued.

Taxonomic group	Common name	Scientific name
	Grunt, Yellow-spotted	*Plectorhinchus cinctus*
	Haddock	*Melanogrammus aeglefinus*
	Hake, European	*Merluccius merluccius*
	Halibut	
	Atlantic	*Hippoglossus hippoglossus*
	California	*Paralichthys californicus*
	Pacific	*Hippoglossus stenolepis*
	Spotted	*Verasper variegatus*
	Hapuku	*Polyprion oxygeneios*
	Humped featherback	*Chitala chitala*
	Knifejaw, Barred	*Oplegnathus fasciatus*
	Kutum	*Rutilus frisii kutum*
	Lambari	
	Silver	*Astamax scarbiprinnus*
	Yellowtail	*Astamax lacustris*
	Lenok	*Brachymystax lenok*
	Loach	
	Large scale	*Paramisgurnus dabryanus*
	Pond	*Misgurnus anguillicaudatus*
	Lumpfish	*Cyclopterus lumpus*
	Mackerel	
	Chub	*Scomber japonicas*
	Horse	*Trachurus mediterraneus*
	Jack	*Trachurus japonicas*
	Mahi-mahi (Dolphinfish)	*Coryphaena hippurus*
	Mandarin fish	*Siniperca chuatsi*
	Meagre	*Argyrosomus regius*
	Milkfish	*Chanos chanos*
	Mojarra, Mexican	*Cichlasoma urophthalmus*
	Mola	*Amblypharyngodon mola*
	Mrigal	*Cirrhinus mrigala*
	Mudskipper	*Pseudopocyptes elongates*
	Mullet	
	Striped	*Mugil cephalus*
	Thicklipped grey	*Chelon labrosus*
	Thinlip	*Mugil ramada*
	Mulloway (Dusty kob)	*Argyrosomus japonicus*
	Pacamã	*Lophiosilurus alexandri*
	Pacific threadfin (Moi)	*Polydactylus sexfilis*
	Pacu	*Piaractus brachypomus* and *Piaractus mesopotamicus*
	Black	*Colossoma macropomum*
	Red	*Piaractus brachypomus*
	Pacama	*Lophiosilurus alexandri*
	Paddlefish	*Poliyodon spathula*
	Palm ruff	*Seriolella violacea*
	Parrot fish	*Oplegnathus faciatus*
	Pearlspot cichlid	*Etroplus suratensis*
	Pejerrey	*Odontesthes bonariensis*
	Perch	
	Eurasian	*Perca fluviatilis*
	Jade	*Scortum barcoo*
	Sea	*Lateolabrax japonicus*

Continued

Table 1.1. Continued.

Taxonomic group	Common name	Scientific name
	Silver	*Bidyanus bidyanus*
	Yellow	*Perca flavescens*
	Permit	*Trachinotus falcatus*
	Pigfish	*Orthopristis chrysoptera*
	Pikeperch	*Sander lucioperca*
	Pink ear emperor	*Lethrinus lentjan*
	Piracanjuba	*Brycon orbignyanus*
	Pirarucu	*Arapaima gigas*
	Plaice	*Pleuronectes platessa*
	Pollack	*Pollachius pollachius*
	Pomfret, Silver	*Pampus argenteus*
	Pompano	*Trachinotus americanus*
	Golden	*Trachinotus blochii*
	Indian	*Trachinotus mookalee*
	Ovate	*Trachinotus ovatus*
	Shortfin	*Trachinotus falcatus*
	Snubnose	*Trachinotus blochii*
	Porgy, Red	*Pagrus pagrus*
	Pufferfish	
	Bullseye	*Sphoeroides annulatus*
	Obscure	*Takifugu fasciatus*
	Striped	*Takifugu obscurus*
	Tawny	*Takifugu flavidus*
	Tiger	*Takifugu rubripes*
	Punti	*Puntius sophore*
	Rabbitfish	
	Pearly spinefoot	*Siganus canaliculatus*
	Spinefoot	*Siganus rivulatus*
	Sablefish	*Anoplopoma fimbria*
	Salmonids	
	Amago	*Oncorhynchus masou*
	Atlantic salmon	*Salmo salar*
	Brown trout	*Salmo trutta*
	Chinook salmon	*Oncorhynchus tshawytscha*
	Chum salmon	*Oncorhynchus keta*
	Coho salmon	*Oncorhynchus kisutch*
	European huchen	*Hucho hucho*
	Masu salmon	*Oncorhynchus masou*
	Rainbow	*Oncorhynchus mykiss*
	Scat, Spotted	*Scatophagus argus*
	Scup	*Stenotomus chrysops*
	Sea bass	
	Barramundi	*Lates calcarifer*
	Black	*Centropristis striata* and *Sparus macrocephalus*
	Brown rockfish	*Sebastes auriculatus*
	Dark-banded rockfish	*Sebastes inermis*
	European	*Dicentrarchus labrax*
	Grass rockfish	*Sebastes rastrelliger*
	Japanese	*Lateolabrax japonicus*
	Korean rockfish	*Sebastes schlegeli*
	Spotted	*Lateolabrax maculatus*
	White	*Aloploma fmbra* and *Atractoscion nobilis*

Continued

Table 1.1. Continued.

Taxonomic group	Common name	Scientific name
	Sea bream	
	Black	*Acanthopagrus schlegeli*
	Blackspot	*Pagellus bogaraveo*
	Blunt snout	*Megalobrama amblycephala*
	Gilthead	*Sparus aurata*
	Red	*Pagrus major*
	Redbanded	*Pagrus auriga*
	Sharpsnout	*Diplodus puntazzo* or *Puntazzo puntazz*
	Sobaity (Bluefin)	*Sparidentex hasta*
	Two-banded	*Diplodus vulgaris*
	White	*Diplodus sargus*
	Yellowfin	*Acanthopagrus latus*
	Vimba	*Vimba vimba*
	Sea trout, Spotted	*Cynoscion nebulosus*
	Sleeper fish	*Odontobutis potamophila*
	Smelt, Japanese	*Hypomesus nipponensis*
	Snakehead	
	Giant	*Channa micropelte*
	Northern	*Ophiocephalus argus*
	Striped	*Channa striata*
	Spotted	*Channa punctata*
	Snapper	
	Australian	*Pagrus auratus*
	Emperor	*Lujanus sebae*
	Mangrove red	*Lutjanus argentimaculatus*
	Pacific red	*Lutjanus peru*
	Pandora	*Pagellus erythrinus*
	Red	*Lutjanus campechanus*
	Spotted rose	*Lutjanus guttatus*
	Yellowtail	*Ocyurus chrysuru*s
	Snook	
	Bay	*Petenia splendida*
	Black	*Centropomus nigrescens*
	Common	*Centropomus undecimalis*
	Fat	*Centropomus parallelus*
	Sole	
	Aguhlas	*Austroglossus pectoralis*
	Chinese tongue	*Cynoglossus semilaevis*
	Common	*Solea solea*
	Half-smooth tongue	*Cynoglossus semilaevis*
	Senegalese	*Solea senegalensis*
	Tongue	*Cynoglossus semilaevis*
	Wedge	*Dicologoglossa cuneata*
	Streaked prochid	*Prochilodus lineatus*
	Striped bass	*Morone saxatilus* and hybrids
	Striped trumpeter	*Latris lineata*
	Sucker	
	Chinese	*Myxocyprinus asiaticus*
	June	*Chasmistes liorus*
	Sweetlips, Indian Ocean oriental	*Plectorhinus vittatus*
	Sturgeon	
	Amur	*Acipenser schrenkii*

Continued

Table 1.1. Continued.

Taxonomic group	Common name	Scientific name
	Beluga	*Huso huso*
	Bester	*Huso huso* × *Acipenser ruthenus*
	Darby's	*Acipenser dabryanus*
	Chinese	*Acipenser sinensis*
	Russian	*Acipenser gueldenstaedtii*
	Ship	*Acipenser nudiventris*
	Shortnose	*Acipenser brevirostrum*
	Siberian	*Acipenser baeri*
	Sterlet	*Acipenser ruthenus*
	Stellate	*Acipenser stellatus*
	White	*Acipenser transmontanus*
	Tambaqui	*Colossoma macropomum*
	Tautog	*Tautoga onitis*
	Tench	*Tinca tinca*
	Tenguayaca (bay snook)	*Petenia splendida*
	Tilapia	
	Blue	*Oreochromis aureus*
	Milawian	*Oreochromis shiranus*
	Mozambique	*Oreochromis mossambicus*
	Nile	*Oreochromis niloticus*
	Redbreast	*Tilapia rendalli*
	Totoaba	*Totoaba macdonaldi*
	Tripletail, Pacific	*Lobotes pacificus*
	Tuna	
	Northern bluefin	*Thunnus thynnus*
	Pacific bluefin	*Thunnus orientalis*
	Southern bluefin	*Thunnus maccoyii*
	Yellowfin	*Thunnus albacares*
	Turbot	*Scophthalmus maximus*
	Waigieu seaperch	*Psammoperca waigiensis*
	Whitebait	*Galaxias maculatus*
	Whitefish, European or Lake	*Coregonus lavaretus*
	White trevally	*Pseudocaranx dentax*
	Wolffish	
	Spotted	*Anarichus minor*
	Striped	*Anarchichas lupus*
	Wreckfish	*Polyprion americanus*
	Yellowtail	*Seriola quinqueradiata* and *Seriola dorsalis*
	Yellowtail kingfish	*Seriola lalandi*
	Yellowtail tetra	*Astyanax altiparanae*
	Zander	*Sander lucioperca*
Amphibians	Bullfrog	*Rana catesbeiana*
	Chinese frog	*Hoplobatrachus rugulosa*
Reptiles	American alligator	*Alligator mississippiensis*
	Big-headed turtle	*Platysternon megacephalum*
	Broad-snouted caiman	*Caiman latirostris*
	Chinese soft-shelled turtle	*Pelodiscus* (*Trionx*) *sinensis*
	Three-keeled pond turtle	*Chinemys reevesii*

[a] The brown mussel is highly invasive in areas outside its native range. For example, brown mussels clog pipelines and attach to boats from which they can be transferred to new sites. However, in some areas they are cultured as a highly desirable human food species.

the anticipated gap between supply of and demand for fisheries products as the predicted peaking of the supply of products from the world's capture fisheries grew increasingly imminent.

In the USA, a few government laboratories and various academic institutions became interested in aquaculture before there was much of a commercial industry outside trout and catfish. Unlike the development of agricultural research, which came in response to the needs of farmers, aquaculture research actually was out in front of the industry's development in many instances (a situation which continues to the present). Part of the explanation for the difference lies in the fact that techniques associated with the culture of the few aquatic species that were commercially reared prior to the 1960s had been developed in government hatcheries for the purpose of stocking the nation's waters, so at least a few universities offered courses in fish culture in their departments of biology, fisheries, or wildlife and fisheries. A College of Fisheries had been established at the University of Washington early in the 19th century. The College offered courses in culturing fish among many other things (e.g. ichthyology, fishery management), but initially focused on seafood science.

However, by the 1960s only a few farmers had adopted aquaculture techniques and begun commercial production. In most instances, researchers in universities evaluated new species that might be of commercial interest and developed the technology needed for successful farming before commercial industries for those new species became established. Techniques for the culture of such recreational fish species as largemouth bass (*Micropterus salmoides*), bluegill (*Lepomis macrochiris*), northern pike (*Esox lucius*) and muskellunge (*Esox masquinongy*) had been developed in government facilities; as had, by the way, the techniques for spawning channel catfish (*I. punctatus*) and other species that were ultimately commercialized.

Most species of interest to terrestrial farmers – both plants and animals – were already being grown in the USA prior to the recognition by producers of the need for research. Thus, farmers drove the impetus for agricultural research. The opposite was largely true for aquaculture, where researchers often developed the techniques required to rear new species before commercial culturists became interested. That was true not only in North America, but also in Europe. As a corollary, there are few – if any – new species being developed for agriculture (genetically engineered organisms aside), while aquaculture researchers continue to search for new species that might be adopted by producers. Today, hundreds of plant species and animals are being produced in aquaculture for human consumption (Table 1.1).

The primary species of terrestrial animals being reared for human consumption compared with species of aquaculture interest is revealing (Box 1.4).

Some species of interest have been found difficult to culture as knowledge about their environmental, nutritional and other unique requirements become better understood, though progress is being made in many cases. Included are American (*H. americanus*) and Florida (*Panulirus argus*) lobsters and spiny lobsters (various species), along with many species of crabs. Some culture of mud crabs is presently underway in South-East Asia. Rearing of lobsters is impeded by the fact that nine months to one year of larval development is required before metamorphosis into the juvenile stage, at which time they, finally and at long last, take on the appearance of the adult. During those months the larvae are rather feathery in appearance and are very fragile. If even as few as two of them come into contact with one another, they are likely to become intertwined, in which case they will die.

American lobsters (*H. americanus*) – the ones with the big claws or chelae – are highly cannibalistic. When one lobster is in a confined area such as an aquaculture tank and moults (sheds its exoskeleton so it can grow), it is vulnerable to attack by the others. Crabs typically exhibit the same behaviour as American lobsters. The stocking of a large number of lobsters or crabs in a single container may result in the production of one large animal. One way around the problem is to stock the animals in separate chambers (sometimes described as lobster

Box 1.4.

Primary livestock species groups being cultured in the world.

- Poultry (chickens, ducks, turkeys, geese)
- Swine
- Cattle (beef cattle, dairy cows, buffalo, water buffalo)
- Camels
- Horses
- Goats
- Sheep

and crab condominiums). There appears to have been some success associated with rearing crabs communally if they are fed frequently enough that they do not attack members of recently moulted individuals. Marine shrimp (family Penaeidae and often referred to as penaeids) tend to be much less cannibalistic, though cannibalism has been a problem with freshwater shrimp such as the Malaysian giant freshwater shrimp (*Macrobrachium rosenbergii*, as described in Box 1.5).

During the 1960s and 1970s, a lot of attention was focused on shrimp culture. Two techniques for larval rearing were developed, one in Taiwan (the green water system), the other in the USA (the Galveston system). The green water system, as the name implies, involves maintaining a high level of phytoplanktonic algae cells in the culture medium where shrimp developing eggs and larvae are being cultured. The Galveston system uses hatching and larval-rearing facilities that do not incorporate added phytoplankton. Because some species of Asian shrimp have been found more amenable to culture than shrimp species that inhabit US waters, culture of native species in North America was largely abandoned, though some production of native shrimp for the bait industry was developed.

Tuna are examples of one of many finfish that have been difficult to culture. While the techniques for spawning and rearing some species have been developed, aquaculture at present primarily involves capturing young fish in purse seines and moving them to grow out in coastal net pens where they are fed until they reach market size. The most lucrative market is Japan where sushi-grade tuna can bring extremely high prices, depending upon the quality of each individual fish. A high-quality tuna can fetch over US$100/kg. Capture of tuna at sea and rearing in captivity was pioneered in Australia and the technique is now widely practised.

Box 1.5.

Freshwater shrimps are commonly referred to as freshwater prawns by both producers and aquaculture scientists. In reality, the term prawn refers to any large shrimp, regardless of the species or where it lives, so we include both marine and freshwater shrimp interchangeably, though the term prawn is used in Table 1.1 where the common name is recognized.

Culture Objectives

Under the definition of aquaculture used in this book, any one or more of a number of objectives may be a focus of the culturist. Production of fish for stocking, which began in the USA, Canada, Europe and elsewhere after hatchery techniques were developed, has been a primary objective as mentioned in the brief history of aquaculture above. Commercial production is not only associated with the production of species that are sold as human food – though that is a large fraction of the global industry – but also involves organisms produced for other purposes. The majority of aquatic animals currently being cultured for human food are members of one of only four phyla: Echinodermata, Mollusca, Arthropoda or Chordata. Other than finfish, the chordates cultured for human consumption include amphibians (frogs) and reptiles (turtles and alligators). Sea urchins are produced for their edible gonads, while frogs and alligators are reared for meat, and in the case of alligators, also for their hides. Sea turtles, in particular green sea turtles (*Chelonia mydas*), have been cultured for human food and some of their body parts have been used for jewellery.

Green turtle shells were collector's items and preserved young animals were also sold. Because of the threatened or endangered status of some sea turtle species, including green sea turtles, the possession of those animals or products produced from them is currently prohibited in some countries, including the USA. A commercial green turtle farm that was established in the Cayman Islands a few decades ago to produce turtles for human food, as well as for marketing carapaces and other body parts, changed to producing turtles for release to augment natural populations, in an effort to promote recovery of the species. The turtle farm became a tourist attraction, which provided the resources required to continue the enhancement stocking programme. In the USA, the eggs of green turtles and others are collected from turtle nesting sites, incubated in hatcheries, reared for a period of time and released into the sea for enhancement. Federal agencies, such as the US National Oceanic and Atmospheric Administration (NOAA) (e.g. the Galveston, Texas laboratory), are involved in those activities.

Sea ranching is a rather unique type of aquaculture. In most but not all cases, sea ranching involves salmon. Sea ranching in the state of Alaska, USA, is a good example. Salmon broodfish (*Oncorhynchus* spp.) are collected when they enter streams to spawn and their eggs are taken from their nests (redds) to hatcheries where their eggs and milt (sperm) are obtained through a process called stripping. Once the eggs hatch and the fry absorb their yolk sacs, young fish are reared to the smolt stage, at which time they are able to enter seawater. They are then released into the stream from which their parents were captured. After they reach maturity at sea (the time required varies by species, but is usually two years or more), they will return to the water outside the hatchery where they were born. The majority of the returning adults are often intercepted by the commercial fishery before the returning fish reach their destinations; however, escapement quotas are established to allow sufficient numbers of them to reach the hatchery where they are used as broodstock to produce the next generation. Commercial fishermen pay for the opportunity to catch the returning fish. It is the fees obtained from commercial fishermen that pay the operating costs of the hatcheries.

A variation of salmon ranching has been used to some extent in Japan with schooling fishes of various species. The fish are reared during the early phase of culture in marine cages associated with feeding stations and are fed in conjunction with an accompanying sound that the fish learn to associate with feeding time. Once trained, the fish are released and will return to the feeding station when they hear the sound. Once they reach market size they can be captured with nets when they are lured to the feeding station.

Stock enhancement of marine fishes is similar to sea ranching as it involves spawning and hatchery rearing of young fish for release, as described in the case of sea turtles. Basically, enhancement stocking had its beginnings with the US Fish and Fisheries Commission's activities in the 1870s. What has changed since is that few species, other than salmon, are being stocked in public marine waters of North America to augment commercial fisheries today, though Japan has been actively producing marine fish and shrimp for enhancement stocking – with varying results – for several decades. The goal is to rebuild stocks that have declined, in many cases due to overfishing, in order to create sustainable fisheries. The difference between stock enhancement and sea ranching is that the adults do not return to a hatchery but must be captured at sea or reared through the life cycle in captivity to be used as replacement broodstock. An increasingly popular form of stock enhancement in the USA is targeted at improving recreational fisheries. For example, red drum (*Sciaenops ocellatus*) and spotted sea trout (*Cynoscion nebulosus*) are two coastal fish species that are produced by state hatcheries to improve stocks for recreational fishing.

Certainly, stocking animals at the proper life stage and size in a hospitable environment that can accommodate them in terms of food resources and in which they will not outcompete other desirable species are considerations that play a role in the success of any enhancement programme. Until recent years, little attention was paid to those factors as the efforts were all expended on releasing animals into the environment, and not on determining if there was a benefit that accrued from the activity. The focus has now been shifted and a considerable amount of effort has been placed on research to develop an understanding of how to use enhancement effectively and wisely. There is also a focus on the hatchery phase of production. The quality of fish produced in hatcheries and then stocked into the wild is of critical importance if the fish are to survive and recruit into a fishery. If released fish only serve as food for wild predators, enhancement will not be successful.

It is probable that the billions, or more likely trillions, of fish eggs and larvae released into the marine environment by the US Fish and Fisheries Commission in the latter quarter of the 19th and the first quarter or longer of the 20th century served largely as food for predators or died because they were stocked into waters of quality they could not tolerate (inappropriate temperature, salinity, etc.). The success rate was somewhat better with respect to stocking freshwater species into low-salinity environments. While Japan has the longest history of enhancement stocking in the modern era, other nations are also conducting programmes and researching how best to employ the practice to achieve maximum success.

In Hawaii, USA, Pacific threadfin, known locally as moi (*Polydactylus sexfilis*), are subjects of enhancement, while in Texas tens of millions of young red drum (*S. ocellatus*), also known as redfish or channel bass in some regions, are released into the Gulf of Mexico each year. That activity, which is meant to enhance the recreational fishery, has been under way for decades and the effort has been extended to spotted sea trout (*C. nebulosus*) and southern flounder (*Paralichthys lethostigma*). China has been involved with an enhancement programme for Chinese sturgeon (*Acipenser sinensis*) for several years. Many other species are currently being produced for enhancement.

Historically, marine ornamental species were only captured from the wild, usually in tropical nations, and shipped to North America, Europe and various other regions for sale. Overfishing, damage to the environment associated with collection methods (cyanide and dynamite have commonly been used to collect marine ornamental fishes with lethal effects on non-target species and frequent latent mortality of the target species as well) and improper handling of captured fish have added to the problems associated with the industry. Those problems can be largely overcome if the species are cultured rather than captured, because regulations have been ineffective for the most part.

Some aquarium fish species, such as zebrafish (*Danio rerio*), are used in biomedical research, as are cuttlefish (order Sepiida). The latter (Fig. 1.3) have been cultured for their giant axons used in the study of nerve transmission. Various other freshwater and marine species are cultured for biomedical research. The Japanese killifish, commonly known as medaka (*Oryzias latipes*), is a species widely cultured for use in biomedical research.

Aquatic plants, like their animal counterparts, have a variety of uses. Many types of seaweed are consumed as human food (Table 1.1). For example, the red algae nori (*Porphyra* spp.) is consumed throughout the world. Markets in Japan feature a wide variety of dried seaweeds that are used in many dishes as well as for sushi wrappers. Kelp is often dried on the beach (Fig. 1.4) and then marketed for

Fig. 1.3. Cuttlefish cultured for biomedical research.

Fig. 1.4. Kelp being laid out on gravel to dry in Japan.

human consumption or used as a food source in abalone culture. Seaweed extracts, including agar, algin and carrageenan, have a broad variety of uses. They can be found in pharmaceutical products, toothpaste, ice cream and even automobile tyres, among many other products. One species of red algae in the genus *Chondrocanthus* is used as the basis for a very expensive facial cream that is supposed to make the user look younger.

Japan is one of a large number of countries that are involved in seaweed culture and harvesting. China, Taiwan, India, Bangladesh, the Philippines, Malaysia, Indonesia, Thailand, Korea, Cambodia, Sri Lanka, the Pacific Islands, Chile, Norway, Brazil and Canada are a few additional examples of nations involved in the activity.

Seaweeds are also sources of chemicals such as iodine and the red pigments, β-carotene and carotenoids. Carotenoids have been used in fish feeds to produce the pink flesh coloration that buyers like to see in salmon. Some trout culturists also use β-carotene to make the flesh appear more like that of salmon. The worldwide commercial harvest of seaweeds has been estimated at some 8 million tonnes, over 85% of which is said to be cultivated.

Other types of algae are sources of nutritional supplements, and a number of species find wide use as food for other cultured species (Table 1.2). Those are primarily microscopic and often single-celled phytoplanktonic algae. There are also companies growing phytoplankton with the idea of producing biodiesel fuel. A few phytoplanktonic algal species are used to remove nutrients from culture water (as are some seaweeds), in human foods, as industrial extracts, or to enhance colour in aquatic species (e.g. *Spirulina* spp.). The topic of growing phytoplankton for feeding aquacultured animals is discussed in Chapter 6 (this volume) and mentioned elsewhere (consult the Index). Freshwater plants such as water chestnuts are also grown in many nations. There are also aquaculturists who specialize in growing water lilies, of which there are many varieties that are often featured in backyard ponds, although these are not used for human consumption. Some varieties that have been developed command high prices.

Various zooplankton species are produced by aquaculturists to feed larval species that will not accept prepared feeds at that stage of their development. Examples are larval shrimp and a number of fish species, including halibut (*Hippoglossus* spp.), the females of which may ultimately reach weights of a few hundred kilograms. A number of zooplankton species that have been used as live food for larval culture animals are presented in Table 1.3.

Another objective of aquaculture is bait production for use by recreational fishermen. In nations where sport fishing is popular, the availability of live bait can be very important, depending upon the species being targeted – many sportfish will take artificial lures, though for others both artificial and live bait work well. Some live baits are from terrestrial sources (e.g. crickets and earthworms). In terms of aquatic organisms, live bait includes minnows (various genera), goldfish (*Carassius auratus*), killifish (e.g. *Fundulus* spp.), polychaete worms (e.g. *Nereis* spp.), marine shrimp (e.g. *Penaeus aztecus*) and a number of other organisms. Of those, minnows of various species are the basis of a large industry in the USA. Technology for the production of bait shrimp has been developed in the USA with native Gulf of Mexico species. Cultured bait shrimp can be used to maintain the supply of bait during periods when wild shrimp are not available in sufficient numbers to meet the demand.

Many aquatic organisms are being evaluated as sources of chemicals that can be used in pharmaceutical products or as nutritional supplements. A few compounds from one or both of those categories have already been put into production and it is likely that many more will join them in the future. The term 'fishpharming' has been coined in conjunction with the development of genetically modified fish to produce pharmaceuticals useful in human medicine and as disease models, particularly in conjunction with cancer. Zebrafish are one example of a fish species that has been used as a bioreactor or incubator to produce beneficial chemicals.

A Wide Variety of Species

We have seen in Table 1.1 a list of what should represent the majority of the species of interest to aquaculturists for production primarily as human food, though some of the species listed have other uses too, as indicated above. Some of the species are relatively new on the aquaculture scene and are currently available only in small numbers, while others support mature industries, and several are in the development stage and may not support an industry as yet. Aquaculturists seem to always be looking for new species to culture, and some of those are ultimately adopted by commercial producers. Thus, it is likely that the list of aquaculture

Table 1.2. Some algae species that are used as food for cultured abalone, humans, industrial extracts, and/or removing nutrients from water associated with aquaculture systems.

Alaria esculenta
Amphora spp.
Amphiprora paludosa
Bangia fuscopurpurea
Chaetoceros calcitrans, *Chaetoceros gracilis*, *Chaetoceros muelleri*, *Chaetoceros neogracile*
Chlorella minutissima, *Chlorella vulgaris*
Chondracanthus chamissoi
Chondrus crispus
Cystoseira spp.
Dunaliella tertiolecta
Ecklonia cava
Enteromorpha prolifera
Eucheuma denticulatum
Gracilaria cervicornis, *Gracilaria chilensis*, *Gracilaria conferta*, *Gracilaria dura*, *Gracilaria edulis*, *Gracilaria gracilis*, *Gracilaria lemaneiformis*, *Gracilaria tikvahiae*, *Gracilaria vermiculophylla*, *Gracilaria verrucosa*
Hizikia fusiformis
Isochrysis galbana
Kappaphycus alvarezii
Koliella antarctica
Laminaria digitata, *Laminaria japonica*, *Laminaria saccharina*
Macrocystis pyrifera
Microcystis aeruginosa
Nannochloropsis oculata
Navicula incerta, *Navicula seminulum*
Nitzschia thermalis
Palmaria palmata
Pavlova lutheri, *Pavlova pinguis*
Phaeodactylum tricornutum
Platymonas helgolandica
Porphyra yezoensis, *Porphyra tenera*
Proschkinia spp.
Rhaphoneis surirella
Saccharina latissima
Sargassum fusiforme, *Sargassum pallidum*
Scenedesmus quadricauda
Skeletonema costatum, *Skeletonema marinoï*
Spirulina spp.
Tisochrysis lutea
Tetraselmis chuii, *Tetraselmis suecica*, *Tetraselmis tetrathele*
Ulvella lens
Ulva lactuca, *Ulva ohnoi*
Undaria pinnatifida

species will continue to grow to some extent, though probably not as rapidly as in the past few decades. For some reason, aquaculture researchers, unlike their counterparts who deal with terrestrial animal production, cannot seem to stick to only a handful of species. They continuously look for new species to culture, often with the intent of ultimately seeing those species serve as the basis for new aquaculture commodities. Beef cattle, swine and poultry researchers must just scratch their heads at the concept of having the option of hundreds of species from which to select.

Table 1.3. Some zooplanktonic species being produced or with potential for use in feeding larval aquaculture species.

Scientific name	Group
Acartia tonsa, *Acartia sinjiensis*	Copepods
Artemia fransiscana, *Artemia salina*, *Artemia urmiana*	Brine shrimp
Apocyclops dengizicus, *Apocyclops royi*	Copepod
Bestiolina similis	Copepod
Brachionus angularis, *Brachionus plicatilis*, *Brachionus rotundiformis*	Rotifers
Calanus finmarchicus	Copepod
Centropages typicus	Copepod
Ceriodaphnia quadrangular	Cladoceran
Daphnia spp.	Cladocerans
Mesopodopsis orientalis	Mysid
Moina macrocopa, *Moina micrura*	Cladocerans
Paracyclopina nana	Copepod
Parvocalanus crassirostris	Copepod
Proales similis	Rotifer
Psuedodiaptomus annandalei, *Psuedodiaptomus euryhalinus*, *Psuedodiaptomus pelagicus*, *Psuedodiaptomus richardi*	Copepods
Schmackeria poplesia	Copepod
Temora stylifera	Copepod
Tigriopus japonicus	Copepod
Tisbe biminiensis	Copepod

An introductory text such as this cannot hope to provide all the details associated with the culture of any single species, but a number of books are available that deal with individual species or species groups. Several of those are listed in the 'Additional Reading' section at the end of this chapter.

Seaweeds are cultured in the marine waters adjacent to most continents, with the greatest amount of activity occurring in Asia. Japan, Korea and the Philippines are among the Asian nations that have large seaweed culture industries. In the western hemisphere, Canada produces a considerable amount of seaweed.

Oysters, mussels, clams, abalones and scallops are grown in marine waters around the world. Both warmwater and coldwater species of oysters and mussels are grown. Natural, perfectly round, jewellery-quality pearls from oysters are rare in nature, but they are being produced in large numbers through aquaculture of several species in the genus *Pinctada* in many nations around the world, though cultured oysters are probably best associated with Mikimoto pearls from Japan. More information on pearl oysters and other species reared for reasons other than or in addition to human food production can be found in Chapter 9. At least two species of freshwater mussels (*Hyriopsis cumingii* and *Hyriopsis schlegeli*) produce irregular pearls that are of value as jewellery due to their range of colours.

Abalone culture occurs in several nations. China was responsible for 85,000 tonnes of production in 2011, with Korea well behind in second place that year with over 6000 tonnes according to the FAO. One species, the blackfoot paua (*Haliotis iris*) from New Zealand, is highly regarded for the multicoloured nacre (mother-of-pearl). Shells are sold as colourful curios or cut into pieces and used in jewellery. Paua also produce pearls.

Geoduck (pronounced 'gooey duck') culture has been initiated on the west coast of North America and in New Zealand. Interest was initiated by the culture of juvenile geoduck for enhancement stocking. Various approaches and intensities of culture are employed in conjunction with mollusc rearing.

Marine shrimp culture involving penaeids of various genera and species (see Table 1.1) in Asia is dominated by Thailand and China, and there is also a significant amount of production in the Philippines, Malaysia, Indonesia, India and other nations in the region. In the western hemisphere, Ecuador has been the leading shrimp-producing nation, though disease has been a major problem there and elsewhere. A number of other Latin American countries also produce shrimp. In the USA, the leading cultured-shrimp-producing state is Texas. There is also some shrimp culture in coastal Florida, Hawaii, South Carolina and the territory of Puerto Rico. The US industry is relatively small overall and suffers from the fact that only one or two crops a year can be produced due to the climate, whereas in tropical areas (Hawaii and Puerto Rico), it is possible to obtain three crops a year.

Freshwater shrimp (*Macrobrachium* spp., primarily *M. rosenbergii*) culture has grown from a few thousand tonnes in the early 1980s to a few hundred thousand tonnes by the end of the first decade of the present century. The industry exists in many tropical regions and also has attracted some interest in temperate regions where a single crop a year can be produced. A cottage industry for freshwater shrimp has been reported from some parts of the USA, where small-scale producers grow sufficient numbers of animals to satisfy local communities at summer festivals. Because of the novelty of such events, the producers can make a good profit from their relatively small levels of production; however, if big producers enter such markets, the price will undoubtedly fall and the approach may become uneconomical for small producers. Globally, there is still significant production of freshwater shrimp in various tropical nations, and there is considerable interest in developing commercial culture of additional freshwater shrimp species (see Table 1.1).

Carp (members of the minnow family, Cyprinidae) are produced throughout the world; however, China continues to be far and away the world's leading carp-producing nation. Various other nations in Asia and Europe, along with the Middle East and the Americas, are also involved in carp production. Common carp (*C. carpio*) introductions into the USA in the 19th century and Israel during the 20th century were in response to the desires of European immigrants to have that fish species available to them because it was traditionally consumed. The US Fish and Fisheries Commission, under the direction of Commissioner Baird, spread common carp throughout much of the USA, but the species is not commercially cultured in the USA. A small capture fishery continues to exist but, in general, the common carp is thought of as a trash fish in the USA. In Israel, common carp has been largely replaced by tilapia (*Oreochromis* spp.) and gilthead sea bream (*Sparus aurata*) as public tastes have changed. Grass carp (*C. idella*) are produced in the USA primarily for weed control in ponds. In many states only triploid grass carp are permitted. Since triploids (which have three sets of chromosomes) are sterile (see Chapter 6), they will not reproduce if they escape from an aquaculture facility. There are also small numbers of silver (*H. molitrix*) and bighead (*A. nobilis*) carp production in a few locations in the USA. Koi (colourful *C. carpio*) were developed through selective breeding centuries ago in Japan. Some types of koi can bring high prices and are popular ornamentals often seen in backyard ponds in the USA. Many colour variations are available.

When I (R.R.S.) visited China in 1988, carp were staple fishes in every restaurant. During a second visit to China in 1999, I was told by government biologists that there was no governmental programme underway to expand carp culture in that nation. The reason given was that while carp are suitable for rural inhabitants, city dwellers are more interested in fish of higher quality, undoubtedly in part because the standard of living of people in the cities had changed considerably in the interim between my visits. One sign of that was that automobiles were scarce in 1988, while bicycles were virtually everywhere on the streets. In 1999 automobiles were plentiful and bicycles had largely been replaced by motor scooters. The statement that carp were not popular in the cities was reinforced when I had the opportunity to dine at several restaurants in Guangzhou and Beijing, which featured a wide variety of excellent seafoods, but carp did not seem to be available; at least, they were not to be found in the display aquaria that showed examples of the available fishes. That doesn't mean carp were not available in the large cities, but they were not the high-profile items they had been during my first trip.

Atlantic salmon (*S. salar*) are grown to market size in captivity, primarily in Norway and Chile. There is also production in Scotland, Ireland, Canada and the USA. Production grew by some 50,000 tonnes a year during the 1990s and reached in excess of 1 million tonnes annually by the early part of the present century. A limited amount of cultured chinook (*O. tshawytscha*) and coho (*Oncorhynchus kisutch*) salmon are grown in aquaculture facilities for direct sale into the market in British Columbia, Canada. Various species of Pacific salmon are produced in hatcheries in Canada, the USA, Japan and Russia for stocking to augment wild populations. Ocean ranching of salmon is practised in the state of Alaska as previously described, but salmon growout is prohibited. There is also some chinook salmon production in New Zealand for the recreational fishery, and Japan has a large sea ranching programme under way with chum salmon (*Oncorhynchus keta*). China has initiated plans to re-establish depleted runs of salmon in some of that nation's northern rivers. Whether an entity producing salmon is private or governmental, and whether the approach involves spawning and rearing the offspring to market size or to smolt size for release to augment commercial fisheries, the approaches are all forms of aquaculture.

The rainbow trout (*O. mykiss*) is the most important trout species being cultured worldwide. That species, native to the cold waters of the far western region of North America and as far south as northern California, is popular with aquaculturists across much of that nation, as well as in Chile and northern Europe. Rainbow trout are also produced for sport fishing in New Zealand. The species was also introduced many years ago to some of the former British colonies where the water is sufficiently cold. During a month that I (R.S.S.) spent in Nepal looking at their fisheries and aquaculture programmes, I saw a few facilities that were culturing rainbow trout. Sea-run rainbow trout, known as steelhead, get much larger than rainbow trout that spend their entire lives in freshwater. Steelhead are popular sportfish and are raised for the seafood market in a few places. Arctic charr (*Salvelinus alpinus*) is another salmonid that is being cultured to food-fish size commercially in a few places, and that species is gaining in popularity.

US fish culture production has been dominated by channel catfish (*I. punctatus*). The commercial industry began to take off in the 1960s, with the early fish farms being located primarily in the states of Alabama and Arkansas. Production in Alabama, while still significant, has been limited by the fact that most culturists depend upon rainfall to fill their ponds, so water supply is a major issue. In Arkansas, the proliferation of catfish farms in rice-growing areas caused the water table to fall significantly, thus limiting expansion of that industry. Mississippi, with what was seemingly an unlimited amount of groundwater, quickly surpassed both Alabama and Arkansas in terms of catfish production. Of course, the water supply in Mississippi is not unlimited, and the withdrawal of groundwater may have reached the limit of what can be sustained. A change in pond management practices which involves only replacing water lost to evaporation and seepage (a pond may not be drained for as long as 10–15 years) has reduced the pressure on the water supply substantially, not only in Mississippi, but also in other states where catfish are cultured in ponds. Large amounts of channel catfish are still produced in Louisiana and Arkansas with lesser amounts in Georgia, Texas, Alabama, California and other states. This includes places as far away from 'catfish country' as Idaho, where catfish, as well as the much less cold-tolerant tilapia, can be produced year-round in outdoor systems supplied with geothermal water. Many states throughout the country have government hatcheries that produce channel catfish for stocking inland waters for recreational fishing.

In recent years producers in the USA have largely shifted from channel catfish to hybrids of channel (*I. punctatus*) and blue (*Ictalurus furcatus*) catfish, which perform better in terms of growth, survival, feed conversion, tolerance to low dissolved oxygen, disease resistance, processing yield and other factors, compared with channel catfish. Of interest is the fact that geneticist John Giudice, who worked at the US Fish Farming Experiment Station in Stuttgart, Arkansas, USA (Box 1.6), produced the various possible crosses of channel catfish with both blue and white catfish (*Ictalurus catus*) during the 1960s, but none of those hybrids were produced commercially for some 30 years. Hybrids accounted for about 20% of US catfish production by 2011 and have continued to increase since that year.

Basa (*Pangasius bocourti*) and, to a lesser extent, tra or striped catfish (*Pangasius hypophthalmus*), which are in a different family from ictalurid catfish such as *I. punctatus*, have been imported to the USA for several years where they compete in the marketplace with domestically reared catfish. Much of the imported fish come from Vietnam, though they are native to Cambodia and Thailand as well and have been introduced into other South-East Asian nations for purposes of culture. That competition has been responsible, in part, for an estimated 50% drop in US catfish production. Other reasons for the decline have been attributed to high energy and feed costs associated with US catfish rearing. While the switch to hybrids has provided some relief to catfish farmers, some producers in Arkansas reportedly reverted to rice farming because catfish farming was not as lucrative as it had been in the past. Importers of basa and tra can no longer use the term 'catfish' on their packages and are required to list country of origin thereon. Both those regulations and others developed by the US Department of Agriculture (USDA) may have resulted in less competition from imports, but the imported competitors continue to compete.

Box 1.6.

The Stuttgart Fish Farming Experimental Laboratory was authorized in 1958 as a warmwater fish research centre under the US Fish and Wildlife Service. The facility was opened in 1961 and was transferred to the US Department of Agriculture in 1996. It was renamed the Harry Dupree Stuttgart National Research Center in 1999 when the longtime director of the facility retired.

Walking catfish (*Clarias* spp.) are reared in Asia, Africa and Europe. Walking catfish get their common name based on their ability to move across land from one water body to another by 'elbowing' their way on their pectoral spines. In order to prevent them from escaping, ponds are often constructed with vertical walls and may also feature low fences to keep the fish contained (Fig. 1.5). Once reared on Florida fish farms in the USA for the home aquarium trade, possession of walking catfish was outlawed several years ago after escapees began to appear throughout the state. Rumours abounded of walking fish attacking and eating small dogs and even human babies. In reality walking catfish can reach lengths of 1–1.5 m and have been known to consume waterbirds whole as they have large mouths. They could potentially consume a relatively small dog swimming in the water, but we haven't found any substantiated case of walking catfish eating a human baby. There is plenty of information that walking catfish eat the eggs and young (babies) of other fishes.

Tilapia (*Oreochromis* spp.) are among the primary fish species being cultured in freshwater in various tropical nations around the world. Tilapia require warm water (growth is severely retarded at temperatures below about 20°C and mortality begins when the temperature drops only a few degrees lower), so the culture of these popular fishes is limited to a single annual crop in temperate regions except under special circumstances, such as when geothermal water is available or when water is heated sufficiently above ambient temperature to ensure good fish growth. Figure 1.6 shows circular tanks in an area of the USA where geothermal water is available even when ambient temperature falls to well below freezing.

The heated water produced by power plants and various industries has sometimes been used in conjunction with tilapia culture in temperate regions. One issue with that approach is that the heated water effluent may not always be available. For example, a power plant may shut down for maintenance, which often happens during the winter when the heated water is essential for keeping the

Fig. 1.5. Vertical walls and associated fencing in these ponds in the Philippines help keep walking catfish from escaping.

Fig. 1.6. A year-round tilapia culture operation in geothermal water near Boise, Idaho, USA, where winter temperatures typically reach –34.5°C.

fish alive. A catastrophic loss may occur as a result. Unless a sufficiently warm water source is available year-round, broodstock will have to be overwintered in an indoor facility that is temperature controlled.

Some tilapia species, and particularly certain crosses that produce red hybrid tilapia, are tolerant of high levels of salinity and can be grown in seawater. Marine culture of tilapia has been researched in the Bahamas, Jamaica, the West Indies, the Philippines and elsewhere, but there do not appear to be high levels of commercial production of tilapia in saline waters.

Atlantic halibut (*Hippoglossus hippoglossus*), plaice (*P. platessa*) and sole (*Solea solea*) are among the flatfish species being cultured in Norway, while flounders (*Paralichthys* spp.) are produced in large numbers in Japan and South Korea and are beginning to be commercially cultured in the USA. Atlantic halibut culture is under way in Canada and the state of Maine.

Milkfish (*Chanos chanos*) are being cultured in the Philippines, Taiwan, Thailand and Indonesia. In the past the approach has been to capture wild juveniles and rear them in ponds. Today most of the fingerlings stocked in ponds for growout come from hatcheries.

Some sturgeon (*Acipenser* spp.) culture is occurring or under development in North America, China, Russia, Iran and Central Europe. The main thrust of the interest in sturgeon is for the production of caviar.

Cobia (*Rachycentron canadum*) culture has become established in Taiwan and at least one culture facility for that fish has been established in Puerto Rico. Research on cobia has been conducted in at least the states of Florida and Texas. There has also been some interest in the culture of dolphinfish (*Coryphaena hippurus*). Dolphinfish are known as mahi-mahi in Hawaii and that name is widely used on restaurant menus throughout the USA, more than likely to assure consumers that they are not eating a marine mammal with the same common name. There are a number of species of amberjacks in the world, and one in particular, *Seriola rivoliana*, known as the Hawaiian amberjack and marketed by one open ocean farm in Hawaii as Kampachi, is popular with tourists and locals in Hawaii. Other yellowtail species include *S. quinqueradiata* which has been cultured in Japan for many years and *Seriola lalandi* in Australia and Chile.

Most sportfish have been excluded from the discussion above and the list in Table 1.1, though there are exceptions such as salmon, trout, halibut, amberjack, red drum, striped bass (*M. saxatilis*) and walleye (*Stizostedion vitreum*) that are of both recreational and commercial aquaculture interest. Sportfish culture for stocking programmes in the USA, Europe, Japan, Australia, New Zealand and elsewhere are well developed and significant.

The species discussed in this section are but a small sample of those listed in Table 1.1. The purpose has been to highlight some of the most widely cultured species and also to highlight some that are under development. To provide details on every species or species group would require another, much larger volume. More details on the culture of some of the organisms described in this section, along with others, can be found in other chapters of this book. Readers may also go to the World Aquaculture Society website and the American Fisheries Society website. Each of those societies has published a number of books focused on individual species or species groups that include aquaculture information.

Selected FAO Data on Capture Fisheries and Aquaculture Production

The contribution of aquaculture to the total amount of fishery production has been steadily increasing with respect to both total production of the various species groups and in the major aquaculture-producing nations. Table 1.4 presents FAO data from recent years with respect to production and utilization from capture fisheries and aquaculture. Table 1.5 presents aquaculture production of finfish, crustaceans and molluscs for various regions of the world.

Table 1.4. Total quantity of world animal aquaculture production and utilization (millions of tonnes, live weight) in 2016, 2017 and 2018. (From FAO, 2020.)

Year	2016	2017	2018
Capture fisheries			
Inland	11.4	11.9	12.0
Marine	78.3	81.2	84.4
Total capture	**89.6**	**93.1**	**96.4**
Aquaculture			
Inland	48.0	49.6	51.3
Marine	28.5	30.0	30.8
Total aquaculture	**76.5**	**79.5**	**96.4**

Table 1.5. Aquaculture production of finfish, crustaceans and molluscs (thousands of tonnes) from Africa, the Americas, Asia and Oceania, along with the world totals in 2018. (From FAO, 2020.)

Category	Continent	Species group	2018 Production
All Aquaculture[a]	Africa	Finfish	2,184
		Crustaceans	2,194
		Molluscs	6
		Others	6
		Subtotal	2,196
	Americas	Finfish	2,197
		Crustaceans	961
		Molluscs	640
		Others	1
		Subtotal	3,799
	Asia	Finfish	47,400
		Crustaceans	8,414
		Molluscs	16,083
		Others	915
		Subtotal	72,812
	Europe	Finfish	2,399
		Crustaceans	0
		Molluscs	680
		Others	3
		Subtotal	3,083
	Oceania	Finfish	97
		Crustaceans	6
		Molluscs	102
		Others	0
		Subtotal	205
	World	Finfish	54,279
		Crustaceans	9,387
		Molluscs	17,511
		Others	919
	Grand total	**Finfish**	**82,095**

[a] All aquaculture includes inland, marine and coastal production.

Oysters and clams are produced in numerous countries and dominate mollusc production, though interest in abalone appears to be increasing. The echinoderms of interest are various species of sea cucumbers and sea urchins. The increase in aquatic plant production during the period is notable.

The leading aquaculture-producing nations are in Asia, with mainland China leading the world in aquaculture production by a wide margin. While carp continued to dominate, China increased its production of other species of freshwater fishes and is also producing a variety of marine species that were not among the species listed in the 3rd edition of this book. China has also become one of the leading nations with respect to the production of marine shrimp and is also a leader in scallop culture (various genera and species as indicated in Table 1.1). The primary species being employed during the development of shrimp culture in China was the coldwater Chinese shrimp (*Fenneropenaeus chinensis*), but disease problems plagued the industry and production shifted to a large extent to warmwater shrimp species native or introduced to the southern coastal region of the country. China is also a leading producer of aquatic algae, primarily seaweeds (Table 1.6).

Japan's aquaculture is highly diversified, while aquaculture in Norway and Chile is mainly Atlantic salmon (*S. salar*), augmented by Atlantic halibut (*H. hippoglossus*) and cod (*G. morhua*) in Norway, along with various mollusc species along with salmon in Chile.

The devastating typhoon that hit Myanmar in 2008 targeted the coastal area where much of the aquaculture production was located and was feared to be devastated in subsequent years. However, production (which had been growing steadily in the years prior to 2008) did not decline, but in fact continued to grow. On the other hand, the large earthquake and tsunami that hit Japan in 2011 had a definite impact on the industry.

As global aquaculture production expands, so does the human population and, importantly, the standard of living in some of the leading aquaculture-producing nations is increasing rapidly. Examples are China and India, where – increasingly – aquaculture products that were once raised primarily or exclusively for export have become available in the domestic markets. On the other hand, how the COVID-19 pandemic has affected not only annual aquaculture production around the world, but also the degree of food production that might be available for export, remains to be seen. In any case, from 2010 to 2018, the major animal species produced in aquaculture were considered to grow in terms of their contribution to the world total (Table 1.7).

A Question of Sustainability

During the last decade of the 20th century, a considerable amount of attention began to focus on the sustainability of both agriculture and aquaculture. The question that is frequently asked when the topic comes up is 'What does sustainable mean?' Among the many definitions that have been proposed for the terms sustainable and sustainable development are the following:

- Sustainable:
  - meeting the needs of the present without compromising the ability of future generations to meet their own needs;
  - exploiting natural resources without destroying ecological balance; and
  - investing in a system of living, projected to be viable on an ongoing basis, which provides quality of life for all individuals of sentient species and preserves natural ecosystems.
- Sustainable development:
  - economic development maintained with acceptable levels of global resource depletion and environmental pollution; and
  - development of systems that will last indefinitely.

While those definitions seem reasonable, they are somewhat open-ended. With respect to the term sustainable: What are the needs of the present? Are those minimal needs for survival or something else? Who decides? How does one determine when and if the ecological balance is being destroyed, or – perhaps as importantly – when it is being disrupted? At what point does some level of disruption become irreversible and lead to environmental destruction? If we define sentient as being able to perceive or feel things, what life forms meet the definition? How do we know if an organism can perceive or feel things, such as pain? That issue has

Table 1.6. Highest aquatic-algae-producing nations (thousands of tonnes, live weight) in 2000 compared with 2018. (From FAO, 2020.)

Nation	2000 Production	2018 Production
China	8,227.6	18,505.7
Indonesia	205.2	9,320.3
Philippines	707.0	1,478.3
Korean Republic	374.5	1,710.5
Japan	528.6	389.8
Total world production	**10,595.6**	**32,386.2**

Table 1.7. Production the major animal aquaculture species (thousands of tonnes) in 2010 compared with 2018. (From FAO, 2020.)

Category	Common name	2010 Production	2018 Production
Finfish	Grass carp	4.213.1	5,704.0
	Silver carp	3,972.0	4,788.5
	Nile tilapia	2,657.7	4,525.4
	Common carp	3,331.0	4,189.5
	Bighead carp	2,496.9	3,143.7
	World total, all finfish	**37,475.1**	**54,279.0**
Crustaceans	Shrimp, crayfish (crawfish), etc.	5,478.8	9,386.5
Molluscs	Mussels, oysters, etc.	13,728.3	17,510.9
Others	Frogs, sea cucumbers, etc.	791.8	918.6

led to a serious debate with respect to finfish. Do we extend that to plant life?

In terms of sustainable development: What is an acceptable level of global resource depletion? What is an acceptable level of environmental pollution? What time frame do we place on the word indefinitely? Does that mean sometime down the road, that we have no idea, or never?

Questions such as those are central to the debate that continues to swirl around sustainability. The bottom line is that virtually every human activity has some measurable impact on the environment. Some of those impacts are readily apparent, such as smog over many of the world's major cities, and untreated or partially treated sewage effluent causing eutrophication of lakes and streams as well as dead zones in the oceans. A dead zone has become a problem off the Mississippi River in the Gulf of Mexico and is attributed to nutrient runoff from farmland. Other impacts are difficult to quantify, but that does not mean they are inconsequential. Also, there are many single, perhaps small environmental insults that are synergistic and by acting in concert may have significant impacts on the environment. Not only do human activities have environmental impacts, every living person utilizes natural resources to one extent or another.

We must acknowledge upfront that aquaculture, in all its forms, exploits natural resources. The degree of that exploitation increases in direct proportion to the intensity of the culture operation. Pond culture systems that depend on rainfall runoff or tidal flooding for their water and rely on natural productivity as the food source for the target species probably have little impact on natural resources, assuming that the construction of the ponds does not result in the destruction of critical habitat that should have been preserved. For example, development of pond systems in coastal areas may disrupt wetlands, mangroves or other types of environments that have significant ecological value, and such development is prohibited in many nations.

Intensive systems such as raceways, high-density ponds, recirculating systems and net pen operations (see Chapter 3 for descriptions of those systems) require energy supplied from, for the most part, fossil fuels. Such systems also utilize living resources or their products, including fishmeal and other sources of animal protein, along with a variety of terrestrial plants, in the manufacture of feed. Fertilizers, pesticides and herbicides may also be used, all of which require exploitation of natural resources.

What about on-bottom oyster culture? All it involves in some cases is using natural substrate or bringing in and spreading oyster shell (cultch) that oyster spat will settle on to allow the oysters to grow until harvest. Tending the beds to remove predators has an impact on the environment, harvesting alters the environment (which may have been altered in the first place by creating a new type of substrate), and fossil fuel is used directly in harvest in many cases and certainly for transporting the oysters to the processing place or directly to the market. Even if the oyster bed supports only a small artisanal culture operation, it still involves human–environment interaction, even though the impact may be small. Even in a case like this where environmental impact is minimal, the removal of the oysters at harvest is utilization of a natural resource.

At the extremes of the debate over the sustainability of aquaculture are individuals and groups that have the goal of eliminating aquaculture in most or all its forms, and those who refuse to acknowledge that aquaculture has any negative environmental impact. Between those extremes are a growing number of people – including researchers and a considerable percentage of the aquaculture producer community, particularly in developed nations – who have been attempting to look at the various issues, determine where science supports or refutes the positions of opponents and proponents alike, and develop methods for making aquaculture more sustainable in instances where there are problems.

Again, there is no doubt that aquaculture practices result in the utilization of at least some natural resources. The question is whether the degree to which that utilization occurs represents a significant environmental insult and is, thus, an irresponsible and unsustainable activity. The facts are that some aquaculture practices have been destructive, while others have had little or no negative impacts and can be judged as meeting the criteria for being sustainable, at least to most reasonable persons. A better term, and one that has been used to some extent, is responsible aquaculture, which we feel is preferable.

Aquaculture, particularly in areas where it competes with other users, such as in lakes, reservoirs, and the coastal and offshore marine environment, needs to be compatible with those other users if it is to prosper. Other users often see aquaculture as being exploitive of natural resources and, when practised in the commons, it is seen as interfering with other activities that were there first. The pre-existing users are often viewed to have priority over aquaculture. The other users are often oblivious to the fact that their activities utilize natural resources directly and/or can only occur because natural resources have been utilized to make their activity possible.

How about sail boating? That only involves the use of wind, which is not a negative environmental impact. That may appear to be true if the sailboat is not equipped with an auxiliary engine. But natural resources were utilized to construct the boat. Some of those may have been renewable (wood), but others are not (fibreglass). What about the energy that was involved in sawing the lumber or moulding the fibreglass? The same rationale can be applied to all other user groups. Sunbathing by those who do not wear sunscreen, swimwear, hats or sunglasses, or who do not take radios or mobile phones to the beach, could come pretty close to not directly using natural resources, so it might be necessary to give those folks a pass, particularly if they walked to the beach. Of course, lack of swimwear implies a nude beach, which may create other problems.

More details on several of the controversies surrounding aquaculture and how they are being dealt with are presented in the next section of this chapter, 'Opposition and Response'. For additional information on sustainable aquaculture and responsible aquaculture consult some of the books listed in the 'Additional Reading' section at the end of this chapter.

Aquaculturists are often quick to point out that a healthy environment is crucial not only for maintenance of the natural ecosystem but also for the benefit of their culture organisms. Thus, it is not only in the interest of the aquaculturist to focus on sustainability and maintenance of a healthy environment; it is imperative if the culturist wishes to reduce the chances of a catastrophic loss. An unwritten law associated with aquaculture is that if the animals are going to die, for whatever reason, it will probably occur just before they are scheduled for harvesting. At that point, most of the time, effort and money associated with the growing season have been expended.

Most developed nations recognized that as aquaculture production was increasing, regulations would need to be promulgated to limit environmental consequences and allow the industry to expand through the use of responsible practices. Lack of regulations or lack of enforcement when regulations were in place has led to significant environmental damage as a result of certain types of aquaculture practices in various developing and some developed countries, however. Increasingly, when such problems occur, nations are not only responding by promulgating sound regulations but are also backing them up with enforcement. Certainly, that is not true everywhere, but pressure on bad players can be imposed by countries that import aquaculture products from the countries with a lack of regulations. That pressure can come from embargoes or the imposition of high tariffs, for example.

While the potential negative impacts of aquaculture have been widely discussed, the role of aquaculture in the amelioration of environmental problems has only emerged as a topic of interest in recent years. When properly sited facilities are stocked with appropriate species or combination of species, an aquaculture facility can actually reduce the levels of nutrients in the water that can result in eutrophication. This can be accomplished by stocking filter-feeding animals that consume phytoplankton, which can form blooms in the presence of high nutrient levels, and/or by producing seaweed as a means of reducing nutrient levels. Of course, seaweed used in conjunction with aquaculture operations will only work in marine situations, while filter-feeders of appropriate species can be found for use in freshwater as well as in the marine environment. The approach has real potential in coastal areas receiving nutrients associated with river inflows containing runoff from agricultural lands, for example.

In addition to having the potential to be integrated into a nutrient management programme for a coastal region, marine cages and net pens (described in Chapter 3) serve as fish aggregating devices. Fish and other types of organisms may reach densities outside the culture chambers that are as great as, or greater than, those within. Thus, aquaculture facilities can actually provide habitat in some instances. Whether they serve merely as fish-attracting devices (FADs), sources of waste feed and nutrients, or actually help expand populations beyond what would otherwise occur naturally in the region is still a matter of debate. Recreational fishing in the immediate vicinity of aquaculture pens or cages may be quite good; however, it can also pose problems for the aquaculturist because of potential damage to facilities (e.g. cutting cage material to remove hooks or lures; poaching by anglers).

Sustainability certification is something that is on the minds of many groups. The Marine Stewardship Council (MSC) has certified several commercial fisheries, aquaculture facilities and other associated facilities. The Aquaculture Certification Council of the Global Seafood Alliance, which was formerly the Global Aquaculture Alliance (GAA), has certified shrimp culture operations for several years and has expanded into certification of other types of aquaculture facilities. The World Wide Fund for Nature (WWF) has a certification programme, as do other organizations. Various seafood retailers and wholesalers have implemented or plan certification of the aquaculture products they sell.

Various non-governmental organizations (NGOs) have produced lists, often in the form of wallet cards, showing which seafoods they recommend as being both healthful and coming from sustainable sources, and which should be consumed with caution or should be avoided. Typically, they use a stoplight system with red, yellow and green indicating poor, acceptable and best choices, respectively.

The major problem with such a system is that it does not provide the consumer with sufficient information. For example, many cards place all cultured shrimp on the red list because some shrimp farms are not operating sustainably. Thus, a few bad actors can damn an entire commodity. Whether the cards have had much impact on the seafood-consuming public is questionable, however, as demand for red list species, such as cultured shrimp, does not seem to have been negatively impacted since the cards were developed.

It should be apparent from the discussion thus far that the concept of sustainability is an elusive one to pin down, so, as indicated, we prefer to use the term responsible aquaculture, as we believe that it better captures the goal of being a good steward of the environment. But responsible aquaculture – or sustainability, if you prefer – is not only respect and care for the environment. It also embodies production of safe and healthful products for human consumption in the case of commercial seafood production. Aquaculture products reaching the seafood markets and restaurants should be as free from harmful chemicals as possible and should also be free of pathogens that might affect human health. Some people, of course, have allergies to various types of seafood, and those products should not be banned when the majority of the people can eat them safely. Also, people with compromised immune systems need to avoid consuming such things as raw oysters, which may have bacteria associated with them that can be deadly to those people, while others might not bother those who have uncompromised immune systems. Products that could cause health problems for certain classes of people should carry a warning to alert consumers who may be at risk. On the other hand, many seafoods contain components that are beneficial to human health, such as high-molecular-weight fatty acids that appear to help ward off a number of health problems. There are also data showing that consuming shellfish, such as oysters, may reduce the risk of breast cancer. In addition, there is also a belief that indicates the consumption of raw oysters can increase libido. Some fish, such as certain species of tuna, can have levels of mercury high enough that pregnant and nursing mothers should avoid eating them as the fetus or baby could be harmed. Current recommendations are to have children avoid eating certain tuna species until the age of 6 years or more. Because cultured tuna, to date, are produced from juveniles captured in the wild and grown out in net pens on sardines, the problem of mercury contamination in those fish has probably not been ameliorated. However, advancements have been made in the preparation of artificial diets to feed tunas which are much lower in mercury than forage fish. There are, incidentally, some wild tuna populations in portions of the world ocean that do not contain high body burdens of mercury, though they are in the minority.

Social scientists who have taken an interest in aquaculture are quick to point out that there is a third topic in addition to concerns about the environment and the health and safety issues that needs to be addressed. That is social justice. The public rarely thinks about that issue, but it is significant, and it is difficult to deal with equitably. In a perfect world, no workers in the aquaculture industry worldwide would be underage (there would be no child labour used), they would be paid a decent wage, have appropriate benefits, would be treated with respect by their fellow workers and managers, and would recognize their responsibilities as environmental stewards to maintain sanitary conditions in conjunction with all of their activities. The reality is that in many countries some or all of those desirable attributes and responsibilities are being violated each and every day. Aquaculture-certifying bodies often ignore social issues, but those issues should become viewed as an important component in the certification process.

Social scientists have examined the role of women in small-scale aquaculture in such countries as Vietnam and Thailand. As rural farmers try to diversify their activities, they often find aquaculture to be an appropriate addition or alternative to terrestrial crop production. It appears that women are active participants in aquaculture in such situations, though they may not always be visible to the casual observer in terms of their level of involvement. Women's role in aquaculture has also been studied in the European Union (EU). Again, women seem to be most heavily involved in small-scale enterprises. In family operations, women may provide labour without pay. Their role in aquaculture may be associated directly with production or involve sales, processing, restaurant work or marketing. In conjunction with processing, women have often come up with new product forms and value-added products.

Finally, no aquaculture venture can be successful in the absence of economic sustainability. To be successful, a commercial aquaculturist needs to be able to continuously produce one or more products at a profit.

There should be well-defined property rights allocated to the culturist. Laws may need to be changed in order to provide those rights. For example, in some parts of the USA there have been laws on the books under which a state owned all the fish, and there were also laws that prevented individuals from selling property of the state. Thus, aquaculturists impacted by such laws did not own the fish and could not legally sell them. Those laws have now been changed, but they were a problem for a period of time when aquaculture was being developed in regions where it had not previously been practised.

Opposition and Response

There appears to have been little opposition to aquaculture until sometime in the 1980s, when the rapid expansion of marine shrimp and salmon culture in coastal waters was occurring. Shrimp ponds in developing countries were often dug in mangrove areas in the tropics and were responsible for destroying many thousands of hectares of valuable habitat. The acidic soils in which the ponds were constructed after removal of the mangroves made it possible for those ponds to be productive for years, after which they were typically abandoned as the shrimp farmers moved to new areas, often once again mangrove swamps. This led to a great deal of opposition from environmental groups and others that recognized the importance of mangroves in protecting coastal areas during storms, as well as providing habitat for a wide variety of marine life. However, it has been shown that other human activities in mangroves, such as expansion of human communities and agriculture, are also implicated in the loss of those valuable parts of the ecosystem.

Salmon farms were first established in fjords in Norway and Scotland, but soon were also developed in Canada, the USA, Chile and Japan in coastal bays. In some of those countries, objections were raised to the presence of commercial aquaculture operations in the commons. Little opposition was initially raised in places like Norway and the west coast of Canada because the facilities were located in sparsely populated areas. That has certainly changed in British Columbia, Canada, where strong opposition has developed, though the government continues to be supportive of salmon farming. Net pen salmon culture and cage culture of yellowtail (*S. quinqueradiata*) and red sea bream (*Pagrus major*) are perfectly acceptable in Japan where the majority of the animal protein in people's diets comes from seafood. In fact, the cages and net pens, along with other types of culture systems for molluscs, are actually seen as amenities by many people (Fig. 1.7), though there have been some problems in the past (Box 1.7).

In the state of Washington, USA, several years ago, cries of *visual pollution* from upland property owners were heard with respect to salmon net pens in the coastal waters, particularly in Puget Sound. Those cries of protest were soon followed by outcries from a variety of individuals and groups with vested interests in areas where aquaculture had been established or were planned. *How dare these fish farmers take valuable space from where I fish, sail, kayak, waterski…!* The fact that there would be virtually no influence on those activities was conveniently ignored.

Fig. 1.7. An aquaculture net-pen facility in a bay in Japan with a resort hotel in the background. Aquaculture is considered an amenity in that location, not an eyesore.

Box 1.7.

In Japan, aquaculture in the bays is largely operated by cooperatives that initially exercised little control over the numbers of cages or fish stocked. Overcrowding led to the deterioration of water quality in some bays to the point that sensitive species, including cultured fishes, were sometimes heavily stressed or killed. Japan promulgated regulations through the fish cooperatives that reduced the density of aquaculture facilities in areas where problems had occurred, and this led to a healthier environment. Sensitive species are often grown near fish cages or net pens so that if there is a water quality problem, the sensitive animals will signal that a problem is developing. This provides the culturist with the opportunity to ameliorate the problem before possibly losing the entire fish crop.

A meeting of the World Aquaculture Society in 1988 was, if memory serves, the first time that the society devoted a special session to issues that were being raised by opponents. The meeting was held in Honolulu, Hawaii, USA, and attracted attendees from around the world as was typical. Many attendees dismissed the criticisms of aquaculture as having no merit, and there were many who felt that if they ignored it the issue would go away. The reality is that in the decades that have passed since that meeting, a great deal of the research conducted by aquaculture scientists has been focused on determining which of the issues raised by opponents of aquaculture have validity and which do not. For those issues that have been found to have validity, in at least some instances, remedies for overcoming them have been developed or are still under development. Best management practices (BMPs) for various types of aquaculture activities have been promulgated by such groups as the FAO, WWF, GAA and probably others.

Environmental issues stemming from mariculture operations were addressed by the National Research Council of the National Academy of

Sciences in a book published in 1992 (see 'Additional Reading' at the end of this chapter). Included in that assessment were discussions of effluent impacts, the impacts from the introduction of exotic species and the use of feed additives. In the state of Washington, those impacts were also discussed, as was a virtual laundry list of other objections to salmon net pen culture, with visual pollution heading the list. Ultimately, the courts indicated that the initial complaint by upland property owners had no merit as those individuals did not have a right to an unaltered view, so the issue of visual pollution was put to rest in a legal sense. That did nothing to curtail the criticisms, which quickly spread to salmon-farming practices in British Columbia, Canada, and to the state of Maine and the Maritime Provinces of Canada. In any case, salmon culture in those areas continues to occur.

Shrimp culture has been attacked for the practice of constructing ponds in coastal wetlands, and in particular in mangrove areas, as previously indicated. Nutrient and sediment loading of waters that received the effluent from shrimp ponds were also in for criticism. In places where shrimp farmers were using non-native species, critics also expressed their concern that escapees from culture ponds would compete with native species.

Critics found a friend in the *precautionary principle*, which basically says that the aquaculturist has to prove that his or her practices are not harming the environment. The critic, on the other hand, has no responsibility in proving that those practices are harmful, but has only to express the opinion that they might cause environmental damage. If the culturist cannot prove that the farm will have no negative impact, permits should, at least in the mind of the critics, not be issued. As expressed by an environmental lawyer in a meeting I (R.R.S.) attended several years ago, '…if there is any change in the environment that can be measured, we'll shut the operation down.' Once again, we believe that virtually every activity conducted by humans has an effect on the environment at some level. Does a change in the background level of a nutrient by a single microgram or even picogram per litre, for example (which can be detected given the analytical techniques currently available), translate into a significant change? Applying such a strict interpretation of the precautionary principle would mean that the change is measurable, therefore the aquaculture facility should lose its permit to operate. Why is that principle not applied to other activities, for instance farming, ranching, lumbering, mining, and virtually every other human activity?

The following is a list of criticisms that have been lodged against aquaculturists, along with some mention of the merits of each and an indication of how the aquaculture community has responded or is developing ways to ameliorate the problem. The major issues are listed first, followed by those that have thus far been of fairly minor importance.

Issue 1: Faeces and waste feed falling to the sediments from sea cages create sterile zones and negatively impact local fauna.

Industry sector: This criticism has been lodged against the cage and net pen industry in the marine environment with respect to salmon and other finfish species.

Reality: The problem can be very real and significant, leading to virtually sterile zones immediately under net pens or cages and extending to some distance laterally before no impact can be detected. The situation will not occur if there is an adequate flow of water through the cages or pens to widely disperse the solids. The problem is exacerbated when cages or net pens are located in bays that have slow currents.

Solution: Proper siting of the facility accompanied by frequent monitoring to detect any changes before they become significant are means of solving the problem. An appropriate site is one that has suitably strong currents to widely disperse any material that exits the culture chambers. Careful monitoring of feeding activity to eliminate the availability of excess feed to the extent possible also helps ameliorate the problem. Periodic sampling of the bottom sediments under facilities or visual inspection by divers is recommended. Certain chemical tests can be run on sediment samples to determine the extent of pollution (e.g. redox potential and acid-volatile sulfides) and benthic community structure changes can be predictive of developing problems. Should waste accumulation occur to the degree that changes in the sediment chemistry and/or benthos (bottom-dwelling animal) community are occurring, the cages or net pens should be moved, and the site should be fallowed until the situation returns to normal. Periodic movement of cages or net pens is another approach that can be used, requiring permitted areas to be significantly larger than the portion of the area actually being used at any given time. Because bottom type can vary significantly from one site to another, each location needs to be monitored independently. Implementation of IMTA systems will typically reduce potential impacts.

Issue 2: Nutrients from faeces and waste feed fertilize the water and promote noxious algal blooms.

Industry sector: This complaint largely targets net pen and cage fish culture in the marine environment.

Reality: Nitrogen and phosphorus are released from faeces and waste feed and enter the water column as dissolved nutrients, the levels of which can be significantly increased in areas where cages or net pens are numerous, particularly in sheltered bays that do not have a high rate of flushing.

Solution: Cages and net pens should be sited in areas where there is sufficient circulation to carry the dissolved nutrients away, and the density of cages within a given area should be controlled to ensure that nutrient loading of the system does not become a problem. Studies have shown that significant nutrient level increases do not occur in either protected or open ocean waters if there is sufficient water exchange through the culture chambers. Frequent monitoring is recommended. Should the bottom immediately under cages or net pens become enriched with organic matter to the extent that changes in the benthic community or sediment chemistry indicate a negative impact is occurring, the culture chambers can be moved to an unaffected area. The impacted area should be allowed to lie fallow until recovery occurs. The required fallowing time will depend upon the extent of the impact and the farm's location (recovery may be affected by the extent to which a site is exposed to currents and wind mixing). Seaweeds grown in the vicinity of cages and net pens have been shown to decrease nutrient levels, as has inclusion of other IMTA components.

Issue 3: Water released from culture systems can cause algal blooms and silting-in of waterways.

Industry sector: This has been an issue associated with pond culture facilities and flow-through raceway culture systems (see Chapter 3).

Reality: When water is released from culture ponds and raceways, it may carry high levels of nutrients and suspended solids that can impact receiving waters. Nutrients can lead to algal blooms, while suspended solids can settle out and build up in public waterways. The increased sediment load can eventually limit the navigability of a waterway and may change the nature of the benthic environment to the detriment of some species.

Solution: Employing feed ingredients that contain forms of phosphorus and proteins (the major source of nitrogen) that are more fully utilized by the culture animals can help resolve the nutrient issue. Some sources of phosphorus are not absorbed well, particularly by fish, so research to find alternative sources with high rates of digestibility and absorption has been, and is being, conducted. The digestibility of some protein sources is poor as well, leading to incomplete absorption of amino acids which are metabolized and excreted as nitrogen. More digestible alternative protein sources to replace fishmeal (which is typically highly digestible) have received a great deal of attention from researchers. Settling basins, recirculation and reuse of the water, and the use of constructed wetlands can effectively ameliorate both the nutrient and suspended solids problems. Catfish farmers in the USA may not drain their ponds for periods of a decade or more, so there is less concern about effluent impacts on receiving waters than when water is continuously released or when ponds are drained during each harvest period. Using water from freshwater ponds to irrigate cropland rather than releasing the water into streams can provide a beneficial use of pond or raceway effluent.

Issue 4: Cultured organisms are likely to transfer diseases to wild organisms.

Industry sector: This criticism has been raised with respect to both finfish and shellfish, particularly shrimp. It has also been raised with respect to exotic finfish and shellfish as it is thought that the culture of non-indigenous species may bring in new diseases and pass them to wild populations.

Reality: The potential exists, but there is likely a higher probability that wild fish or invertebrates will pass a disease to the cultured species, because the high density of animals in a pond, cage, net pen or other facility exposed to surface freshwater or saltwater can distribute pathogens within the cultured species population very rapidly compared with transmission among more widely dispersed animals in the wild.

Solution: Native species should be stocked when possible. If a non-indigenous species is used, the animals should be quarantined for several weeks in a facility that does not produce effluent that enters natural waters, prior to being stocked in the grow-out facility. In some instances, it is possible for aquaculturists to purchase post-larval shrimp or other species that have been certified specific-pathogen-free. To help ensure that non-indigenous species are not carrying pathogens, careful monitoring should be conducted of all cultured animals in the hatchery prior to release. Certification of the cultured species' health from an animal health professional; careful monitoring to detect a disease occurrence early, no matter what the source; and prompt treatment when a disease is detected are all ways to address the problem.

Issue 5: Cultured fish that escape will negatively impact wild populations by competing with, and possibly dislocating, them.

Industry sector: This concern has been focused primarily on finfish and shrimp reared in systems that are in the natural environment or in which the effluent enters the natural environment, providing a pathway for escapement. It has been raised with respect to cultured exotic species as well as native species (see also related Issue 6, below).

Reality: Escapement has been a problem, and is rarely going to be 100% preventable, though aquaculturists do everything they can to prevent escapes from occurring since lost animals represent lost revenues. A major concern in the state of Washington, USA, has been that Atlantic salmon escapees would become established as reproducing populations (this ignores the fact that the US government stocked Atlantic salmon along the Pacific coast for decades beginning in the 1870s without establishing breeding populations). There seems to be little evidence to indicate that Atlantic salmon escapees are successfully competing with wild Pacific salmon. In Texas, USA, the issue has been raised with respect to the rearing of exotic Pacific white shrimp in ponds along the Gulf of Mexico. Escapes have occurred, particularly in the past, but apparently no cultured shrimp have been observed in the commercial trawl fishery. Tilapia have escaped from culture systems in several countries and become established in the wild, apparently without creating significant environmental problems, though the deterioration of dead tilapia killed by low temperatures in temperate climates can cause odour problems.

Solution: Improved biosecurity has reduced the escapement problem, though catastrophic failures of such facilities as net pens and cages can still occur due to storms, vandalism and poaching. There is always the chance that screens preventing shrimp from leaving ponds could fail as well, or that shrimp could be lost during harvesting. Pond levees can overflow during heavy rains, allowing fish to escape. So, while the problem can be limited to a large extent, it will probably never be completely resolved.

Issue 6: When cultured species are reared in waters where wild animals of the same species live, escapees from aquaculture can breed with their wild counterparts, resulting in change to the genetic diversity of the wild population. A major concern is that exotic species will escape and reproduce in their new environment. They may then compete with native species, and even displace some local species. They may also disrupt habitat, and in some cases interbreed with local species.

Industry sector: The escapement issue has primarily been associated with Atlantic salmon farming in Norway and along the North Atlantic region of North America, but it has been mentioned in relation to various other species as well and is certainly on the minds of those who are concerned about the use of exotic species in aquaculture.

Reality: This issue has been a major one in Maine, USA, where native Atlantic salmon populations have declined precipitously even though hatcheries have been producing fish for stocking for over 130 years using Maine broodstock (though Canadian broodfish have also been used in the past). The cultured fish on Maine commercial farms are thought to have arisen from crossbreeding Maine, Canadian and European stocks. Geneticists believe that, if the wild and cultured fish interbreed, significant changes in genetic diversity may occur, leading to less adaptability of the fish to the wild and further reduction of populations of wild fish in the state. As a result, Maine salmon farms are allowed to use only Maine broodstock. In Norway, where wild and cultured salmon come from the same stock, researchers have determined that escapees from aquaculture do not have much impact on the wild salmon runs since the cultured fish are competitively inferior and have poor reproductive success. In any case, the issue has been hotly debated and can be expected to expand with the growth of marine fish culture. With respect to exotics, there has been virtually no control in many parts of the world on exotic introductions, though that situation is changing.

However, in many countries, the horse, as they say, is already out of the barn and it may be impossible to get it back in.

Solution: Prevention of escapement is the most important step that the aquaculturist can take with respect to fish that have been altered in terms of their genotype through many years and generations of selective breeding. In Maine, USA, a fisheries agency has placed traps near the mouths of some rivers to capture salmon returning to the spawning grounds. Biologists say they can visually discriminate the wild from the cultured fish that are trapped. They release the fish identified as being wild upstream and sacrifice fish they determine to be from fish farms. Cultured salmon in Norway have also been genetically modified through selective breeding. For other species, the best approach may be to maintain the wild genotype to the extent possible by random selection and frequent replacement of broodstock from the wild population. Another approach, which has been used with grass carp, is to stock triploid fish. The process of producing triploids is discussed in Chapter 6. If exotic species are used, strict biosecurity needs to be practised. The best solution is to avoid the use of exotic species in marine aquaculture. One thing is almost a certainty: at some point, escapes will happen.

Issue 7: The use of antibiotics in salmon feeds leads to the development of antibiotic-resistant strains of bacteria.

Industry sector: All sectors of aquaculture could be targeted, though the issue has mostly been raised in culture practised in public waters or in water that is released to public waters.

Reality: Indiscriminate use of antibiotics is a legitimate issue and research has identified increasing numbers of antibiotic-resistant bacterial species. Some antibiotics are excreted by fish through their urine and enter the water in that manner. Some are used as feed additives and can get directly into the water as excess feed dissolves. It should also be noted that the amounts of antibiotics that enter the water through sewage outfalls (antibiotics entering the water with human waste and from people dumping unused antibiotics down the toilet and into a sewage system) and from pastures and feedlots (antibiotics used to treat livestock) also pose a threat, and one that is probably more significant than that from aquaculture, because the amount of chemical entering the water is much higher than the amount associated with fish farms (assuming farmers follow recommended dosage levels). Another more serious problem is the presence of traces of unapproved antibiotics found in cultured shrimp imported by countries that prohibit those antibiotics. Exposure to even minute traces of certain antibiotics can be deadly to people who are allergic to those drugs.

Solution: Maintaining the proper culture conditions to keep stress on the animals to an absolute minimum can play a major role in reducing the incidence of epizootic diseases (Box 1.8). Treatment is necessary when a disease is detected, and epizootics will occur from time to time, even in the best-managed facilities. In many countries only governmentally approved antibiotics can be used and there are regulations concerning which species can be treated, the amount of the drug that can be utilized, the number of days an approved antibiotic can be used and, importantly, the amount of time after completion of treatment that must pass before the treated animals can be harvested and marketed. The latter is known as the withdrawal period. Responsible aquaculturists only use antibiotics when a disease problem has been identified. They do not use them prophylactically, not only because the chance of creating disease resistance to antibiotics would increase, but also because the cost would be prohibitive. Some nations have banned importation from countries that export such aquaculture products as shrimp that contain residues of unapproved antibiotics at any level, while other countries screen incoming shipments to ensure that minimum acceptable levels of residues are not exceeded.

Box 1.8.

A disease outbreak in humans is, of course, referred to as an epidemic. For species other than humans, the term epizootic is used.

Issue 8: Destruction of mangrove areas for aquaculture ponds results in a number of significant ecological impacts.

Industry sector: This issue has focused primarily on the shrimp-farming industry in South-East Asia and Latin America. Mangroves have also been cleared for fishpond construction in parts of Africa, but not to the same extent as has occurred in conjunction with shrimp farms.

Reality: Shrimp farms in tropical Asia and Latin America have been blamed for wholesale destruction of mangrove areas. This has previously been discussed and will not be repeated, other than to reiterate that regulations have been put in place to control or eliminate the practice in many areas.

Solution: In part due to pressure from environmental groups, and also through their recognition of the significance of the problem, governments in many affected nations have come to appreciate the importance of their mangroves and have limited or stopped destruction of them for any purpose, including aquaculture. Some restoration of pond areas by planting mangroves has also been initiated.

Issue 9: Using fishmeal and fish oil in aquaculture feeds is unsustainable and improper. It makes no sense to feed fish to fish, and aquaculture of carnivorous species should be discontinued.

Industry sector: Salmon and shrimp culture have been the primary targets of the opposition, but any carnivorous aquaculture species may be the subject of attack based on use of fishmeal and fish oil as dietary ingredients.

Reality: The aquaculture species most in demand in developed nations are often dominated by carnivores that grow best on animal-protein-based feeds, which can be best produced using fishmeal. Fishmeal is a widely used ingredient in aquaculture feeds. It is obtained from species such as Peruvian anchoveta (*Engraulis ringens*), herring (*Clupea* spp.), pollock (*Pollachius* spp.), sand eels (*Hyperoplus* spp.), sardines from various genera and menhaden (*Brevoortia* spp.). Some of those species, such as anchovies, sardines and menhaden, are very high in oil, which is also a valuable commodity. The oil is extracted from the fish after which they are dried and ground into a fine meal. Those who object to the use of fishmeal as an ingredient in aquaculture feeds often use the argument that it takes 2 kg or more of fishmeal to produce 1 kg of edible fish, which, following their logic, is an indication that aquaculture is not a sustainable practice. There is also a perception that aquaculture is the primary user of fishmeal in the world. The fact is that the amount of fishmeal used in feeding terrestrial livestock, poultry, housecats and other terrestrial animals exceeds that used in aquaculture, though the percentage going to aquaculture is increasing as production expands. Aquaculture utilized about 10% of the world's fishmeal supply in 1990, then it reached 46% in 2002, and 69% in 2016, but now is over 75%.

Fish oil is also used in aquaculture feeds because it contains an abundance of highly unsaturated fatty acids (HUFAs) that are required by many fishes of aquaculture importance, particularly marine species. There is also competition for fish oil in the marketplace. It is found in certain human foods such as margarine in some parts of the world and is becoming increasingly popular as a dietary supplement because various studies have shown human health benefits of various kinds.

While it may appear to make no sense to feed fishmeal to fish (and shrimp), the reality is that something less than 1.5 kg of feed (dry weight) can produce 1.0 kg of salmon (wet weight). Compare that with poultry, where production of 1 kg of chicken requires at least 2.0 kg of feed; and with swine, where the feed conversion efficiency is much lower than for chickens.

Both fishmeal and fish oil supplies, and consequently their prices, can vary considerably, often driven by the annual Peruvian catch of anchoveta. That catch is sustainable because the fish is short-lived, but it does fluctuate greatly as a consequence of El Niño and La Niña years that impact the nutrient levels off Peru which support the plankton upon which the anchoveta depend for food.

Solution: Aquaculture nutritionists have, in recent years, been attempting to reduce the percentage of fishmeal used in aquaculture feeds and have made significant progress in that endeavour, even to the extent that for some species fishmeal can be entirely replaced with alternative protein sources (details are presented in Chapter 8). That ingredient has been reduced to zero in many channel catfish feed formulations and has been reduced significantly through the use of alternative protein sources in feeds manufactured for various other aquatic species, including salmon and shrimp. Researchers continue to develop diets for additional species that produce good performance but contain little or no fishmeal. Some success has been achieved in genetically modifying plants to yield higher levels of the amino acids and HUFAs that aquatic animals require. Of interest is that world fishmeal supply dropped 12% from 2000 to 2008 while aquaculture production increased by 62% during that same period (www.fao.org/fishery/statistics/en, accessed 10 December 2021).

Issue 10: The use of genetically modified organisms (GMOs) in aquaculture threatens other species, including humans.

Industry sector: All sectors of aquaculture, including plant culture, are being criticized.

Reality: GMO or transgenic species are organisms in which one or more genes from one species have been incorporated into the genome of another to alter some characteristic of the recipient organism. One example is incorporation of a growth hormone gene from one species into another to enhance the growth of the latter. Stories have been circulated in the press about GMO 'Frankenfish' (in reference to the monster created by Dr Frankenstein in the novel by Mary Shelley). The prediction has been that these dreaded superfish could wreak havoc on the aquatic environment and inhabitants therein. Improved growth rates have been realized, but they are of the order of 10% in most cases, rather than several hundred per cent, though some instances of substantial increases in growth rate have been reported. Still, production of giant fish is unlikely. Unsubstantiated claims of GMO fish growing much faster and getting much larger than their non-GMO cousins have appeared in the press and one of my (R.R.S.) favourite authors, Clive Cussler, wrote in his novel *White Death* about an unscrupulous aquaculture firm that produced voracious GMO salmon that were depleting the oceans of their non-GMO counterparts and numerous other species until the protagonists in the book managed to deal with the problem.

Solution: In the USA, the USDA developed the National Biological Impact Assessment Programme to facilitate safe field testing of transgenic organisms. The USDA took the view that products developed through biotechnology are not considered to have fundamental differences from products developed through traditional types of research. Many transgenic crops are currently being grown in the USA, including those that may provide increased levels of amino and fatty acids essential for good growth of aquacultured species. Transgenic Atlantic salmon, containing a growth hormone gene from another species, received approval for human consumption in the USA by the Food and Drug Administration (FDA) in 2015, but production of GMO salmon in the USA has been prohibited. Transgenic zebrafish, tetras and tiger barbs that contain fluorescent proteins are currently being sold commercially in the ornamental trade in the USA. They come in several colours, but apparently are considered safe since they are unlikely to be consumed by people, though swallowing goldfish was once popular in the USA, so one never knows.

Permission to maintain transgenic fish under aquaculture conditions has been granted by the USDA to researchers, but only in instances where it can be demonstrated that the fish and their progeny cannot escape and possibly establish reproducing populations in nature. Use of GMOs in aquaculture is strictly prohibited in many nations, particularly in Europe. The EU does not allow the production or import of GMOs, even in the case of fruits, vegetables and grains. One arena where GMOs may see a great deal of use is in feed ingredients used in aquaculture in areas where they are allowed. GMO plants that have enhanced protein levels that may be more digestible or have other positive attributes could play major roles in aquaculture feeds in the future as replacements for fishmeal and other expensive ingredients.

Issue 11: Aquacultured organisms are inferior to those that are wild caught in many respects, including their levels of mercury and polychlorinated biphenyls (PCBs).

Industry sector: Fish and shrimp are the primary targets. The issue does not seem to carry over to molluscs, where the problem is primarily associated with the potential for transmission of human pathogens.

Reality: Claims have been made that the flavour of cultured species such as salmon and shrimp is inferior to that of their wild counterparts or that their texture is inferior. In blind sensory evaluations by taste panels, aquaculture products often are judged as superior to wild ones, though that is not universally true. R.R.S. participated in a blind taste test that evaluated three sources of salmon (wild from Alaska, cultured from the west coast of the USA and cultured from the east coast of the USA) at a meeting several years ago. About 140 people attending an international convention of chefs and writers for food magazines were involved. The three samples were evaluated as being virtually equivalent in terms of appearance (colour), texture and flavour. While this was an unscientific test, it did involve a number of people who were previously convinced that cultured salmon are inferior, and perhaps changed a few minds.

Laboratory tests have not shown that chemicals such as mercury and heavy metals or PCBs in cultured fish pose an added threat to humans. Widely published reports of high levels of PCBs in cultured salmon as compared with wild salmon have been refuted by additional studies. In more recent studies, the levels in cultured salmon were actually lower than in wild salmon. The same is true for mercury. There are exceptions where fish are living in highly contaminated waters, which is not surprising. An example is salmon in the Great Lakes of the USA and Canada where PCB levels are far above acceptable levels and people are told either to not eat the fish or to limit their consumption to very small amounts at long intervals.

It has been suggested by some critics that cultured fish and shrimp reared on formulated feeds cannot be considered organic and should be avoided. There have also been statements made and studies published arguing that aquaculture feeds contain organic chemical contaminants that could be dangerous to humans who consume the cultured animals. Support for that position has often been based on such small sample sizes that a valid statistical analysis is not possible. Those who recommend against eating cultured fish have also been taken to task for expressing concern about public health when the levels of organic chemicals or trace metals contaminants found were orders of magnitude below those thought to have any effect on human health. In fact, one recent study of wild and cultured salmon that looked at the levels of a flame-retardant chemical indicated that the average 70 kg human would have to eat 6 tonnes of salmon a day to incur health problems! What with claims and counterclaims about the safety of wild versus cultured fish, it is little wonder that the public is confused.

Solution: The only solution to misconceptions about contamination in cultured seafood lies in conducting valid research to investigate the claims and to widely disseminate the results through aggressive public education programmes. Such studies need to be pursued with all due diligence to scientific integrity. There is too much 'junk science' made available through the media, on the Internet and, regrettably, in the scientific literature.

Issue 12: Diseases of aquacultured species can be passed to humans.

Industry sector: Fish and shellfish are both considered as reservoirs of human pathogens.

Reality: There seems to be little or no scientific basis for this objection in conjunction with finfish and crustaceans. Most diseases that affect those groups cannot generally be transmitted to humans. Human pathogens that may be on the surface of fish or crustaceans or that have been consumed by filter-feeding shellfish can affect humans. Some pathogenic bacteria have been known to infect people who clean fish and other groups that had somehow become contaminated (such as when fish were exposed to sewage effluents or were reared in ponds fertilized with manure or night soil). Bacteria from the surface of the animals can enter a human through an open wound or if the individual is cut or spined while cleaning the animal. Shellfish, such as oysters, can accumulate human pathogens and pass them along to humans, particularly if the shellfish are consumed raw.

Solution: Individuals who clean aquatic animals should take care to avoid being cut by spines or knives. Consumption of raw fish or shellfish that have been reared or captured from the wild in contaminated water should be avoided, particularly by people with compromised immune systems. Public health officials in some countries monitor public waters for such contamination and close waters that are found to be affected from any harvest of the shellfish until the animals are purged of the cause of the problem, which may be a pathogen or a chemical such as domoic acid (which can cause paralysis and death in humans and is associated with toxic algal blooms).

Issue 13: Aquaculture interferes with access by other users of public waters.

Industry sector: This issue has primarily been raised with regard to cage and net pen culture and could apply to raft and longline mollusc culture as well.

Reality: Concerns expressed by critics include the contention that cage and net pen culture interfere with navigation and access to traditional commercial fishing and recreational fishing grounds. That can certainly happen, particularly when the proper regulatory environment is not in place, though some opponents will not be satisfied until all aquaculture in public waters is banned.

Solution: Develop a regulatory framework that ensures traditional users of public waters access in cases where that is appropriate or necessary. Traditional fishing grounds, military exclusion areas and shipping lanes are locations that should not be permitted for aquaculture.

Issue 14: Aquaculture has negative impacts on marine mammals.

Industry sector: Marine cage and net pen culture are the primary targets, but shellfish beds have also been mentioned in some cases where entanglement of marine mammals with ropes could occur.

Reality: The primary concern of aquaculturists is marine mammals that tear nets and allow fish to escape, while those opposed to aquaculture tend to worry about mammals becoming entangled and drowning. Incidents of mammals being negatively impacted through entanglement appear to be rare, except in commercial fisheries where drift nets (which can be kilometres long) are used. While most of the attention has been related to marine mammal interactions with net pen facilities, marine mammals can also cause shellfish beds to become contaminated with faecal coliform bacteria, making the shellfish unfit for human consumption until they are purged of the bacteria.

Solution: Marine mammal predator nets placed outside the more easily torn net pen enclosures are being employed in areas where marine mammal interactions with aquaculture have been, or could be, a problem. Those nets are generally effective in protecting both the marine mammals and the net pens from damage. There has also been some use of acoustic harassment devices that emit loud noises to keep seals away from net pens. Loud noises may also cause stress to the aquaculture species, so that could be an issue.

Issue 15: Capture of wild animals for stocking in growout facilities will lead to decimation of existing stocks.

Industry sector: This activity applies to a few cultured species of finfish and shellfish.

Reality: In some nations, collection of wild postlarval shrimp, young milkfish or immature tuna from nature for stocking aquaculture facilities is taking place. That practice apparently has had a negative impact on wild stocks of shrimp in some locations and, while the problem does not seem to be significant for other species, it could become serious if it expands in the absence of annual stock assessments to determine that taking the wild animals is done at a sustainable level.

Solution: Researchers have developed techniques to culture each of the organisms mentioned, so it is now possible to close their life cycles. Milkfish and shrimp are largely produced in hatcheries today, and progress has been made in the case of some tuna species. Economic and government regulations are considerations that will influence the course of action taken by culturists. While most wild species captured for growout have involved larval or other early life stages, tuna culture involves capturing fish that each weigh several kilograms and towing them from open ocean areas in purse seines to coastal net pens for growout. The long-term sustainability of that practice is unknown, but rearing tuna from egg to market size would increase the culture period by up to perhaps several years and add greatly to the expense associated with tuna culture.

American lobsters of marketable size are sometimes captured in Maine, USA, placed in lobster pounds, which are floating boxes typically tied to a dock, and held until either the price goes up or until lobsters that have recently moulted, and have soft exoskeletons, harden up. The technique also provides the market with live lobsters during periods when the fishery is closed. The practice is sustainable so long as there are proper seasonal quotas set by the management agency.

Issue 16: Aquaculture facilities are sources of excessive noise and foul odours.

Industry sector: This is another complaint aimed primarily at cage and net pen fish culture facilities, but also some raceway systems.

Reality: Very little noise or odours are associated with cage or net pen operations, at least those we have visited in the USA, Norway, Scotland, Chile, Malaysia, Nepal, the Philippines, Japan and elsewhere.

Solution: Noise appears not to be a real issue, though it could be around facilities that use sound cannons to deter bird predation. That has been common on salmonid raceway facilities where birds can consume large numbers of pre-smolt fish. During harvest of facilities immediately adjacent to shore, there may be some noise that occurs if boats and other types of equipment are used during the process. When that is the case, harvesting operations typically do not begin until well after dawn and are terminated well before nightfall so as to reduce the disturbance in the evening and at night. BMPs call for picking up any mortalities that occur and properly disposing of them daily, which eliminates any potential odour problem from decomposing carcasses.

As each objection is addressed by the aquaculture community, new ones quickly arise. Thus, the items listed above do not by any means exhaust the supply of objections, either current or forthcoming. In addition, the objections that are lodged in one country or against practices associated with one component of the industry are often not universal, so different parts of the world and different aquaculture sectors are fighting different battles. For example, lethal control of predatory birds around fish farms is prohibited or strictly regulated in some countries, but no such prohibition exists in other nations.

Coastal aquaculturists who have pond systems, whether for rearing vertebrates or invertebrates, have come into conflict with single family homes, condominiums and shopping centre developers; with industries interested in expansion; and with wetland protection and preservation laws. The competition for land adjacent to the seacoast in many parts of the world – particularly in developed nations – is great, and the amount of suitable available land area for aquaculture, assuming the land can be economically purchased for that use, is shrinking. At the same time, there is competition for space in coastal waters that would be suitable for cage or net pen operations. Many believe that the future of aquaculture expansion in developed nations will be associated with recirculating systems on land and with offshore facilities in the ocean (see Chapter 3).

Worldwide, the aquaculture community has been reactive rather than proactive when addressing the real problems that have been identified in association with the sustainability of aquaculture. In recent years, various groups, including FAO and GAA, have developed codes of conduct for aquaculture, as previously indicated. Several individual nations also have devised such codes of conduct, including Australia, Belize, Malaysia and Thailand. Such a code has been developed by the Department of Commerce in the USA as well. Guidelines for responsible aquaculture have also been formulated by international conventions.

Animal Welfare

Like the term sustainability, animal welfare, and in particular aquatic animal welfare, is a difficult concept to get one's arms around. It has far different meanings to different people. At one extreme are those who want to ban all aquaculture, or at least all finfish aquaculture, because fish should not be confined in any way but should be able to roam freely and enjoy life. That view would generally include that fish in confinement are stressed and may be suffering and that they have feelings much like humans. That view is not widely shared currently, though increasing numbers of people are moving in that direction. We know of no one who argues the other end of the spectrum, which would indicate that we should have no concern whatsoever about inhumane treatment of animals, including aquatic species.

There is an ongoing discussion as to whether fish feel pain. Does jumping around after being hooked mean that a fish caught by an angler is in pain? Does the neural physiology of a fish incorporate pain receptors? Some say yes, others say no. Science may eventually work that out, but whatever the answer, many sceptics will not be swayed one way or the other. To some, the emotional argument supersedes anything that science might provide as a definitive answer.

Can we accept the fact that aquaculture has some level of importance in providing food for people as well as enjoyment to aquarists, breakthroughs in medicine as surrogates for humans in research and a source of pharmaceutical products, among other things? Further, can we acknowledge that aquaculture is here to stay? If the answers to those questions are yes, then we should make some effort to treat the animals in a manner that reduces their level of stress to the extent possible. If we provide a low-stress environment, we get better growth, improved disease resistance and have a better-quality product in the end. There are various ways of measuring stress in finfish, though perhaps not in some other aquatic species of culture interest. Stress can be measured through increased levels of cortisol in the blood, for example. Whether or not one subscribes to the theory that fish have 'feelings', it is well known that stress can lead to all sorts of problems in cultured aquatic animals, some of which were just mentioned. What was not mentioned is that stress can also lead to death, which is not desirable if the culturist is interested in eventually marketing the product.

It has been argued that disease problems are more prevalent in cultured than in wild fishes, so not only are cultured species unhealthy, but their welfare is compromised. However, the opposite view has also been espoused, with the argument that because of good environmental management and prophylaxis, cultured species are actually less likely to experience a disease outbreak than are their wild counterparts; thus, it can be argued that fish welfare is actually improved under culture conditions. The extent of mortality in wild populations is typically not quantified, except in certain instances, so the comparisons with cultured animals are largely unknown.

You may have noticed that when we mentioned the benefits to mankind of food and ornamental species, among other positives that can come from aquaculture, we did not include production of bait for recreational (and in some cases) commercial fishing. Each individual should make up his or her own mind as to how he or she feels about putting a minnow, polychaete or earthworm on a hook or using some other type of bait to chum the water to attract fish. Then there are those who object to using one type of fish to feed another. For example, small goldfish are sometimes used by aquarists as live food for ornamentals. So, the issue of animal welfare can become quite complicated, particularly when human emotions enter the debate.

As discussed in the Branson book mentioned in the 'Additional Reading' section, several effects of fish culture can adversely affect the animals. These include the density at which the fish are confined, feeding practices, handling, transportation and slaughter (which may not take place at the site of the aquaculture facility). Taking just the first item on the list, the argument has been made that the higher the density in the confinement system, the more stress is placed on the animals. Ultimately, that is true, but in some cases, species actually perform better at fairly high density than at low density. Schooling fishes might be an example of fish that have evolved to be in close proximity to others of their species. Or, for those people who want to be anthropomorphic, the fish feel better when they have their friends and families around them. Research has determined the optimum stocking density ranges for various finfish species and for some invertebrates based on their performance under different levels of crowding. It is often necessary to reduce the density as the animals grow, because actual numbers per unit volume of water are usually not nearly as important as total biomass per unit volume of water. It just makes sense that large fish take up more of the space in a culture chamber than the same number of small fish. Performance can be affected through deteriorating water quality, inability to move about and other factors. There are even reports, though somewhat isolated and not fully substantiated, that at least a few fish species are able to produce a chemical that causes an autoimmune response resulting in mortality to a portion of the population when a certain level of overcrowding occurs. That hypothesis is revisited later when stress is more completely discussed. Another interesting finding is that the stocking density of European eels (*Anguilla anguilla*) from the glass eel to the elver stage influences the ultimate sex of the animals. High stocking densities produce eels that tend to become females (Box 1.9).

Box 1.9.

The life cycle for many eel species of interest to aquaculturists has not been closed; that is, captive spawning and early life cycle rearing have not been successfully conducted to date. An exception is the Japanese eel, *Anguilla japonica*. In most cases, as with American and European eels (*Anguilla rostrata* and *A. anguilla*), glass eels are typically collected from nature for growout. The glass eel stage is the one into which the leptocephalus larva metamorphoses.

Ethics

For the vast majority of commercial aquaculturists, the bottom line is to make a profit. Other than hobbyists, those involved with aquaculture usually have an interest in producing a product for sale or providing food for their families. There may be some aquaculturists who are so independently wealthy they can produce at a financial loss and stay in the business for the pleasure they obtain from their involvement, but such individuals are going to be scarce. It is true that many go into aquaculture to a large extent because they are interested in providing food for others, and many also enjoy working on, in and around the water. But financial gain is typically a major motivating factor. However, some take the concept of financial gain to the extreme and go beyond what is ethical, or even legal. We refer to those individuals as *aquashysters* or *bioshysters*.

There are not all that many unscrupulous people involved with aquaculture, but it only takes a few to give the discipline a very bad name, particularly to the people whom the aquashysters prey upon and scam out of their money. Those whose ethics are questionable often claim to have a revolutionary new product under development; plan to establish a major aquaculture facility using technology that they have developed that promises to return hundreds of per cent on investment within a year or two; or make some other, often outrageous claim to talk investors out of their money. Another scheme might involve what is claimed to be a major breakthrough in the successful culture of a species that has never been produced commercially in the past. An example of the latter would be the claim that the aquashyster has found a way to spawn and grow bluefin tuna (*Thunnus thynnus*) from egg to market size in the amazing time of six months.

Whatever the scheme may entail, it is highly unlikely that any product, facility or animal will be produced; or, if they are, the activity will largely be a show to provide a means of obtaining more money to flow into the pocket of the aquashyster. In one instance, I (R.R.S.) heard about a couple of disreputable individuals who claimed to have developed the technology to culture Florida spiny lobsters (*P. argus*) from egg to market with low levels of mortality. When they spoke to prospective investors, they showed off a tank with a few immature lobsters that they claimed had been produced from eggs that they had hatched and produced larvae that they had grown through metamorphosis. The reality was that they caught some undersized (read illegal) lobsters, put them in a tank and claimed they had grown them.

R.R.S. once talked to a person who was selling a product that was supposed to greatly enhance water quality when added to a closed recirculating culture system (see Chapter 3). Improved fish growth and reduced disease resistance would occur and all it would take is a small amount of the magic liquid to get amazing results. Also, if you were to take a sample of this miracle product to a laboratory for analysis, all they would be able to detect would be H_2O: yes, that's right, it would analyse as pure water. Truly amazing and unbelievable unless you happen to be very gullible or just interested in throwing away some investment money. Our lab at Texas A&M University was offered a barrel of the stuff to try out in our culture systems, but it never materialized.

Another person dropped by our laboratory and said he had developed a culture system that would fit in the bed of a pickup truck so one could grow fish while driving down the highway. Yes, you read that correctly. The system was not designed to keep fish alive while you hauled them to another site for stocking or to the local processing plant. The system was actually meant to be a growout facility. What the market for such a system would be is unknown, but it probably would not be very large. We cannot imagine why you would want a mobile culture system unless you were moving from town to town over a period of several days or even weeks selling small numbers of small live fish for stocking farm ponds; and that's a stretch, as those who deliver fish to those wishing to stock their ponds typically advertise when and where interested parties can obtain fish with or without obtaining orders in advance. In any event the distance of travel from the production facility to the point of sale is generally relatively short. The producer may limit delivery sites to no more than a few hours from the production facility and haul fish numbers that can be sustained with aeration. Thus, a complicated system of water treatment on the hauling truck is not required. They do not stay on the road for several days. For the way they operate a simple live-hauling tank will be sufficient (see Chapter 9). With respect to that individual, we did not get the impression we were dealing with a bioshyster, but just with somebody with an idea for something that nobody needs.

Short of having a facility to show the prospective investor, or at least an actual site where construction is planned or is under way, the aquashyster may have a set of elaborate plans, perhaps including blueprints drawn up by a presumably respectable architectural or engineering firm. In many cases, the proposed culture site is not convenient to the place where the aquashyster is soliciting investment money. For example, perhaps you are in America being solicited by one of these people who says: 'I can't take you to the site, which I have found in the far-off reaches of Pago Pago, but I can show you the blueprints for the farm. Of course, you will have to swear not to divulge the various top secrets that will be revealed.' That should cause the alarms to go off, but the promise of a quick large percentage return on investment tends to make some people unable to recognize they are being led down the proverbial garden path.

It is a good thing that the majority of those involved with aquaculture are honest people dedicated to producing high-quality, healthful products and making reasonable profits. Those legitimate people often look for investment capital because banks are often unwilling to take a chance on aquaculture – largely because many banks have no experience with such facilities and do not know the level of risk, except in regions where aquaculture has already been established and is flourishing. However, if you are approached by someone with an aquaculture idea that just seems too good to be true and will provide an incredible return on your investment, you might want to turn your back and go after some of those millions of dollars that are being discovered in an account you didn't know you have in some country you've never heard of but contacted you via email.

Before leaving this topic, we would be remiss in not indicating that unethical behaviour is not limited to the private sector. Some scientists also push the bounds of honesty or even trample over the concept when they search for answers in their research that support their personal theories or beliefs, or in all too many cases, search for the answers that the sponsoring entity of the research would like to have. Just as one can hire a lawyer to argue just about any position that someone might develop on virtually any issue, it appears as though at least some scientists have that same ability. Much of the controversy that surrounds aquaculture is based on 'studies' in the published literature which either ignore the facts, bend the facts to fit the author's views on the topic or misinterpret the research results, whether accidentally or intentionally. Junk science attesting to horrible aquaculture practices and outcomes has received a lot of attention in the media, while the peer-reviewed research that demonstrates the actual situation is often ignored. It is even more disturbing when opinion pieces that are based on partial truths or all-out falsehoods are published in what are considered distinguished scientific organs which later refuse, in many cases, to publish rebuttals.

How about the imposition of the views of one human culture upon another? What I (R.R.S.) mean by that is associated with an experience we had several years ago when we were involved with a grant from the US Agency for International Development (USAID) to Texas A&M University to work with the Bureau of Fisheries and Aquatic Resources (BFAR) in the Philippines to develop a hatchery that was supposed to produce millions of Nile tilapia (*Oreochromis niloticus*) and common carp (*C. carpio*) fingerlings annually. The grant called for the selection and training of BFAR extension workers who would operate the hatchery and distribute the fish to rice–fish farmers. Those were farmers who, with slight modification of their rice paddies, could develop an additional product. The typical Filipino farm family at the time had 7.8 children on average, and their dietary staple was rice. Much of the production from the rice paddies went to feed the family, with the rest being sold or bartered for other necessities of life. In many cases, the children were undernourished because of the absence of animal protein in their diet. The idea of the programme was for the families to produce fish so that they would get some animal protein into their diet. What we found out was that after the fish were harvested, the appearance of a television antenna was seen for the first sign. Instead of keeping the fish for family use, the farmer would typically take them to market and sell them. He would then use the money to buy a television set for his one- or two-room cottage. Some people I have told that story to were of the opinion that while we were trying to improve human nutrition, the farmers were irresponsible in selling the fish and using the money for a luxury item. 'Here you are, trying to help people out, and what do they do but take advantage of your charity and squander it on something they really don't need,' was the opinion. My response to that was if the farmer felt that the purchase of a television or some other household item that the family wanted was the highest priority, and that was his decision (or commonly his wife's, I imagine, as the women are often the ones who run the financial end of things in the rice-farming community), who were we, as outsiders from an entirely different background and culture, to impose our will, even with the best of intentions, upon the Filipino rice–fish-farming families? Maybe the nutritional plane of the family was not improved, but the farmer would tell you: 'My parents and their parents for generations were raised on rice. I was raised on rice, so why shouldn't my children be raised on rice?' It's hard to argue with that.

R.R.S. spent a few months spread out over a period of three years in the Philippines at the site, which was located on land where Central Luzon State University (CLSU) had a research fish farm near the main campus. A colleague at Texas A&M University, Jim Davis, who was a fisheries extension specialist, spent the first month of the project working with USAID and BFAR to get the project started (the site for the hatchery had been chosen and bulldozers were beginning to clear the vegetation to prepare the site for pond construction). In a second trip, R.R.S. spent two months at the site while the ponds were starting to take shape, and the hatchery and office buildings were under construction. Another couple of trips were of shorter duration and during the last one the ponds were beginning to produce, and only the housing for the BFAR staff had yet to be built. Rice farmers were not interested in carp, so the facility was producing only tilapia. By that time Meryl Broussard (a former PhD student at Texas A&M University) was advising on hatchery and pond production and Joe Lock (with the Texas Agricultural Extension

Service) trained rice–fish farmers, along with advising on hatchery and pond production. They were in place for about the last half of the five-year grant period.

In 1984, R.R.S. left Texas A&M University to take a position at Southern Illinois University (SIU) in Carbondale, Illinois. He had the opportunity to go to the University of Washington as Director of the School of Fisheries in 1985 after only 18 months at SIU. He returned to Texas A&M as Sea Grant Director and Professor of Oceanography in 1996. He had only been at Texas A&M again for a few months when Jim Davis said the two of us had been invited by the President of CLSU to visit the project site. We had hoped that monthly production could ultimately reach 300,000 fingerlings each month; we learned that the production had steadily increased over the years to well beyond that number.

Incredibly, of the group of nine BFAR extension workers who had been on US short-term stints at Texas A&M University for training, with four receiving M.S. degrees, all were still affiliated with the CLSU facility. In addition, nearly all the others we had worked with years earlier were still actively producing and delivering fingerling tilapia to the rice–fish farmers. We were very pleased with the success achieved by the programme and also proud of everyone who had been involved.

Changing Consumer Preferences

In the developed nations, many consumers are becoming increasingly aware of environmental issues associated with the production of their food supply, and this awareness often focuses on aquacultured species. Yet, as we have seen, there are a number of concerns that have been expressed by various groups who often get the ear of the media. Convinced that pond construction is defiling the environment, effluents are polluting every water body in sight and cultured aquatic species are inferior to wild ones, there are those who would just outlaw aquaculture, or if that did not work, would rather see it develop in another country than theirs. Upland indoor culture might be acceptable in recirculating systems, and even marine culture might be acceptable so long as it is far enough away to be out of sight from land. The mantra is: 'Put them anywhere, but not here!' That is the 'not in my back yard' (NIMBY) phenomenon. Yet, as we have seen, global aquaculture continues to grow, as does per capita seafood consumption in many developed, as well as developing, countries. So, there is a dichotomy among consumers. Some, and we believe they are the minority, are totally opposed to aquaculture, while most people are ambivalent or proponents. For the majority, being able to find good-quality seafood at reasonable prices and in the types of commodities they prefer trumps other factors. That is why the demand for cultured shrimp and salmon continues to grow. The wild product just cannot satisfy the demand.

It is a little frustrating that many influential chefs have bought into the idea that cultured salmon are inferior. In the USA, cooking shows on television have become addictive to many people who enjoy cooking – and that is both males and females. R.R.S. does not personally watch those shows, but his wife does, and a few times when he has walked through the room where she is watching some well-known chefs, he has heard things like: '*Make sure you purchase wild salmon. You don't want to eat cultured salmon as it has no flavour and is raised under feedlot conditions*.' As you have seen, when a group of seafood chefs and seafood writers has the opportunity to compare cultured and wild salmon in blind appearance and taste tests, they cannot tell the difference. If they can't, then it is unlikely the typical consumer can either. More recently, there appears to have been some turnaround in the opinion of chefs that cultured salmon are inferior to their wild counterparts.

The taste testing previously discussed with respect to salmon included a blind taste comparison of three shrimp from different sources: wild shrimp from the Gulf of Mexico, cultured shrimp from the USA and imported cultured shrimp. Those involved could not distinguish the wild from the US cultured shrimp, but the imported cultured shrimp apparently had been in the freezer too long as it was considered less desirable.

While a relatively small percentage of people shop only for organically grown foods, a much larger portion of the population does purchase organic foods at least part of the time. They may not be looking for the word 'organic' on the label, but they in all likelihood have tried a particular product not caring one way or another and decided that they preferred it, so they buy it again. In any case, the trend towards organic is growing, and the aquaculture industry is responding by attempting to develop production methods that provide products that can be certified as organic. Standards for certifying aquaculture products as organic have not been finalized in the USA by the USDA. As such, aquaculture products in the nation are not certifiable as organic but that is not the case in other countries. It is difficult, though, to gain organic certification, because of non-organic ingredients in aquaculture feeds. That is changing, however, as culturists interested in the organic niche food market have turned to ingredients that can be certified organic. Once a facility is certified, a higher price can be demanded for the product (Box 1.10).

Box 1.10.

How one defines organic with respect to aquaculture varies. We have yet to see an inorganic live fish. In any case, there seems to be a controversy brewing with respect to whether a cultured species can be labelled organic if it is fed fishmeal due to concerns over the sustainable use of that resource. It seems to us that it would be difficult to say that fishmeal is inorganic, but since its use is controversial, purists must believe that fishmeal cannot carry that label; thus, they conclude that cultured species that are fed diets with fishmeal in them at or above a certain percentage should not be considered organic.

One more thing about consumer preference is a growing trend, at least in the USA, and probably also in many other countries, to purchase locally grown food. Of course, in many parts of developing countries all or nearly all of the food available is locally produced, and often is purchased on a daily basis because the people often do not have refrigerators or even electricity. By locally, we do not mean grown in a particular country, but truly locally – within several kilometres of where it is marketed. Fruit-and-vegetable stands with locally grown products; farmers' markets; and, increasingly, the sale of locally cultured or captured seafood is a growth industry in at least some developed nations or parts thereof. The buyer often knows the seller personally, the products have not had to travel long distances to reach the market, and there is little question that the foods are fresh. That trend will probably continue to grow and may provide some unique niche market opportunities for aquaculturists to fill.

Regulation

Discussing aquaculture regulations in a general fashion is difficult because the regulatory situation both within and among the nations that have active aquaculture programmes tends to be extremely complex. While aquaculture is practised in some nations virtually without government regulation, others have adopted national regulations, state or provincial regulations and even local regulations. A good way to determine what regulations are in place is to go to the Internet and conduct a search for aquaculture regulation or aquaculture policy and specify the nation or region of interest. As a general statement, the regulatory environment with respect to aquaculture is *similar* in, at a minimum, the EU, Australia, the USA and Canada. We stress the word similar because there are many differences among them.

Permits to operate aquaculture facilities may or may not be required. Depending on where the aquaculturist is in the world and what the aquaculturist plans to do, getting a permit may be as simple as filling out a form and paying a small fee. In other cases, it may be far more difficult. The prospective aquaculturist may have to visit several different agency offices at various levels of government. At one time, to obtain a permit in the state of California, USA, the applicant was required to contact 25 different offices. The process was simplified as the industry advanced but is illustrative of how convoluted the situation can be. In any case, once the applicant has determined the steps in the process, it may be necessary to obtain and fill out complicated forms, and to collect environmental data in support of the application at the proposed site. The environmental data would be used for the development of an environmental impact statement (EIS), which would be reviewed by one or more agencies; and there may be a request for additional information and revision. The EIS may also be made available for public comment, which would have to be responded to. One or more public hearings may be held, at which opponents often show up in force while the only proponent who attends is, more often than not, the applicant. All this can take months and, in some cases, years. If the permit is finally granted, the applicant may have to pay a significant amount of money for it, and possibly pay a lease fee in order to utilize the proposed site if it involves the use of public waters. Once the facility is established, it may be necessary to continuously monitor the environment and report on a regular basis to the responsible regulatory agency, which can shut down the facility if it goes out of compliance. There is also the possibility that, after the expenditure of large amounts of time and money, the permit application will ultimately be denied. There have been cases where a permit has finally been granted but the applicant had gone through all available financial resources and could not afford to activate the permit.

The two scenarios in the preceding paragraph represent the possible range of what might be involved in obtaining a permit in places where permits are required. Is it any wonder that many aquaculturists from developed countries establish facilities in nations that have either no permit system – the 'come one, come all and do your thing' approach – or have a very simple regulatory system in place? That said, I (R.R.S.) should also add that obtaining permits, if any are required, is usually a simpler process in conjunction with pond facilities and recirculating systems and in conjunction with freshwater than in marine systems (unless the freshwater facility continuously discharges water into the environment, e.g. trout raceway systems).

Developing countries in the tropics are major producers of aquaculture products and have attracted foreign investments for a number of reasons, not the least of which, as suggested, is often a lax regulatory environment. In some instances where regulations have been promulgated, enforcement has been weak to non-existent. Some nations provide tax breaks to aquaculturists, and there has also been the lure of inexpensive land and labour in many developing countries. The situation with respect to government involvement appears to be changing in some countries, but the long-held belief that it is easier to establish an aquaculture facility in a developing country than a developed one continues to prevail and is supported by the fact that much of the expansion of aquaculture continues to occur in developing nations.

The desire of opponents to employ the precautionary principle has already been mentioned. As has been stated and reiterated, aquaculture, like any human activity, will have a measurable effect on the environment at some level. The extent to which that effect is allowed to occur is the province of the regulators. The number of parameters that the aquaculturist is required to measure should ensure that negative impacts on the environment can be detected early, but they should not be so numerous or so expensive to obtain that they become unreasonable, which can happen to the point that the project becomes economically unfeasible. While it may be possible to identify any of the thousands of chemicals that might be found in a water sample and determine the level of each, to do so would cost exorbitant amounts of money. Thus, a few of the most important parameters should be selected; ones that are indicative of the health of the environment and can be measured easily, quickly and inexpensively. Certainly, a regulatory agency would be wise to have the aquaculturist routinely determine the levels of ammonia, nitrate, nitrite, phosphorus and dissolved oxygen in the water. In terms of other parameters, water current speed, character of the bottom and the fauna in association with the bottom might be recommended for cage and net pen culture in lakes or the ocean. Temperature (in all systems) and salinity (in marine systems) should be routinely measured as well, because the culturist will get useful information from those data that may not be related to what a regulatory agency requires. There certainly may be other appropriate items to add, depending on the particular type of system and its location.

As important as routine monitoring and timely reporting of the results is the provision by the regulatory agency to allow aquaculturists to modify their management activities as the situation changes. If a problem is detected, the culturist should be allowed to search for a way to ameliorate that problem in a timely fashion, but the facility should not be immediately shut down. That step should only be taken for flagrant or repetitive violations or when no way was found to reduce the environmental impact without making the facility uneconomical. Allowing the operator time to adjust and try one or more new approaches is called adaptive management. It is a trial-and-error process that should *eventually* lead to the development of a series of BMPs as a result of modifications in operating procedures that ultimately will ensure that the facility stays within the range of values set for water quality and other parameters by the regulatory agency. Modifications in operating procedures can be made very quickly, after which the results can be determined over relatively short periods of time, and then further modifications can be made, if necessary. Compliance should be obtained within weeks, if not months, but it may take up to a few years to develop a final series of BMPs. The adaptive management approach is fair to both the operator and the regulator, who should work cooperatively and not be adversaries. An entire book on BMPs for aquaculture is the one by Tucker and Hargreaves described in the 'Additional Reading' section at the end of this chapter.

Challenges to, and Opportunities for, Expansion

It was once thought that moving marine finfish aquaculture away from the coast would reduce the complaints because coastal residents would not see the facilities from their residences, places of business or where they go to the beach for recreation and/or relaxation. But the opposition has, at least in some places, been as vocal about the mere idea of developing open ocean aquaculture as it was in response to aquaculture development in protected coastal waters. The opponents to aquaculture development target specific regions and practices, and they often have different goals. Those range from the laudable one of getting rogue aquaculturists to clean up their acts and move to more environmentally conscious practices to just trying to shut down aquaculture operations without regard to whether or not they are sustainable.

In general, we can anticipate that opposition to aquaculture will continue, though there seems to be some progress away from total condemnation, particularly by various environmental groups that are now developing codes of conduct, lists of BMPs and trying to help find solutions to some of the issues rather than ignoring the efforts by the aquaculture community to address those issues. Thus, while new issues are likely to arise in the future, more reason is being interjected into the discussion. As that happens and compromises are reached, both sides can feel that they have achieved something positive.

Some specific challenges for aquaculture expansion are:

- Finding areas for warmwater marine shrimp pond farms that do not encroach on mangrove or other sensitive habitats.
- Finding coastal areas for upland aquaculture facilities in developed nations where land prices do not doom the activity from the onset.
- Continuing to operate at a profit in the face of high energy and feed costs.
- Finding species that can be grown profitably in offshore waters where the logistical problems and facilities costs are much higher than for similar facilities in protected coastal waters.
- Recovering from severe storms and earthquakes that have destroyed aquaculture facilities and supporting infrastructure.
- Competing with lower-priced imports such as has happened with marine shrimp and basa catfish in the USA.
- Finding reliable supplies of high-quality water and, in particular, freshwater, in the face of increasing demands by industrial, agricultural and domestic users.
- Developing nutritionally complete prepared feeds as the availability of fishmeal and fish oil for aquaculture feeds decreases or their prices increase to the extent that profit potential is eroded or eliminated.

We cannot question the fact that demand for seafood is not going to decrease but will in fact continue to increase as the human population continues to grow. The demand will also increase because per capita consumption is growing, fuelled in no small part because of the clearly demonstrated health benefits from consuming finfish and other seafoods. Many capture fisheries landings have basically levelled off, are in decline, or are greatly overfished, and the prospect of them recovering in the near future is unlikely. The only way supply can expand to any degree is for aquaculture production to increase to meet the growing demand. The trick will be to have continued development that is sustainable.

Climate Change

A few decades ago climatologists told us that the world appeared to be entering a new Ice Age. That notion was soon abandoned as there was a return to global warming, a phenomenon attributed to human activities, particularly increased levels of carbon dioxide in the atmosphere primarily due to the burning of fossil fuels. Another result of climate change is ocean acidification with the resulting dissolution of calcium carbonate on coral reefs and mollusc shells in the marine environment.

There is no question that climate changes and, in fact, has changed measurably, with temperatures increasing and decreasing over hundreds of millions of years according to the geological and fossil records. How much of recent climate change can be attributed to human activity seems to us to be an open question. Some years have been warmer than average, some have been cooler or closer to the long-term average. It is interesting that global warming is blamed both in years when the average temperature is higher than average and in those in which the temperature is lower than average.

As indicated, climate changes. Where it is headed in the near future appears to be towards a warmer planet. International conventions on climate change have led to promises by various nations to put large amounts of money towards reducing carbon dioxide emissions. In some cases, those reductions may or may not be initiated in the next few decades by some of the countries that are the greatest emitters of carbon dioxide and other chemicals that are said to be involved in global warming. As nations begin putting billions of dollars or other currencies into reducing emissions, there will be a massive experiment to determine if the problem can be addressed to any extent. One bright spot is the USA where carbon dioxide levels have fallen by several per cent in recent years. However, the levels in some nations continue to increase and there appears to have been few, if any, attempts to address the problem.

While there appears to be a considerable range of theories as to how climate change will affect aquaculture, there seems to be a lack of empirical evidence. Most of the research to date on the impact of climate change on fisheries and aquaculture has focused on fisheries. There is anecdotal evidence on the effects of climate change on aquaculture, which may or may not be reliable, but it is not difficult to speculate on what some of those effects might be in the future. Warmwater species could be cultured in regions where they could not formerly be cultured successfully in freshwater ponds and the marine environment. Coldwater species could be extirpated in areas where they now flourish in aquaculture facilities that employ surface water supplies as average annual water temperatures increase. The ability to culture midrange species with respect to temperature could be moved either north or south. Sea level rise could be expected to inundate many coastal aquaculture facilities as glaciers continue to melt. The economic impacts of having to abandon facilities and find new locations to re-establish them would be considerable; potentially devastating to many producers. Because climate change is a slow process, the impacts will be expected to creep up on the aquaculture industries that are susceptible to water temperature change.

If worst-case scenario projections of sea level rise between now and 2100 are correct, or even close, many of the world's major cities will be flooded to the extent that all or major portions of them become inundated. Protecting them by constructing dikes or seawalls would be an extraordinary expense, adding another layer on the costs of reducing carbon dioxide and other emissions considered to influence global climate change. Further, some island nations, for example in the South Pacific, are currently being impacted by sea level rise and there is talk of moving some populations to continental areas. Climate scientists have predicted increasing numbers of severe storms. El Niño and La Niña events can also be seen as being associated with climate change.

We currently live in interesting and challenging times. The future may be even more interesting and challenging, particularly because we can't really tell what Mother Nature will do in the future. We can only speculate, and speculation often turns out to be wrong.

Summary

Aquaculture is the rearing of aquatic species under controlled or semi-controlled conditions and is equivalent to underwater agriculture. It involves a wide variety of species from various trophic levels that are produced for a variety of uses. Included are organisms grown for human consumption, as food for other species, for the ornamental trade, for bait, for stocking recreational fisheries, for enhancement of commercial fisheries, for their use in biomedical research, or for their value as nutritional supplements or pharmaceutical products. Currently, there are well over 200 species being produced by or of interest to aquaculturists for human consumption, with many more being produced for the ornamental fish trade. If one adds in ornamental invertebrates the list becomes much longer. For such species as shrimp and marine finfish with very small eggs (the majority), the aquaculturist may have to produce algae to feed zooplankton that are used to feed the early life stages of the target species.

The annual catch from the world's capture fisheries peaked in the 1990s and has been fairly level ever since. As the human population expands and per capita consumption of seafood grows around the world, the only way that demand can be met is through aquaculture. So far, aquaculture expansion has done a fairly good job of keeping up, but whether that can continue indefinitely is a major issue. There is an increasing movement towards making aquaculture more sustainable. That term has a number of definitions, but basically sustainability involves the judicious use of natural resources and minimizing impact on the environment in the pursuit of an activity – in this case, aquaculture production. A major challenge to future aquaculture development will be sustainable industry expansion. Sustainability also implies social justice. In addition, aquaculture products need to be healthful and nutritious.

There are many opponents of aquaculture development and there are a variety of reasons for that opposition. Many issues that have been raised have merit, while some do not. Aquaculturists have been trying to address the real issues raised by opponents since at least the 1980s and, though significant progress has been made, more needs to be done.

While there are many challenges to continued aquaculture development, demand will continue to increase for aquacultured food products that are nutritious and delicious. There will also be increased demand for ornamentals, bait and the many other products that come from or will be developed through aquaculture.

Global climate change has become a concern with respect to potential impacts on aquaculture. Those impacts remain to be determined, but climate change models that predict water acidification, sea level rise and increasing water temperatures are of concern. The climate changes and has changed over eons. In which direction it will change is considered to be settled science by some, but is still considered to be nothing more than speculative by others. Only time will tell.

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2 Getting Started

Site and Species Selection

An aquaculture facility needs a sufficient quantity of good-quality water in order to produce one or more crops annually in sufficient amounts to make the operation profitable. Depending on the level of technology employed, sites that meet those broad qualifications can be found in many locations around the world. Aquaculture is even being practised in some areas that seem unlikely candidates, such as deserts. Thus far, the only places where there is no aquaculture are the Arctic and Antarctic regions. There have even been discussions about developing aquaculture systems in space in conjunction with manned space stations or the colonization of other planets.

Just because a functioning aquaculture facility can be established in a particular place does not mean the venture will be profitable. Requirements for treating incoming and/or effluent water, or simply paying for the costs associated with obtaining the necessary supply of water, can exceed the profit potential of a facility.

Having a good supply of water is, of course, not the only consideration associated with site selection. One firm, for example, established an indoor facility around 1980 to grow marine shrimp in Chicago, Illinois, USA, several hundred kilometres from the nearest ocean and in a climate that features very cold winters. Since the species involved was of the warmwater variety, it was necessary to heat the water during a considerable portion of the year. The operation was housed in a large warehouse and was designed as both a hatchery and production facility; however, it was never scaled up beyond producing a few kilograms of product monthly, so it did not get beyond the development stage. The system was of the recirculating type (see Chapter 3), which meant that very little new water had to be added once the system was filled. However, the cost of purchasing bags of a salt mixture that mimics seawater when mixed with freshwater, coupled with the major cost of heating the water, were among the reasons the venture failed. The need to employ several highly skilled engineers and biologists to design and operate the facility was costly, and the owners who paid the costs of establishing and supporting the operation were facing difficult times because the USA was going through an economic recession. The concept of growing shrimp far from the sea was proven, but the business closed down before it even began to approach a level of production that would make it profitable. Establishing an indoor shrimp farm far from the sea with a species that only survives in saltwater may seem unrealistic at best; but if it had been successful, having the production, harvesting, processing and marketing in a major metropolitan area could reasonably have been seen to have an economic advantage in terms of shipping the product, and the probability that a fresh, locally produced shrimp may have been the preference of local consumers as compared with imported frozen shrimp.

In many cases the aquaculturist selects the species to be grown before selecting the site though, as is evidenced by the Chicago experience, some culturists have attempted to force the species selected into an available site that is not necessarily compatible. A culturist may have training and experience with a particular species and concentrate on that species because they are most comfortable with it. That said, many techniques are similar for species within a particular phylum or medium requirement (freshwater as compared with marine or estuarine salinities), though nuances in the culture requirements among even closely related species can be significant.

On the other hand, a perspective aquaculturist may already own a piece of land and have the desire to establish an aquaculture facility in that location. In such instances, or in the case where the culturist purchases an existing aquaculture facility, the most

DOI: 10.1079/9781800621145.0002

logical course of action is to select a culture species that is appropriate for the site (which would probably already be determined if the aquaculturist procured an active facility that had been showing a profit). Sometimes it is possible to rear a species that might seem unsuitable for a particular site because of extenuating conditions that alter that situation. For example, geothermal water and power-plant-heated water effluent have been used to produce warmwater species in cold climates, while cold groundwater or spring water can sometimes be available for use to rear coldwater species in warm climates. Marine species can be reared inland in areas with saline groundwater and, in some cases, when the selected marine species is sufficiently euryhaline (Box 2.1) to thrive in hard water. Hardness is discussed in Chapter 4. Buildings such as warehouses and greenhouses have sometimes been sites for successful aquaculture operations.

Soil properties are an important consideration in cases where the facility involves the construction and use of earthen ponds. Inferior soil characteristics, such as an insufficient percentage of clay, can lead to extensive seepage, thereby increasing operational costs because of having to provide replacement water almost continuously. Pond liners are an option to reduce or eliminate seepage. More on that topic is included in the 'Ponds' section of Chapter 3.

Land costs can also be a factor that contributes to failure in the profitability of an aquaculture operation. This is particularly true in the case of coastal land in developed nations where the competition with waterfront home developments, commercial buildings, marinas, ports and harbours, and various other enterprises has drastically inflated the price of coastal land. That is one of the reasons many aquaculture operations have been established in developing nations where sufficient quantities of coastal land have historically been available, often at very reasonable prices. Developing nations also often promote aquaculture development and have few, if any, permitting requirements and limited operational regulations. However, many nations have come to recognize the need to maintain the quality of the coastal environment and have imposed requirements for prospective aquaculturists to employ methods that help protect, not degrade, the environment in which they plan to operate. Disregard for environmental impacts by aquaculture can certainly lead to negative impact on the environment and therefore on the species under culture. However, in general, because of their concern for maintaining the best possible conditions for the growth and welfare of the species they are producing, aquaculturists are typically also environmentalists and, therefore, operate their facilities in a responsible manner. Of course, there are exceptions, but those producers operate at their own peril.

> **Box 2.1.**
>
> An aquatic species that is euryhaline is one that can adapt to a wide range of salinities. Estuarine species are typically euryhaline because the salinity in an estuary can range from full-strength seawater to freshwater from the mouth of the estuary to the area of freshwater inflow. Moreover, the salinity in any particular location will fluctuate significantly due to tidal water exchange.

The Business of Aquaculture

Many aquaculturists have established their aquatic farming activities as one part of a larger agribusiness enterprise. This has been true for portions of the catfish industry in the USA, salmon culture in Chile and shrimp culture in many nations, among many other examples. In the USA, Mississippi cotton growers turned to channel catfish farming as an additional crop, as did rice producers in Arkansas. Similarly, rice farmers in Louisiana and Texas turned to crayfish production in their rice fields. There have also been cases where international corporations, some of which were not previously affiliated with any aspect of food production, expanded their activities into aquaculture. Several years in the past an automobile tyre company in the USA was involved in an aquaculture venture, for example. A number of other examples could undoubtedly be found, but chances are that most of those successful industries that put their foot in the aquaculture water returned to concentrating on their earlier enterprises.

When a new aquaculture species reaches the market, it often demands a high, even premium, price because it is not readily available in large quantities; is often a novel product that consumers are willing to try (at least once); and, initially, is available in most cases from only one or a very few sources. Also, a new aquaculture species may be available from capture fisheries in some places, but not others, which would mean the aquacultured product would have to be priced similar to the wild; thus, marketing the aquacultured product in areas where the wild one is not available provides the opportunity to sell it at a premium price. Subsequently, as other culturists begin producing the same species, competition will cause the price paid to the producer to drop. Ultimately, the amount of the product in the marketplace may become so large that the price paid to producers will fall to the point that little or no profit margin remains.

Those who get into the business early and are able to pay off their facility development costs before the market becomes saturated may survive, but those who arrive late and have heavy debt loads may end up bankrupt. We have seen this in the Atlantic salmon (*Salmo salar*) aquaculture industry. During at least part of the 1980s as the industry was becoming established in the state of Washington, USA, the fish at harvest brought a price that yielded a net profit to the growers of over US$2.00/kg. However, within a few years, as fresh salmon became available throughout the country and imports from Norway and eventually Chile began to compete with domestically produced salmon, the profit dropped to around US$0.20/kg.

Prices paid to producers for channel catfish have increased only marginally in the last few decades (US$1.10/kg in 1960 to US$1.76/kg in 2010, and US$2.24 during one month in 2012) according to the USDA. So, over a period of nearly 50 years, the profit per unit weight of channel catfish only doubled.

Compare the catfish data with the difference in the cost of an automobile or home 50 years ago and currently. When you factor in inflation, catfish farmers today are making only a fraction of what they were on 1 kg of fish when the industry was young. Those who entered the business in the early years and were able to pay off their debts have been able to continue operating at a profit, though in many cases, a modest profit. Others, who had high debt burdens, have been forced to sell out, often to the successful farmers who were interested in expanding their holdings. In the channel catfish industry, the producers are also often members of cooperatives that produce the feed and process the fish grown on their farms. For each kilogram of feed purchased or kilogram of fish taken to the processor, the members share in the profits of the cooperative, so there are additional revenue streams to the farmers. In some cases, farmers process and market their own fish, which can also increase profitability.

Aquaculture is a particularly high-risk type of farming. The aquaculturist selling fish to live markets tends to command higher prices than fish sold to processing plants. However, today the farm-gate price of catfish sold to processing plants is still hovering around US$4.00/kg while various production costs, including energy and feed costs, have increased to a much greater extent. For example, feed costs, which represent the greater variable cost associated with intensive fish production, increased to approximately US$660/tonne in 2012 while three decades ago feed was approximately half of that amount per tonne. The price of feed has risen after the COVID-19 pandemic due to dynamic commodity markets and has approached US$770/tonne.

The culturist is rarely able to know with certainty exactly how many animals there are in his or her culture system. Since aquatic organisms live underwater, they are often difficult to observe and never easy to count. Mortalities may occur that are never discovered. Dead animals may be eaten by other animals in the water system, or they may decay without floating to the surface where they can be observed and retrieved for disposal. Bird predation has been a significant problem for many pond culturists, and other animals – including water snakes and some mammals – prey upon fish in ponds. Excessive amounts of feed may be provided when the numbers and biomass of organisms in the system are overestimated. As a result, water quality problems may arise. In any event, uneaten feed equates to money wasted. Crop insurance is available in some countries, but the expense of that insurance is high, so many aquaculturists who may be eligible for crop insurance often take the risk instead. In places where aquaculture is a new activity or has only been present for a few years, insurance may not be available until the aquaculturists can show that their operations are profitable.

Without being on a sound economic footing, no commercial venture can be sustained. In order to keep a finger on the pulse of the enterprise, it is important to maintain accurate and complete records and constantly pay attention to the details involved in managing the business. As indicated, having a good estimate of the number (and biomass) of fish in a pond is difficult. While typically the culturist overestimates the population, there are also instances where the opposite occurs. Growing catfish in ponds that are only drained every few years is an example (see Chapter 4).

The Business Plan

Having a good business plan is a necessity for the prospective aquaculturist who needs, as do most in developed countries, to borrow money in order to establish and maintain the enterprise. In the past, bankers and venture capitalists in many places were not familiar with aquaculture and had to be convinced that there was a reasonable expectation that their loan or investment would be sound. That situation has changed to some extent as aquaculture has expanded, but investors and bankers still recognize that aquaculture is risky and there are still many lending institutions that are insufficiently knowledgeable to take the risk of loaning money to aquaculturists. As is the case with obtaining crop insurance, when the prospective borrower needs to establish a facility in a region where little or no aquaculture has previously had a presence of successful operations.

Thus, the job of convincing bankers and investors to support the development of an aquaculture facility may still be a major one. Selling the concept of a new facility is still required even in places where aquaculture is commonplace. Just because others are successful in a particular region does not mean that the newcomer has what it takes to operate profitably.

By considering all the costs of start-up and operation, and by being realistic with respect to projected production levels and the price that the product will bring at harvest, the culturist can establish his or her credibility. Outrageous claims of future profits will drive savvy investors away. Bankers who have previously funded aquaculture will know what the profit potential is and will avoid loaning money to people who have profit expectations that are unlikely to be realized. Development of a realistic business plan is critical.

The budget developed with respect to the business plan needs to identify the fixed or ownership costs – the one-time expenses, such as for purchase and modification of land (e.g. pond and/or construction), cost of other types of production systems (net pens, tanks, raceways, recirculating systems, etc.) and costs of buildings that will be built and for purchase of durable equipment (things that have life expectancies measured in terms of years: trucks, tractors, processing equipment, aerators, pumps, cages, net pens, culture tanks, etc.). Then there are the variable or operating costs – the costs for items that are frequently replaced and that may be required in different amounts from one growing season to the next. Variable costs include such items as feed, purchase of larvae, post-larvae or fingerlings for stocking if the culturist does not have a hatchery, labour, chemicals, utility expenses, nets and/or seines and various supplies. While the specific items required for inclusion in the budget can vary significantly in relation to the type of facility that is proposed, many items will appear on nearly every aquaculture budget.

The business plan should include a marketing component whether the aquaculturist plans to sell directly to the public, to a wholesaler or into retail outlets. In many nations there are aquaculture associations or cooperatives that do the marketing for the industry. To pay for those marketing activities, there may be a fee added to each tonne of feed purchased and/or quantity of fish processed. The revenue from the fees can go to support activities such as conducting consumer surveys, advertising and the development of new markets. If the prospective culturist plans to process and market the product, details of the types of processing that will be employed (whole fresh, frozen, filleted, or gilled and gutted in the case of finfish; whole, peeled and headed in the case of shrimp, etc.) should be provided, along with anticipated farm-gate price. That price will relate to where the product(s) will be sold.

Investors and banks will obviously want to see profit projections. The business plan should include the estimated amount of production that will be harvested each year projected out for several years, the price per kilogram that can be anticipated from the sale of the animals, gross profit (price per kilogram produced multiplied by the total amount of production) and net profit (money remaining after all expenses are paid). A mortality estimate for each crop should be developed (incorporating the fact that crop failures typically occur every few years).

Water: The Common Factor

Over 70% of the surface of the earth is covered by water (the vast majority of this, about 97%, is saline). While amounting to only a few per cent of the total, freshwater is currently used in the production of the largest proportion of aquacultured animals. There is an abundant supply of groundwater in some areas, and surface water supplies are often available for aquaculture. Some aquaculturists depend upon rainfall runoff as their water source. At the same time, there are parts of our planet where surface water is not to be found, and groundwater may be absent or the quality of it makes it useless for aquaculture or for much of anything else. There are, in any case, vast areas where suitable amounts of water of good quality are available. However, increasingly, competition for freshwater, in particular, is increasing with ever-growing human demands to support agriculture, industry and domestic consumption. In some places, aquaculture ventures may be at risk of losing their source of water. For example, falling water tables in some areas have already constrained expansion of an industry, causing it to seek alternative locations or perhaps move to recirculating systems (see Chapter 3). The reason channel catfish (*Ictalurus punctatus*) culture moved to a considerable extent from Arkansas to Mississippi, USA, was because the water table in Arkansas dropped due to all the pumping that was occurring for both rice and fish culture, with the latter beginning in the 1960s.

Aquaculturists have taken advantage of freshwater sources that include surface water, groundwater, rainwater runoff and snowmelt runoff. Municipal drinking-water may come from any of those sources, typically after some type of treatment. Increasingly, aquaculture is taking place in coastal and, in some cases, inland saltwaters (Box 2.2), and is expanding into the open ocean where an unlimited supply of water is often available, though there may be competition by other users. In the following subsections of this chapter, we look at many of the different sources of water that can be used for aquaculture and discuss some of the advantages and disadvantages of each. Water quality issues are discussed in Chapter 4.

Box 2.2.

Over geological time, many locations that are currently well inland were formerly marine basins. They may be located hundreds of kilometres from current oceans but, because of the existing salt deposits in such areas, the groundwater may range from slightly to highly saline. Assuming the salinity of the water is not excessive and that other aspects of water quality are appropriate, areas where such waters are available can be excellent locations for aquaculture. Since the culture species is not found in such areas until it is introduced, disease problems can be greatly reduced or entirely avoided unless they are brought in with the culture species.

Municipal water

People who live in places where there are abundant supplies of clear, clean tap water are fortunate indeed. At first glance it might seem highly desirable to use that water in aquaculture; however, there may be major drawbacks. First, the cost of municipal water is typically considerably higher than the cost per unit volume of water from other sources. For the average home, the monthly water bill is acceptable since it typically involves only a few thousand to several thousand litres a month per person. To use that water in an aquaculture facility would be prohibitive unless it is recycled – that is, it will be used over and over again – as is the case with recirculating water systems (see Chapter 3). Thus, the cost of water to supply the needs of a pond or flow-through raceway system is prohibitive (again, see Chapter 3 for details on such systems).

Another major drawback is that municipal water in many nations, particularly in the developed world, contains chlorine or chloramines that are added to kill bacteria to make the water safe for drinking. Those chemicals are present at levels that are lethal to many aquatic animals and would have to be removed prior to exposing the culture species to the water. Removal of the chemicals is not difficult, but it does impose an added expense, particularly for chloramines. Chlorine can be eliminated by letting the water stand for 24 h or by aerating it for a shorter period of time to drive off the chemical. That technique is a good one to know about if you have a home aquarium and want to ensure the water you use when you clean and replace the aquarium water, or the water you add to replace evaporation of the aquarium water, is safe. Chloramines are not removed using those methods; however, both chemicals can be removed by passing the water through a column containing activated charcoal or by adding sodium thiosulfate. In systems that use a lot of water, whether routinely or periodically, you need to ensure the chemicals are removed, so the water needs to be carefully monitored to ensure that the charcoal filter is working properly or that the amount of sodium thiosulfate is sufficient to produce the desired results. Methods to analyse for chlorine and chloramines are available.

The use of municipal water for aquaculture is relatively rare. It has been tried in conjunction with recirculating systems in some large cities where other water sources were not available. The success rates have been variable, with failures of various components in recirculating systems being more common than in flow-through systems. Using municipal water may not have been the only factor involved in failed operations, but it must certainly have been one of them.

Runoff water

A large proportion of the runoff rainwater and snowmelt water that flows across the land ultimately enters lakes, streams, ponds and the ocean. A considerable percentage of runoff water is also available for groundwater recharge. Runoff water is the primary or only source of water for many aquaculturists. Ponds that employ runoff as the primary source of water are commonly called watershed ponds. They can be found in a variety of sizes, from a fraction of a hectare (Figs 2.1 and 2.2) to several hectares in area. Runoff water can be a reliable source, particularly in areas where the amount of annual rainfall is considerably higher than the rate of annual evaporation. Ponds are constructed in areas that have sufficiently large watersheds and reliable rainfall seasonally to fill the ponds and keep them filled. Reservoirs may also be constructed to hold extra water that might be needed to fill production ponds during periods when rainfall is scarce. For example, parts of the world that experience monsoon rains may be arid during part of the year but flood-prone during the monsoon season. Catching and retaining water in holding reservoirs during the rainy period for use during the dry period may be a good strategy in such locations.

Surface water

Saltwater is associated with the world's oceans, bays, sounds, estuaries, fjords and even lakes. Surface freshwater sources include springs, ponds, lakes, streams and reservoirs. Virtually all of these sources of water are commonly used for aquaculture. While the open ocean has not been a site of aquaculture in the past, there are now facilities

Fig. 2.1. A pond area featuring medium and small ponds.

Fig. 2.2. Small artisanal runoff ponds.

sited in exposed ocean waters, usually fairly near the shore but in areas where they are not protected from storms. Open ocean aquaculture is expanding. Aquaculturists are now establishing facilities well offshore in the exclusive economic zone (EEZ), which is 200 nautical miles (1 nautical mile = 1.852 km or 13250 yards) off their nations and beyond. State waters (at least in the USA) vary to some extent, but they are typically 12 nautical miles. Interest in aquaculture in the EEZ is prompting nations to promulgate regulations in that part of the ocean that had never been anticipated prior to the development of interest in open ocean aquaculture (usually associated with the production of finfish). The Gulf of Mexico Fisheries Management Council began developing an Aquaculture Fishery Management Plan for the EEZ off US waters in 2009, but only a few operations have been permitted for the live rock culture (placing substrates in the sea to allow the settlement of various sessile organisms and harvest primarily for amenities in aquaria). Several facilities have been provided with permits to conduct research in state waters off the coasts of California, New Hampshire, Hawaii, Washington, Maine and Florida.

While the Gulf of Mexico aquaculture plan continues to be awaiting approval for implementation as of 2021, it does address an approach to avoid many of the issues raised by those opposed to offshore aquaculture (Box 2.3).

In Europe, granting of permits for open ocean aquaculture appears to vary from country to country. While many culturists exclusively rear finfish in the open ocean in cages or net pens, a considerable amount of research has also been aimed at developing offshore systems for rearing molluscs. Ocean ranching appears to be less difficult to undertake. Ranching of salmon is well developed in Japan and Alaska. Net pen culture of salmon (or any other type of salmon culture) is, on the other hand, prohibited in Alaska. This is because ocean ranching provides opportunities for commercial fishermen to harvest most of the returning fish and they are concerned that their livelihood would be impacted if captive culture of salmon to market size was to be allowed. The bumper sticker, ‘Real fish don’t eat pellets’, was frequently seen in Alaska a few years ago and may still be common in that state.

Resistance to salmon net pen culture in the USA is not limited to the state of Alaska. Commercial fishermen who live in Washington State (and who do their commercial fishing in Alaska, by the way) are also opposed, as one would anticipate. I (R.R.S.) was once on a ferry in Puget Sound when the ferry passed a commercial salmon cage culture facility located across a narrow area in the sound. The

Box 2.3.

Some important objectives and components of the Gulf of Mexico Fishery Management Plan (FMP):

1. To develop a permitting process for an economically sustainable aquaculture industry in the federal waters of the Gulf of Mexico.
2. To provide an environmentally sound and sustainable offshore aquaculture industry.
3. To preserve and protect fish habitat through proper siting of aquaculture facilities.
4. To obtain the necessary information required for the issuances of permits.
5. To minimize user conflicts.
6. To prevent or mitigate environmental impacts to wild stocks, protected resources and habitat.
7. To establish monitoring, recording and reporting requirements.
8. To provide a public comment period before a company can obtain a permit.
9. To enable permit holders to use approved drugs, pesticides and biologics.

The above list is only a portion of the responsibilities of permit seekers or holders. While the FMP appears to be comprehensive, there remain significant objections to the establishment of aquaculture in the EEZ. The overall objective of aquaculture in the EEZ is to enhance the volume of fish products in the marketplace to help meet the ever-increasing demand. The FMP has been focused on that objective while also being committed to protection of the environment. Those opposed to aquaculture apparently are not impressed.

facility was associated with a National Marine Fisheries Service research facility, which also had some net pens and shared their embayment with a commercial salmon cage culture facility. A woman who was standing beside me on the ferry pointed to the net pens and asked: 'What's that?' I told her and she said: 'My husband is a salmon fisherman, and he would really like to look into salmon farming, but if he did he would be in serious trouble with his friends who are so opposed.'

The surface water source that is used by the culturist will depend upon the species being raised and, of course, the sources that might be available, which can dictate species selection, at least with regard to freshwater versus marine species. An overriding factor is that the water source must be sufficient to fill the needs of the aquaculturist and it must be reliable. Springs can dry up seasonally, though there are those that reliably flow enormous quantities of water year-round (Fig. 2.3). Upstream users of river water may be able to deplete the supply by taking it first, thereby leaving the downstream aquaculturist without a reliable water source. Such taking may be illegal in some places, but in others it is legitimate and there is not much the downstream user can do about it. The prospective aquaculturist should make sure his or her water rights are protected from acquisition by upstream users. If those rights are not protected, it might be wise to find another site or determine if another source of water (runoff or groundwater) can be obtained in sufficient quantities for the proposed operation.

One government-operated fish production facility that R.R.S. was involved with in the Philippines depended on water from an irrigation canal for filling their ponds. (That was the BFAR tilapia culture facility described in Chapter 1.) The irrigation canal was reliable much of the time but, if breached (which occurred on occasion), or if pumps failed, it could be shut down without notice by the responsible government agency, leaving no water available at the aquaculture facility for an indefinite period of time. While the BFAR facility and the agency operating the irrigation system were both government agencies, those activities were in separate branches of the government and the irrigation folks showed no interest or obligation to alert the aquaculture group if the canal was going to be shut down. To ameliorate the problem, the BFAR design included two holding reservoirs that could provide water to replace water lost to evaporation or pond draining when the irrigation canal was taken out of operation.

Lakes and reservoirs can be good sources of water. The water from them can be flowed by gravity or pumped (depending on the elevational difference between the lake or reservoir and the aquaculture units) into ponds or through raceways (see Chapter 3). The effluent water from raceways can be returned to the lake or reservoir via gravity or pumping, again depending on the relative elevations – in either case pumping will be required if recirculation is employed. In cases where the lake or reservoir is sufficiently large, the water will undergo natural treatment and will be suitable for reuse; thus, the reservoir or lake and pond combination would, in reality, become a large recirculating water system. The effluent from the aquaculture units should be returned to the receiving water body as far from the point of removal as possible

Fig. 2.3. Springs from the canyon walls provide water for trout raceways in the Snake River Canyon of Idaho, USA.

to provide as much residence time in the lake or reservoir before reuse is possible. In addition, lakes and reservoirs can also be used for cage culture.

All water sources should be checked for such contaminants as PCBs, dioxin, trace metals, herbicides and pesticides if there is the potential that toxic levels of such substances might be present. Contamination by biocides (herbicides and pesticides) may be seasonal, as in the case of agricultural regions where fields near aquaculture facilities may be accidentally sprayed by aerial applicators (and sometimes from ground spray applications) during the growing season. Spray drift can cause direct toxicity and runoff water containing biocides following a rain event shortly after fields are sprayed may lead to toxicity. The source of high levels of trace metals can come from prior users of the land, particularly mines or industrial plants, or they may occur as natural levels in the water. Another common source of contamination is terrestrial animal waste and fertilizer runoff from pastures into surface waters used for aquaculture. Excessive levels of organic or inorganic fertilizer in pond water can lead to algal blooms and subsequent oxygen depletions (Box 2.4).

Box 2.4.

Fertilizer adds nitrogen and phosphorus to runoff water. Both elements are required by phytoplankton and, when present at high levels, can cause an explosion of growth known as a bloom. In freshwater, phosphorus is the limiting nutrient, while nitrogen tends to be the limiting nutrient in saltwater. Algae produce oxygen during daylight but respire and utilize oxygen at night. When a bloom is present along with a high biomass of the culture species in a pond, oxygen depletion can occur, typically just before dawn. More about this can be found in the section on dissolved oxygen in Chapter 4.

Groundwater

Wells are often the preferred source of water for aquaculture, particularly if an abundant supply of good-quality water can be obtained from a reasonable depth. Deep wells are not only more expensive to drill than shallow ones, but also require larger pumps to bring the water to the surface if pumping is necessary, thereby increasing energy costs. Artesian wells are best as they flow out of the ground under pressure, thus possibly eliminating or greatly reducing the need for additional pumping. Prospective aquaculturists can talk to the appropriate government agency, well drillers or their neighbours to get an indication of the depth of various water tables in the region; the amount of water that can be removed, which may be controlled by regulations; the water quality, including its temperature; whether or not the water is artesian; and whether permits for well drilling and water removal are required. The last point can be very important. I (R.R.S.) once participated in a meeting with landowners in eastern Washington State, USA, who wanted to look at alternative options to growing wheat, which at the time was not a highly profitable crop. Some of the farmers thought fish culture might be an option and the more I discussed it with them, the more interested the farmers became. They had wells or pumping permits for obtaining river water from the Columbia River to irrigate their wheat fields and thought that the water could just as easily be put towards raceway trout production. The whole idea was quickly abandoned, however, when a state agency official said that under the regulations in place at the time, water could only be pumped a certain number of days per year, which covered the wheat growing during the normal crop-growing season (around 200 days, as I recall), but at no other time. That made trout farming impractical since the activity depends on a consistent year-round supply of water. In nearly all cases, trout farming involves constantly flowing water through the culture units. It is possible to culture trout in ponds if the summer air temperature does not heat the water beyond what can be tolerated by the fish, but such farms typically do not have nearly the production rates that can be obtained from springs (Fig. 2.3) and passed through raceways (again, see Chapter 3 for details on raceway systems).

For static ponds (i.e. ponds that do not receive water continuously), we have been told that it is desirable to have a water volume of at least 150 l/min available for each hectare of water under culture. The primary reason for having that amount of water available is to fill the ponds initially during a reasonable period of time. Other types of water systems may be less demanding (recirculating systems) or much more demanding (open raceway systems). Raceways may require complete changes of water from once an hour or less to even more frequently depending on the species being reared and the biomass of fish in the raceway. Once the water quality and volume requirements for water are known, the well driller, working in conjunction with the aquaculturist, can recommend which water stratum to utilize, the number of wells that will be required to accommodate the needs of the facility and determine the diameter of the wells such that the needed flow rate can be obtained. The driller can also size pumps appropriately for each particular situation. After a well is drilled, the driller will test pump it to determine how much water can be removed on a continuous basis before the volume begins to fall (indicating drawdown). Once that is known, the driller can recommend the pump size that is appropriate to avoid over-pumping the well. Pumps can be at ground level, which means they will pull water up from the ground, or they may be submersible, meaning they will be located at or near the bottom of the well and push water up to the surface.

As more and more wells are drilled and the volume of withdrawal increases in a region, drawdown of the water table may occur, such as when a facility is expanded or when neighbours construct their own aquaculture facilities, turn to crop irrigation or operate an industry that requires a great deal of water. In some cases, the farmer can obtain suitable water by having additional wells drilled into another water table, but that may only provide temporary relief if other users adopt the same approach. Searching for even deeper water tables may be an option but, for each increase in depth required to hit suitable water the cost increases, not only for drilling, but also for the energy increases associated with pumping.

In general, the temperature of well water increases with well depth. In some geologically active regions, warm or hot water of good quality can be obtained from geothermal wells. Such wells are most commonly found in geologically active areas, but not always. Warmwater wells often have high levels of undesirable chemicals, such as sulfides and heavy metals. Such water should not be used directly to support aquaculture species but may sometimes be appropriate by passing the water through heat exchangers that adjust the water temperature in the culture chambers to the appropriate level. In some instances, the water can be used directly in the culture chambers after being passed through appropriate filters that remove the contaminants.

Saline wells can be drilled in some regions, including some areas far from today's oceans but in areas that were once inundated by the sea. Saltwater wells can also be drilled below or adjacent to marine waters. Using saltwater wells is particularly advantageous in coastal areas with porous sediments (e.g. sand). Recharge of such wells from the overlying or adjacent estuarine or marine waters tends to be rapid, and the sediments serve as a natural filter to remove organisms and suspended materials such as silt and clay from the recharge water. Disease organisms may also be reduced or eliminated from the incoming water (Box 2.5).

Well water can come to the surface depleted of oxygen and may contain relatively high levels of such things as hydrogen sulfide, iron and/or carbon dioxide. I (R.R.S.) have even seen well water that was high in ammonia; the source of which was not clear, though it was in a region where oil and gas were present deep beneath the surface, so the presence of hydrocarbons could have played a role. Aeration will solve most of the problems mentioned. Bubbling air through the water or splashing it over rocks, for example, causes iron to precipitate to form ferric hydroxide ($Fe(OH)_3$). That precipitate can be removed through the use of sand filters. If not removed, the $Fe(OH)_3$ will stain pipes and other surfaces; and, if present at high enough levels, it can clog gills. Aeration will drive off hydrogen sulfide and carbon dioxide, as well as oxygenating the water. In the ammonia case, the total level was high, but it was largely in a non-toxic form and could therefore be used for fish rearing without treatment.

If the water contains high levels of dissolved nitrogen, gas bubble disease can occur in fish that are exposed to that water. Gas bubble disease is similar to the bends in human scuba divers whose blood becomes supersaturated with nitrogen when they have been at depth for sufficiently long periods. As they surface, the gas comes out as bubbles in the bloodstream (Box 2.6). The same can happen to fish exposed to water that is supersaturated with nitrogen. Bubbles typically form behind the eyes (causing exophthalmia or pop-eye) and in the fin rays. The nitrogen level will decrease once the well water is allowed to stand or if it is aerated. The problem has been associated with fish exposed to the heated water effluents from electric-power-generating plants, particularly in the winter. Water entering the cooling pipes is placed under pressure and rapidly warmed. This causes nitrogen and other dissolved gases to supersaturate and can affect fish exposed to that water as it leaves the plant, usually in a discharge canal. The problem occurs commonly during winter when fish reared in cages are towed into the discharge canal so that advantage can be taken of the warmed water to enhance their growth. I (R.R.S.) have also seen supersaturation occur in culture chambers into which water of normal temperature was introduced in jet-like streams. That appears to be a rare occurrence, however.

Box 2.5.

Throughout this book, the term 'diseases' includes parasites as well as bacterial, fungal and viral outbreaks.

Summary

Developing an extensive business plan is a requisite for establishing an aquaculture facility, particularly

Box 2.6.

To avoid the bends, human scuba divers may come to the surface in stages, resting for periods of time (given in dive tables) at various depths to purge the nitrogen from their bodies through respiration until they can surface safely. If they have been underwater for quite a long period (such as divers who spend time in underwater habitats), they can surface at a normal rate and then be immediately placed in a hyperbaric chamber and taken back to the pressure that they were under before surfacing. The pressure is slowly brought down to decompress the diver. This may take several hours. A fish brought up from depth by fishermen may have its stomach extruding from its mouth or part of its intestines protruding from its anus due to expansion of the swim bladder in those species that have a swim bladder. Degassing the bladder or returning the fish to depth may help it survive. Cultured fish in shallow water cannot avoid the exposure to supersaturated nitrogen by diving and degassing them individually with a needle is not practical.

if the prospective culturist requires a loan to establish the facility. The business plan should include a detailed marketing plan. The business plan should also include a projection of profit and loss over a period of several years based on costs of land, facilities construction, fixed costs, variable costs and anticipated income from sales.

The water supply and its quality are absolutely critical factors associated with a successful aquaculture facility. Water can be obtained from a variety of sources including freshwater from rainwater or snowmelt runoff, springs, rivers or streams, reservoirs and lakes. Another source is the domestic water supply, which also comes from one or more of the sources previously mentioned. Saltwater sources are the oceans, bays, estuaries, fjords, coastal wells and inland saltwater wells in areas where saline strata are present.

Water from any source should be tested to determine that its quality is appropriate for the one or more species that are going to be reared. Treatment for some issues associated with water quality can be resolved before introducing that water into culture chambers without too much expense, but others such as biocides and high trace metal levels are not readily dealt with, so water containing those entities should be avoided.

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3 Culture Systems

Introduction

There is a variety of options available for culture systems. Some can be used for purposes of rearing a range of species, though a few have been developed specifically for one species or a few related species or similar species groups. Once you have seen an example of any type of water system you will immediately recognize others of the same type. However, you will rarely see two culture systems that are identical. There are almost always differences in design that are readily apparent. Some culturists are so dedicated to their design that they are protective about showing outsiders what they have. They tend to be concerned that their 'secrets' will be stolen. Having visited several aquaculture facilities and been told in some instances not to take photos or reveal what we have seen, we can only say that we have yet to have a so-called secret revealed from observing some type of equipment or approach that we had not seen before or subsequently. In most instances the so-called secret had already appeared in the literature associated with aquaculture research papers or had been in general use by at least a portion of the aquaculture community. On the other hand, many aquaculturists – and perhaps the majority – are happy to show visitors around their facilities and to point out innovations they have made with respect to the design of their culture systems. They usually allow visitors to take photos and are more than willing to share their innovations with other aquaculturists. Aquaculture is not a discipline where an innovation is likely to give one producer such an advantage that it can control the industry, so innovators tend to consider other producers less as competitors and more as colleagues who have the same goals and objectives.

As mentioned in Chapter 1, culture systems range from extensive (exemplified by most pond approaches) to intensive (closed recirculating systems, for example). Semi-intensive systems would include linear and circular raceways. Hyper-intensive systems are sometimes mentioned; these might be recirculating systems with treatments of the water that go beyond the normal. These definitions are somewhat fuzzy. Oyster culture on natural or enhanced substrate (adding oyster shell, for example) would be considered extensive. Oysters (or other types of molluscs) cultured on strings or in bags (as described later in this chapter) might be considered as semi-intensive culture. Ocean ranching would be considered extensive if one doesn't include the hatchery and fingerling stage of the process, which would be more appropriately described as intensive. There are so many nuances in the culture approaches for most species that ascribing labels of extensive, intensive, etc. doesn't make a great deal of sense. Thus, we don't think it is useful to employ those terms except to say that we think of extensive aquaculture as resulting in low levels of production per unit area of water volume, semi-intensive as moderate levels (most systems), intensive as high levels, and hyper-intensive as testing the limits of possibility and causing constant anxiety for those involved.

In this chapter, several types of culture systems are described. Some can be found in both freshwater and marine environments, while a few are completely or nearly exclusively used in saltwater – for example, mollusc, echinoderm or the culture of certain species of finfishes. While we have seen that freshwater production of aquatic animals dominates global aquaculture, marine species dominate with respect to the number of species under culture, under development or being considered for development for human food.

Ponds

Much of the world's aquaculture is conducted in ponds. Ponds are used in conjunction with growing freshwater and marine fishes and shrimp for human consumption, along with ornamentals, bait

DOI: 10.1079/9781800621145.0003

species and even algae that are used as nutritional supplements. Ponds are often used to hold broodfish and often for spawning. Many finfish species can be grown in ponds throughout their entire life cycles. Others, on the other hand, along with invertebrate species, are produced in hatcheries and stocked in ponds, usually as juveniles.

The typical earthen pond is constructed with sloping levees and bottoms, though some ponds are constructed with vertical walls and earthen bottoms (Fig. 3.1). One advantage of vertical sides rather than sloping ones is that nearly uniform depth can be maintained throughout the pond. That means there will be no shallow water areas that can provide ideal locations for the establishment of unwanted rooted higher plants such as cattails. The bottom of such ponds should, as is true of the more typical pond with sloped levees, slope towards the drain end to provide complete water drainage when desired.

In most cases, once a pond is filled, additional water is only added to replace losses through seepage and evaporation. One exception we have seen involved trout ponds through which water was being continuously flowed at a low rate of exchange, probably not more than one or two exchanges per day. Most trout culturists use open raceways (as described below) rather than earthen ponds.

Location

Where ponds are constructed depends to a considerable degree on water source and topography. Watershed ponds, because of their dependency on rainfall runoff to fill them, need to be constructed where they can catch that runoff. Thus, there needs to be a large area of higher-elevation land on one or more sides of the pond complex to provide inflow. The ponds should not be at the lowest elevation in the area, however, as there will be times when the water needs to be drained and that water has to have a place to go. The alternative is to pump water from the pond uphill so that it can be sent to another lower-elevation location for disposal, which will be costly because of the energy involved. Properly designed drain structures or

Fig. 3.1. An example of ponds with vertical reinforced side walls.

spillways can keep watershed ponds from overflowing when the amount of runoff exceeds the need for additional water. Watershed ponds are often constructed by excavation or can be formed in the middle of small valleys with a levee at the downstream end. In the watershed case, the earth removed during excavation is used to construct the levee. The total pond area and volume that can be placed in a watershed depend on the size of that watershed and average annual rainfall. When collection of rainwater runoff is not a necessity, as in the case of facilities that use well water or pumped seawater, it is possible to have many ponds at a site that can be filled and kept topped off from the available water supply.

To avoid excessive loss of water due to seepage, the soil should contain a minimum of 25% clay. Soil composition can change significantly over short distances, particularly in river valley sites where historical meanders of a stream can leave deposits of sand or gravel in one location and heavy clay deposits in another only a short distance away. Unless the culturist knows with certainty that the pond site has a consistent soil type throughout, it will be necessary to collect soil cores from several locations to ensure that the required clay content is present. The cores need to be sufficiently long to reach what will be the bottoms of the ponds to be constructed. A thin clay layer over sand would not be detected if the cores are insufficiently long (Box 3.1). Ponds constructed in the ground in such areas would be sources of constant frustration (and cost) due to seepage.

Pond liners can be effective at controlling seepage, but they can also be very expensive. Polyethylene plastic has been used as pond liner material, as have been various other types of material. Very thin liner material is subject to damage when workers enter the pond and walk on the material as it is relatively easy to punch holes in the plastic. Heavy liners are much more durable but are costly. Sites near saltwater are sometimes characterized by very sandy soils, in which case liners of some type are a necessity to maintain pond water level unless water must be constantly added – again adding to expense associated with pumping or potentially utilizing all the water stored in storage reservoirs.

Hauling in soil having high clay content and blanketing the bottoms of leaky ponds with that material can help reduce seepage. Bentonite – a clay mineral that expands to several times its volume when wet – has been recommended by some culturists as a material that can fill void spaces in porous soils and help seal leaky ponds. Our experience with bentonite has been almost entirely negative though others claim to have had good success. The effectiveness of bentonite is undoubtedly influenced by the amount of the material used and the porosity of the soil in the first place.

A rather unique solution with respect to the need for pond liners was found at an ornamental-fish-growing facility in Hawaii, USA, where several ponds were constructed by cutting them out of lava rock. That material is very hard, extremely porous and has very sharp surfaces associated with it. To avoid high-cost liners that would resist tearing if walked upon, the ponds were first lined with discarded carpeting obtained at no cost from buildings, such as hotels, that were undergoing renovation. A relatively lightweight and inexpensive polyethylene plastic sheet placed over the carpet prevented seepage losses. A second layer of carpet over the plastic helped protect the liner from the activities conducted by the culturists who entered the ponds. The two layers of carpet protect both the liner and the feet of the employees. Carpets had also been spread over the tops of the levees and anywhere else where people walked when working around the ponds.

Ponds can be constructed above ground level, in the ground or partially in the ground. Levees are typically earthen and sloped. Above-ground ponds are those where the initial ground elevation becomes the pond bottom. The levees are constructed from soil that was removed through excavation. The source of that soil is often from in-ground ponds where the levee top is at the initial ground elevation and soil is removed to create the pond. Typically, about half of the pond depth in a completed partially in-the-ground pond will be below original ground elevation and half above. On a sloping site, the pond system can be designed so that the final facility will have in-ground ponds at the upper elevations, partially in-ground ponds at the middle elevations and above-ground ponds at the lower elevations, resulting in all the levee tops being at approximately the same elevation or with the site still sloping, but at much less of an angle than was the case originally. Having an experienced engineering firm survey the site and draw up the plans for pond construction is money well spent and is an item that needs to be put into the business plan expense category under the heading of construction.

If the culturist has a level site, the most economical approach may be to build partially in-ground

Box 3.1.

A couple of stories will illustrate the point. The research facility that R.R.S. was involved with at Texas A&M University from 1975 to 1984 had been constructed in a river flood plain after only a very small number of core samples had been taken, and those were only a few centimetres long. Those cores apparently revealed good clay levels but, as it turned out, did not reveal that a little deeper the soil was very porous. Concurrently, a reservoir that could be filled by pumping water from a river and flowing it by gravity to the ponds was under construction. However, before the reservoir was available, the only water source for filling the ponds was from a shallow irrigation well. It was necessary to pump the well water through irrigation pipes that had to be moved daily from one pond to another in order to maintain the desired water levels. The well water was also relatively cold, which inhibited growth of the fish in the ponds.

Once the reservoir was completed and filled, the daily chore of moving heavy irrigation pipes ended, but it was still necessary to run water constantly to keep up with seepage from the ponds. Water from the reservoir also introduced wild fish that had been pumped out of the river. In an attempt to ameliorate the problem, we had a shallow water well drilled which turned out to contain a high level of iron that stained all the plumbing. That water also contained a measurable level of ammonia for several months before, mysteriously, it disappeared. The source of the ammonia and why it vanished are still a mystery. The well produced about 600 l/min, which was insufficient.

Finally, we were able to lay pipe from our facility into a well about 0.5 km away that had been drilled to supply water to a service facility that supported activity on the Texas Agricultural Experiment Station farm (involved primarily with cotton and grain sorghum research). That well was about 275 m deep and water came out of the ground at 30°C year-round: perfect for our research on channel catfish, tilapia and red drum. That well produced less than 200 l/min and was only used to supply our indoor wet laboratory. Subsequently, after R.R.S. left Texas A&M in 1984 (he returned in 1996 and retired in 2011), funds were obtained by D.M.G. to put rubber liners in the ponds and that finally resolved the problem (see Fig. 4.2). The rubber liners cover the pond bottoms and levees sides and tops.

Several years ago, while I (R.R.S.) was at the University of Washington, I was asked to help design a pond tilapia facility in the Caribbean on the island of Jamaica. The project was funded in part by USAID. A prospective aquaculturist had his own construction business and had the heavy equipment needed to construct ponds. He took me to the site and asked to have several holes dug with a backhoe to determine the quality of the soil. Based on those observations, an area where clay soil suitable for ponds was located were areas which should be avoided because the soil was sandy to the bottom of the pits that had been dug. Several months later I returned to view the first fish harvest only to find that the ponds had been dug in exactly the wrong location. The soil was very porous. As a result, the novice fish farmer had found it necessary to pump water 24 h a day from his water source (an irrigation canal) using a diesel pump. The cost of fuel alone doomed any prospect of a profit, not to mention that there were very few fish in the ponds at harvest. Poachers may have been responsible for at least part of the poor production.

Those two examples demonstrate the importance of determining that a water source has the proper quality and volume needed to support the proposed facility; and, in the case of a pond facility, to make sure the ponds that are constructed will hold water, or if they are going to leak, to have sufficient money in the budget to purchase and install liners.

ponds. The removed soil would all go into levee construction, so it would not have to be moved far from its source. Moving soil long distances, such as might be required if above-ground ponds are constructed on a level site, involves significant expense and the use of trucks if a large amount of available and suitable soil is not close enough to be moved conveniently by bulldozer. Similarly, constructing all in-ground ponds on a site might require trucks to haul away the removed soil to an appropriate fill site – again leading to additional expense.

Size, shape and depth

The size of aquaculture ponds is highly variable (often from about 0.05 to 10 ha). Small ponds are easier to manage and feed than large ones. Large ponds are difficult and expensive to treat if there is a weed or disease problem that requires the application of a chemical. Also, should there be a mass mortality from a disease, an incident involving low dissolved oxygen (DO) or some other reason, the financial loss will obviously be greater in a large pond stocked at the same density per unit area as a smaller pond that experiences mass mortality. The initial cost of construction of smaller versus larger ponds is a consideration, but there is also the fact that mass mortalities are typically isolated instances that may occur in one or only a few ponds during a given growing season. Managing relatively small ponds can be considered easier than managing a few large ones. Relatively greater ease of feeding, maintaining water quality and harvesting are among the advantages of smaller ponds (Box 3.2).

One advantage that large ponds have over small ones is that a greater area of water is available in the same total amount of land area when the ponds are large than when smaller ponds have been constructed. The reason is that levees reduce the available water area of the farm. The decision on pond size rests with the culturist, who needs to take all the factors mentioned into consideration.

Box 3.2.

A harvest seine is a net that is at least one-third longer than the pond is wide. The seine should be at least as tall as the maximum water depth and preferably at least several centimetres taller so it can hold the bottom without pulling the top line (float line) below the water surface. Mesh size can vary depending upon what size animals are desired. Large mesh sizes provide the opportunity for sub-marketable animals to escape while retaining the larger ones, often in a bag in the middle of the seine. A line at the bottom of the seine, the lead line, is either weighted or is a rope with many strands of cotton twine or other material that will absorb water and help keep the seine on the bottom while it is being towed. Similarly, the float line should be fitted at intervals with cork or plastic floats to keep the top of the net at the water surface. A bag in the middle of the seine is often provided to concentrate the fish when the seine is hauled out of the pond. Seines should be slowly pulled through the length of the pond using human or machine power, such as tractors, which are commonly used to seine large ponds. Trucks may also be used to pull long seines. Multiple seine hauls are usually required to capture the majority of the fish. To completely harvest a pond, the water level is often reduced by 30 cm or so after each seine haul. Once the water has been drained, any remaining escapees can be harvested by hand and/or from a harvest basin (discussed later in this chapter).

The wider the levee, the more space it requires. In addition, at least one side of each pond levee needs to be wide enough for a vehicle to drive on so workers to have access for feeding, collecting water quality information, harvesting, mowing and so forth. To accommodate trucks, the road levee should be at least 2.5–3.0 m wide. Many aquaculturists prefer to be able to drive completely around every pond and construct all their levees appropriately wide, though often only certain levee areas are gravelled to provide all-weather access to every pond. The other levee tops can be grass covered and may be driven on when conditions permit.

Pond shape should provide for the economical use of available space but, if you travel around from one aquaculture site to another, you can observe ponds of various shapes, including circular, oval, triangular and irregular. A variety of shapes may be seen on the same facility. Sometimes pond shapes follow natural ground contours, and their shapes take advantage of those contours to reduce the amount of earthwork involved in construction. Old facilities, particularly those constructed before heavy mechanized equipment was available, were often constructed using existing land contours to the extent possible to reduce the amount of hand or horse-drawn labour involved in moving soil. In many parts of the world, heavy equipment is still either not readily available or beyond the financial ability of the prospective aquaculturist to pay for the cost of using it. In those cases, manual labour to dig a pond or to dam a creek in one or more places to create a single pond or a string of ponds provides an alternative. Again, such ponds may be irregular in shape, though rectangular ponds often still dominate, particularly on flat terrain. Rectangular ponds are easier to harvest than irregular ones.

Prior to construction, the land should be cleared of all vegetation, including tree roots. The topsoil should be stockpiled to the side during construction. Any woody debris that ends up in a levee will eventually rot, and the void space that is created can provide an opportunity for water to find its way into, and ultimately through the levee, which will then leak and may eventually fail (Box 3.3). Once levee construction is complete, the stockpiled topsoil can be used to top-dress the levees. It is much easier in most cases to establish grass on topsoil than on the less-rich underlying material (preferably heavy clay) that is used to form the levees.

In cases where above-ground ponds are constructed, a ditch should be dug 1 m or so deep around the perimeter of each pond under the middle of where the levees will be constructed. This is known as a core trench. If you do not want to dig the trench under each levee, there should, at a minimum, be a core trench dug under the outside perimeter of the entire pond site (Fig. 3.2).

Core trenches are generally dug using heavy equipment, primarily backhoes. However, in some instances, such as in developing nations, core trenches may be dug by hand.

The core trench should be filled with the same material used to construct the levees. The core trench should be compacted after it is filled and the levee itself should be compacted periodically during construction. Compaction provides a seal between the material in the core trench and the material used to construct the levee. When the pond is filled, water would naturally seep under the levee at the point where the original soil composition is different from that of the levee material placed on top of it. However, if the core trench soil and overlying material are sufficiently compacted, when water hits the core trench area, it will flow down into the trench, after which, due to the nature of the hydraulics involved, seepage will be interrupted and the water cannot proceed further than the trench. Lacking a core trench, the water may undermine the levee and lead to leakage and potential levee failure. Trenches are also necessary for the installation of drain lines that need to be located at an elevation below the pond bottom, to allow the ponds to drain completely. Core trenches serve double duty in being able to carry drain lines as well as preventing seepage.

Levees should be constructed with side slopes at a height:width ratio from 1:1 to 1:3; that is, for

Box 3.3.

Decaying organic matter is not the only reason levees fail. Improper compaction of the levees during construction and the activities of burrowing mammals are also associated with levee failures.

Fig. 3.2. A core trench.

every unit of elevation, there should be one to three units of width. The 1:1 configuration (45° angle) is the steepest recommended – the exception being ponds with vertical walls. The 45° angle is desirable from the standpoint of limiting the amount of levee area where invasive rooted plants can take hold and grow, but it is difficult for workers to enter or leave a pond with a 1:1 slope once it is put into production unless there is a stairway present as described in the 'Inflow and drain options' subsection below. Angles that are less steep, such as 1:2 or 1:3, provide easier access but also translate to more shallow water areas where aquatic weeds may become established. Examples of each of the three levee slope ratios are commonly seen (Fig. 3.3) but there can also be ratios between the ones listed, such as 1:2.5. Rarely would a pond have a ratio higher than 1:3, however.

Pond construction is commonly accomplished with bulldozers, but draglines, backhoes and scraper pans pulled behind tractors are among the variety of other types of machinery that can be used. The typical aquaculture pond is constructed to hold water to a depth of approximately 1.5–1.75 m as measured at the end of the pond opposite the drain from the pond bottom at the base of the levee to the water surface. Deeper ponds are often constructed in high-temperate climates where winter temperatures could cause the water to freeze at the bottom of a pond less than 2 m deep. Levee height should be at least several centimetres to 0.5 m higher than the intended water level.

There are some forms of aquaculture that use ponds much shallower than the typical pond described in the previous paragraph. Rice–fish farming and crayfish farming are two examples of aquaculture that are practised in shallow ponds. Rice–fish farming can be seen in many rice-growing nations, including Egypt and various countries in South-East Asia. Chinese farmers have reportedly been practising rice–fish farming for some 1700 years. Today, tilapia (*Oreochromis* spp.) and common carp (*Cyprinus carpio*) seem to be the most commonly used species in conjunction with rice–fish culture, though other species are sometimes involved, either alone or with other aquatic species. For example, freshwater shrimp (*Macrobrachium* spp.) have been produced successfully in rice ponds. Technically, that should be identified as rice–shrimp farming. In the case of crayfish culture in the USA, the industry began in Louisiana where farmers were looking for an alternative use or supplemental crop that could be reared in their rice ponds. The rice farmers found that they could obtain a good profit from crayfish, particularly in years when wild crayfish yields were below normal. In the coastal region of south-east Texas, USA, which has long been a rice-growing area, crayfish farming began in the 1980s. Louisiana continues to be the largest crayfish-producing state, with the wild crop from the Atchafalaya River Basin supplemented by pond-cultured crayfish.

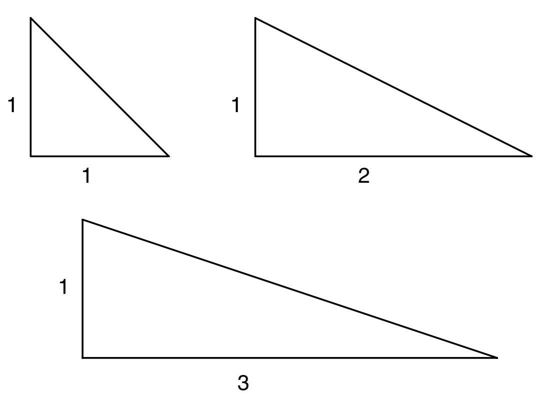

Fig. 3.3. Diagram of cross-sections of pond levees showing height to width ratios of 1:1, 1:2 and 1:3.

Rice ponds have low levees (about 15 cm). When used for crayfish production, the ponds are modified by increasing the levee height to 30–75 cm. The farmer may plant domestic or wild rice, millet, alligator weed or some other type of plant as forage for the crayfish. In rice–fish farming, the fish forage on animals that grow on the rice (aquatic insect larvae, for example). Tilapia will also graze on the algae (periphyton) that attach to the rice plants.

It is not necessary to raise pond levels to accommodate rice–fish culture; instead, the ponds may be modified through construction of a trench about 1 m deep and 0.5–1 m wide down the middle or on one side of each pond (similar to a core trench except for a different purpose). When the ponds are flooded, the fish can swim about foraging. When the pond is drained, however, there will be sufficient water remaining in the trenches to accommodate the fish. Draining of the rice field might be in conjunction with spraying for pests or for harvesting the rice. In either case, the pond needs to be dewatered. Trenches are not provided in all cases where rice–fish farming is practised, but they are a good option. It is easier to harvest the fish with dip nets from a trench where they will congregate when the pond is drained than by having to pick them up out of the mud from a drained pond that has no trench.

'My pond is small, but it is deep.' We have commonly heard that expression. The implication is that because of the significant depth, the farmer imagines that more fish can be stocked than would be possible in a pond of standard depth. In reality, that is not the case.

During summer in temperate climates and even tropical climates, there is a noticeable decrease in water temperature with depth in the water column. This is due to a process called stratification. Wind mixing will break or prevent stratification and keep pond water temperature uniform but, typically, ponds will stratify as the upper water column warms and the temperature becomes increasingly cooler with depth. The upper, warmwater mixed layer is technically referred to as the epilimnion, while the layer where temperature declines rapidly is called the thermocline. Technically, the thermocline is a region where temperature falls by about 1°C/m of depth. In aquaculture ponds of typical depth, the thermocline, when present, will extend to the bottom of the water column. In ponds that are several metres deep, a layer called the hypolimnion can form below the thermocline. That layer may be cooler than the optimal range for warmwater fish but, more importantly, it also commonly becomes oxygen-depleted due to the lack of circulation with the epilimnion water (the thermocline serves as a barrier to mixing). The result is that the fish tend to remain in the epilimnion and thermocline but avoid the hypolimnion. Thus, a deep pond has about the same carrying capacity as a more typical pond having the same surface area, so there is no advantage gained from added depth.

That does not mean there are no deep ponds used for aquaculture. They are just not commonly seen.

Inflow and drain options

Each pond should be plumbed with at least one inflow line and each pond needs to be equipped with a drain. While it is possible to pump water out of a pond, it is not desirable to do so as it is costly. Draining water by gravity costs nothing, other than the one-time cost of the plumbing. Pumping requires electricity or the use of gasoline or diesel fuel. Inflow can be through open sluiceways (channels that have side channels that can carry water to the individual ponds) or through pipes. Open channels providing inflow water are commonly seen (Fig. 3.4). They may present some impedance to vehicular traffic.

Some of the early hatcheries in the USA used wooden pipes for inflow (Fig. 3.5) and drainage. Bamboo pipes are still sometimes used in developing countries. Wooden pipes were replaced by steel, galvanized or, for some applications, copper pipes as time passed. In the last few decades, the most popular type of plumbing involves the use of PVC plastic pipes and fittings. Other types of plastic pipe include chlorinated polyvinyl chloride (CPVC), polypropylene and a high-molecular-weight polymer of vinylidene fluoride (PVDF). The latter types are less frequently found in aquaculture facilities than is PVC. Plastic pipe, usually PVC, is not only used in conjunction with pond plumbing, but is the plumbing material of choice in virtually all aquaculture systems that require plumbing.

PVC has largely replaced metal pipes that are subject to corrosion and can be a source of heavy

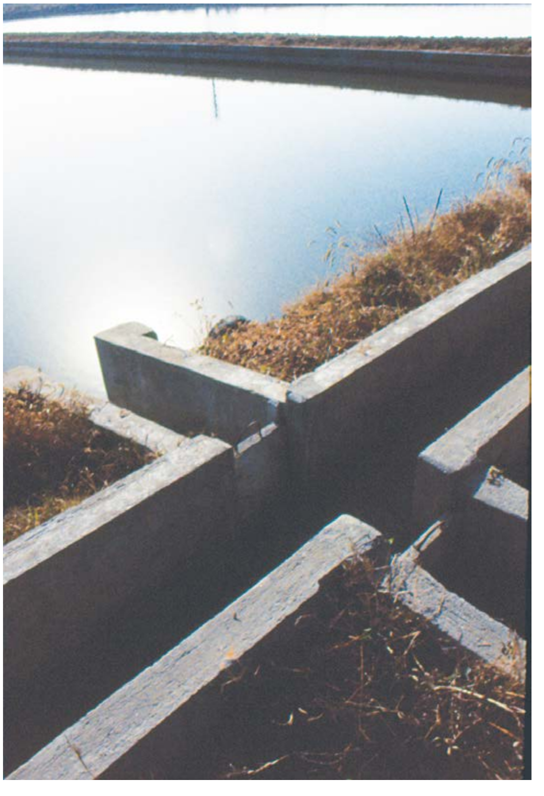

Fig. 3.4. Example of an open channel water inflow distribution system.

Fig. 3.5. A section of wooden pipe on display at a fish culture facility in Idaho, USA. This type of pipe was used in some of the hatcheries dating back to the 19th century.

metals at toxic levels. Connecting PVC pipes to fittings is a simple matter of gluing them together. PVC can be cut with a handsaw and easily reconfigured when necessary – just cut out the part you want to modify and glue in the new fittings. Metal pipes, on the other hand, need to be threaded (steel and galvanized pipe) or soldered together (copper pipe) at the joints and require hacksaws or specialized tools for cutting and/or threading them. PVC is much less expensive than metal, is non-toxic and is very durable. PVC schedule 40 pipe and fittings should be used since they can handle a wide range of temperatures and withstand the levels of water pressure used on most aquaculture facilities. The higher temperatures and pressures that can be withstood by schedule 80 pipe are not typically found in association with aquaculture facilities and schedule 80 pipe is more expensive, so it is not recommended except in unusual circumstances – such as in association with very-high-temperature geothermal water. Drain-quality PVC is available but should not be used in pressurized water systems. A disadvantage of drain PVC is that it can shatter if exposed to freezing temperatures. We prefer to use schedule 40 PVC exclusively for both inflow and drain lines.

The pipes that carry water from the main water line to the individual ponds should each have a valve installed in them at the points where the water enters the ponds so that inflow can be turned on and off as needed. Having a valve associated with each pond allows the culturist to add water to one or more ponds while leaving the remaining ponds unaffected.

Pipes and fittings should be sized to allow flow rates that can provide sufficient water to fill each pond within 72–96 h. Not every pond on a facility needs to be filled simultaneously, but the culturist should carefully consider what the maximum amount of flow might be and design accordingly. It would certainly make sense to have a sufficient amount of flow capability to fill all the ponds on the facility completely within a total of a few weeks. Thereafter, additional inflow water would be used primarily to maintain pond water levels as there would be loss due to evaporation and perhaps seepage.

Larger pipe diameters will be needed for gravity inflow systems, such as where water flows by gravity from a holding reservoir, than for those that are under pressure. For pressurized systems, pumps need to be properly sized relative to the size of the well, total lift and height from the pump in the well to the delivery point. In calculating water flow, one needs to be aware that there are frictional losses in water velocity with distance through a pipe. In addition, there are frictional losses when the water passes through various types of standard fittings such as elbows, tees and valves. Tables for determining pump size, frictional losses and a large variety of other useful information specifically for aquaculture can be found in the book by Creswell listed in the 'Additional Reading' section of this chapter.

It is important to realize that two pipes of the same diameter will not carry the same amount of water as a single pipe that is twice the diameter of the other two. For example, two 5-cm diameter pipes will not carry as much water as one 10-cm pipe. Recall the formula for the area of a circle that you learned some years ago? That formula applies to the cross-sectional opening of a pipe and is πr^2, where π (pi) = 3.14 and r^2 = the radius of the circle squared. Thus in our example the area of two 5-cm diameter pipes is 2.52 × 3.14 × 2 = 39.25 cm^2, while that of a single 10-cm diameter pipe is 52 × 3.14 = 78.5 cm^2, or twice as large (Box 3.4).

Some culturists put an inflow line at both ends of their ponds, though most ponds one sees will have a single inflow line. When there is only one inflow line, it is usually located at the drain end of the pond so the water can be added to maintain water quality during the late stages of harvesting when the fish can still be captured from good water quality before the pond is completely drained.

Water can be removed from ponds with pumps; however, that approach increases the expense of pond draining because of the need to provide the energy required, as previously mentioned. The best approach is to put in a drain system that allows water to be removed by gravity. Drains may be relatively simple. Figure 3.6 shows a concrete structure with boards in slots to control water level. Two stacks of boards with the space between filled with clay will reduce or eliminate seepage. When the pond is drained the clay is removed and the boards are removed sequentially until the water level is low enough to allow for seining. They can be removed completely to totally drain the pond. Also note that an inflow valve provides water for filling the pond initially and supplies additional water as needed to replace evaporation and/or leakage.

Figure 3.7 shows another simple drain structure with water boards with wooden plugs that can be pulled out or put into the holes to control water level.

Box 3.4.

A real-world case illustrates the importance of knowing how to compare the cross-sectional area of pipes of various dimensions. When R.R.S. was involved with a USAID project in the Philippines, one of the contractors said he wanted to substitute two small pipes for one larger one (since the two smaller ones had the same total diameter as the large one as in our example above). Because the water flow requirement was based on the single larger pipe diameter, the contractor's plan was rejected in favour of the one large pipe that was specified in the blueprints the engineering firm provided.

An even simpler system, which can be simply made with either metal or PVC plumbing, involves a drain line through the levee attached to a 90° elbow and a vertical standpipe. By using threaded

Fig. 3.6. Simple drain structure with baffle boards to control water level.

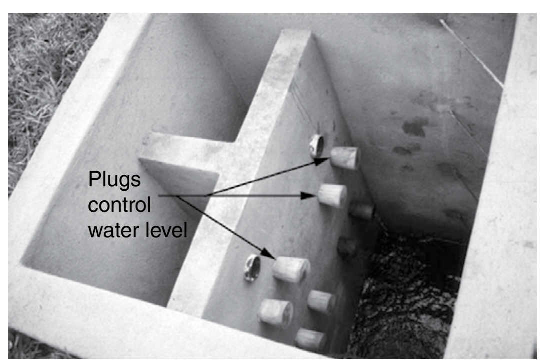

Fig. 3.7. Another simple drain structure.

metal pipe or not gluing the PVC elbow where it fits over the drain line, it will be possible to tilt the standpipe from the vertical to any desired angle to control water level. A cheater bar (a long, sturdy steel rod, such as a rebar, or a length of steel pipe) may be required to tilt a threaded pipe that is to turn, particularly after it has been under water for a long period. On the other hand, with PVC it might be necessary to drive a sufficiently long metal rod, or a small-diameter steel pipe, into the pond bottom next to the standpipe and strap the two together so the standpipe will not tip over on its own, because it is not threaded or glued into position. When lowering the water level using the previous approach, the standpipe can be lowered so its mouth is at the desired depth, and then tie it to the vertical pipe to keep it at the desired angle.

Before a pipe through the levee is used to drain a pond, it should be fitted with an antiseep collar. The collar can be metal (Figs 3.8 and 3.9) or might be formed from poured concrete several centimetres thick. A pipe of the desired length is either passed through a metal antiseep collar or set in place

Fig. 3.8. A metal antiseep collar and some of the PVC components prior to being assembled.

Fig. 3.9. A metal antiseep collar set in place immediately prior to having the levee built over it.

before the concrete is poured. The levee is then constructed over it. The antiseep collar acts in a manner similar to a core trench in that it keeps water that might seep along the pipe from leaking all the way through the levee. When the water hits the collar, it disperses laterally.

A variety of other, sometimes very elaborate, drain structures are in use, most commonly at research facilities and state and federal hatcheries because commercial aquaculturists tend to be more conservative in the amount of money they expend on luxury drains. High-end drain structures typically involve concrete structures that go by different names depending on the country where they are located. In the USA, they are usually called kettles. In Israel, they are referred to as monks. Other countries certainly have other names for them. Using the US designation, a kettle may control only the water level with baffle boards, or it may have other features such as a valved inflow water pipe and screen (rather than baffle boards) to keep fish from escaping during draining, and often they also have steps alongside them for ingress and egress of personnel. There also may be a harvest basin, a shallow area just outside the kettle where fish that have not been seined become concentrated as the pond is completely drained. All those features (except the screen) are shown in Fig. 3.10.

Fig. 3.10. A kettle drain structure.

Raceways

Culture units through which water continuously flows are called raceways. The most common shapes are circular (Figs 1.6 and 3.11) and rectangular (Figs 3.12 and 3.13). Rectangular units are called linear raceways. They were the first type to be developed and are commonly seen throughout the world. They have been widely used in conjunction with the early rearing of salmon and for rearing trout from fingerling to market size. They have also been adopted in conjunction with various other species for growout and are used in hatcheries for larval rearing of fish and invertebrates. The first raceways were constructed of wood. Modern raceways are usually composed of concrete, aluminium, some type of plastic or fibreglass. In a linear raceway, water enters at one end and exits at the other. Linear raceways may be grouped side by side or in series whereby the effluent from one raceway enters the next in line. To maintain DO in a series of raceways, the effluent from each unit in the series will typically be passed over splashboards to aerate the water. A typical length:width:depth ratio in linear raceways is 30:3:1.

Circular raceways, or tanks, vary greatly in size. Small units are used for research and in some hatcheries (Fig. 3.11), while large ones can be used for growout (Figs 1.6, 3.12, 3.13 and 3.14). The largest practical size seems to be about 10 m in diameter. Fibreglass and various types of plastic, such as polypropylene, are the most common materials used in the manufacture of circular tanks, with fibreglass being the material of choice for tanks larger than 1 m or so in diameter. Typically, large circular raceways contain water to a depth of about 1–2 m, though tanks up to 4–5 m deep – called silos – have been employed in at least a few instances.

Water entering circular tanks is usually flowed in at an angle to the water surface so that a current is created in the tank. In linear raceways, water flow is maintained as it enters at one end and exits at the other. The most common location for the drain in circular raceways is in the centre of the tank.

Fig. 3.11. Small circular raceways in a research laboratory.

Fig. 3.12. Raceways at a commercial trout farm.

Fig. 3.13. Tilapia raceways.

Fig. 3.14. Large circular tilapia growout tanks using seawater in the Bahamas.

The exit plumbing fitting inside the tank is often a coupling into which a PVC pipe of the appropriate diameter is inserted that controls water height. That pipe is called a standpipe. There are also drain designs that have the standpipe located on the outside of the tank. Many tanks have a bottom that slopes towards the centre drain from the sides. If the standpipe is on the outside of the tank, suspended solids, primarily faeces and unconsumed feed particles, will move to the drain and exit the tank over the effluent stream from the standpipe, thereby helping maintain water quality. The circular movement of the water caused by incoming water entering at an angle to the surface and near the outside edge of the tank also helps guide particulate matter to the drain.

A venturi drain that features two standpipes – one to control water level and a second taller one to collect solids – has become a fairly standard feature of circular raceways. Holes drilled near the bottom of the outside standpipe allow exiting water to pull solids into the area between the pipes, while the water exits via the inner standpipe. The inner standpipe should be pulled periodically to remove the solids from the tank. When the culturist wants to remove the solids, all he/she has to do is to pull the internal standpipe out of its fitting for a few seconds, allowing the solids to go down the drain. The venturi drain can be located inside or outside the tank. Having the venturi system outside the tank is best on large tanks where the culturist cannot reach the inside standpipe from outside the tank.

The self-cleaning feature that has been developed for circular raceways can be adapted to linear raceways as well, though it is not as efficient since the drain is located at one end of the raceway and some solids will tend to settle in the corners at the opposite (inflow) end. Siphoning of deposited waste may be required periodically and is a must in all hatchery raceways (linear or circular) where low flow rates lead to accumulations that do not get carried out through the drains (Box 3.5). Daily, or perhaps more frequent, siphoning is required until flow rates can be sufficiently increased to have the venturi drains function effectively. That can occur when the larvae develop strong enough swimming ability to avoid being sucked into the drain area.

Factors affecting the carrying capacity of a raceway are water flow rate (l/min), raceway volume (cm^3, m^3 or l), water temperature (°C), DO content (mg/l), pH, weight of the culture animals (g, kg) and the species under culture. Formulas for calculating carrying capacity, given knowledge of the other factors, have been developed for some species, though experience gained through trial and error is undoubtedly still used by many culturists. The typical aquaculturist, in the interest of maximizing profits, will push the water system to its limits, and many times push the system beyond those limits, thereby stressing the animals, which can mean facing disease epizootics or direct mortality due to water quality degradation.

High flow rates and the strong currents that may result can be used with juvenile fish species that are exposed to, and can tolerate, those conditions in nature. Salmon and trout are examples. Juveniles of other species and the early life stages of virtually all aquaculture species may only be able to tolerate low flow rates, and in some instances, will tolerate virtually no current. Extremely low flow rates or static (no flow) conditions are sometimes maintained during the hatching of eggs, particularly the very small and often extremely fragile eggs (the majority of marine fish species) and may also be required during larval rearing (Box 3.6). By cutting holes or slots in a large percentage of the outer standpipe of the drain and covering the openings with

Box 3.5.

Newly hatched larvae and fry of cultured fish and invertebrates are weak swimmers. If hatchery raceways, whether circular or linear, have high water turnover rates, the young animals can easily be damaged or killed by contacting raceway walls, standpipes, and even one another. Drain structures have to be screened (Fig. 3.15) to keep the small animals from being flushed out of the system; and strong currents would push the animals against such screens, again causing damage or death. With very low turnover rates – perhaps only one or two exchanges a day, and even less in some cases – particulate matter accumulates quickly but can be removed by daily siphoning. Care must be taken to avoid siphoning the animals out with the waste. Once the animals develop the ability to swim against currents, the turnover rate can be increased.

Box 3.6.

Atlantic and Pacific halibut (*Hippoglossus hippoglossus* and *Hippoglossus stenolepis*, respectively) are excellent examples. Adult females can reach weights of 200 kg (the maximum weight of males is probably less than one-quarter of that). During the spawning season the females produce batches of several thousand eggs every few days. The eggs, which take around 1 month to hatch, along with the larvae (which do not begin feeding for another month or more) have to be under quiescent conditions. They should not be in a current of any kind as, should two eggs bump into one another or if an egg hits the side of the culture tank, death will occur. The same is true of the sac fry (fry that are living on a yolk sac until they begin to feed). The fragility of the eggs and sac fry is not such a critical factor in the open ocean where the adults spawn, because the eggs are unlikely to come into contact with one another, though they are easy targets for predators, which may account for high egg and larvae mortality in nature. The fragility of halibut eggs and fry is in direct opposition to the heartiness of the adults, which fishermen typically shoot (with a handgun or rifle) before bringing them into their boats, as the fish have been known to cause significant damage, including knocking the transoms off small craft, not to mention the potential harm they may cause to the boat crew. Obviously, it is important to shoot the fish while they are in the water as doing so after they are pulled into the boat alive can lead to undesired results. Again, common sense is required.

fine-mesh nylon screen material, or by fabricating what amounts to an outer standpipe that is almost entirely made up of fine-mesh screen, it may be possible to maintain a very slow water exchange rate, but care should be taken not to establish currents that would entrap the larvae on the screen material. Frequent cleaning of the screen may be necessary to remove debris and keep as much of the mesh open as possible.

Removal of waste feed and other solids that may accumulate in a culture chamber, but not go through screens, can be accomplished by siphoning. Water should not be splashed into the tank, nor should it enter at an angle that will create a current. It is best to introduce water below the surface and to do it very slowly.

Open raceway systems

When water flows continuously through a linear raceway or tank system and then leaves the culture system, the culturist is using what is known as an open system. The water that leaves an open system may enter surface waters such as a lake, reservoir, stream or the ocean, though it might also be used to irrigate pastures or row crops. If the water source is a stream, the water may be diverted from the stream, pass through the culture system and re-enter the stream downstream of the aquaculture facility. It is not reused by that culture facility, though it could quite possibly be used in the same way by one or more aquaculture facilities located downstream from previous users so long as water quality in the downstream facilities recovers prior to being used.

Another option is to dispose of water into a municipal sewage system, but that, like using municipal water, can be very expensive in the case of open systems that use high flow rates and no reuse of the water. Municipal sewage systems would more than likely set their fees based on the volume of water that would have to be treated. In some cases, regulations may require that the aquaculturist treat at least a percentage of the effluent from the culture facility before it can be released into the receiving stream or other water body. That is the case in some trout farms in the USA that obtain their water from enormous springs (see Fig. 2.3), pass it through raceways and release it into a river. This approach does not meet the definition of a recirculating system if the treated water is not returned back to the raceways. If treated water is reused, the system would be of the recirculating type, though only partial recirculation would be involved. Treatment of a portion of the water used by the US trout industry along the Snake River canyon is mandated by the state of Idaho.

When raceways are operated in series (one raceway flows into another, which flows into another, etc.), the number of raceways in a series can vary considerably. In any case, it is wise to provide some means of aeration from raceway to raceway in order that DO levels are maintained. Aeration can be as simple as passing effluent from raceways over washboards (see Fig. 3.16). Various types of mechanical aerators have also been developed for use in raceways and ponds.

Microalgae Culture

Microalgae (phytoplankton and benthic algal species) are produced as first food for the larvae of

Fig. 3.15. Centre standpipe with screened openings to allow slow water exchange.

many vertebrate and invertebrate larvae and as food for zooplankton that are also used to feed such larvae. Microalgae may also be used to support the entire life cycles of some aquaculture species (e.g. many molluscs). Typically, though, cultured algae are only used early in the culture process and the animals rely on natural productivity, though, depending upon species, they may exist primarily or entirely on prepared feed. Animals moved from the hatchery to indoor raceway or tank systems usually depend exclusively on prepared feed. Shrimp cultured in indoor biofloc systems (discussed in another section in this chapter) are an exception, as they get their nutrients from both the biofloc and prepared feed.

Mass microalgae culture is usually conducted in aerated static water. Typically, a sterile stock culture of each algal species is maintained in test tubes or small flasks containing a nutrient solution. The nutrient solution varies depending on the species of algae being produced. All algal species require nitrogen and phosphorus while, in addition, silicon is required by diatoms. The stock cultures are kept in a lighted incubator (usually about the size of a household refrigerator). When the cell density is high – hundreds of thousands to millions of cells per millilitre – a portion of the contents of each test tube or flask is used to inoculate a new flask or test tube of nutrient broth and the remainder is used to

Fig. 3.16. Baffleboards between raceways provide aeration.

inoculate a larger container, such as a glass carboy or transparent plastic bag that contains the nutrient medium in several litres of water. The carboys or plastic bags are exposed to bright artificial light that mimics daylight and aeration is provided to stimulate movement of the cells so that they get maximum exposure to the light (Figs 3.17 and 3.18). Carbon dioxide, which provides the carbon source for phytoplankton growth, may be supplemented by introducing it with the air. Adding carbon dioxide helps speed up development of the algal bloom because the concentration of that chemical in the atmosphere is quite low as a percentage of atmospheric gases (about 0.5%). After a few days, cell density will be maximized and the algae can either be used directly as food for filter-feeding aquaculture animals or, when large volumes of algae are required (such as in a commercial oyster hatchery), the cells in the containers may be used to inoculate tanks with capacities of up to several thousand litres.

Fig. 3.17. Carboys of aerated high densities of multiplying algal cells.

Fig. 3.18. Plastic bags of multiplying algal cells.

When it is time for final harvest, the algae may be siphoned or pumped into tanks containing larval fish or invertebrates that are to be fed. However, culturists may wish to prepare additional supplies of algae and store them for later use. In some instances those supplies may be shipped to another facility which may be operated by the same company, or they may be sold to another company. The algae cells can be concentrated into a paste using a continuous centrifuge, frozen or freeze-dried, and stored. While some mass algae culture is conducted outdoors in raceways or tanks, most culturists prefer to culture algae in a building or greenhouse to limit the possibility of contamination with unwanted algal species that could outcompete the species of choice. We have seen cases where a culturist thought a particular culture was uncontaminated when, in reality, it had become dominated by another species.

Periodically, algal culture samples should be checked microscopically to ensure they are not contaminated. Because algal spores can travel long distances in the atmosphere, contamination is a very real threat to outdoor systems, but it can also occur indoors. The invading species may ultimately outcompete the desired species, in which case the culture may not be appropriate to feed the animals for which it is being produced. It may also be necessary to replace stock cultures from time to time as they can become senescent or contaminated. Cross-contamination is particularly likely when two or more species of algae are being produced in the same facility. That approach may be required when different larval stages require different algal species – for example, larger cell sizes may be required as the larvae grow – or when a variety of different species that vary in size is being grown so that a mixture can be provided to the larvae being cultured. In addition, if two or more species of animals are being reared, each may require different species of algae either throughout the larval phases or during growout. It is not uncommon to see several species of algae being produced in the same culture facility, so care to eliminate cross-contamination should be a top priority.

Algae may be fed directly to larvae or to more advanced stages of zooplanktonic species that are used as live food for the early life stages of primary aquaculture species (see Chapter 6), or they may be used throughout the life cycle of groups, such as species that filter-feed on phytoplankton (oysters, mussels, scallops) or graze on benthic algae, such as diatoms (sea urchins); or feed on seaweed (abalone).

Partitioned Aquaculture Systems

Partitioned aquaculture systems are those that involve retrofitting existing systems (or building new ones) that employ some approaches to pond and raceway culture that have been developed within the last several years. They are called split-pond and in-pond raceway systems. Both were initially developed from research focused on the US catfish industry but certainly have application to other species.

The split-pond system involves dividing a culture pond with a levee that separates one portion of the pond from the other (basically making one pond into two). The levee can be constructed from soil removed from what will become the fish-holding end of the pond, allowing for more volume of water for the fish. Typically, the fish-holding portion is 15–20% of the pond area and the waste treatment portion is the remainder. Channels or pipes separate the two pond areas. Water is circulated from one portion to the other with slow-turning paddlewheels or pumps. High concentrations of algae become established in the waste treatment portion of the pond. The algae produce oxygen during daylight but respire carbon dioxide during the night and can deplete the DO in the system, so the circulating paddlewheels or pumps are shut down at night. Supplemental aeration is provided to the fish-containing portion of the pond at night as required to keep the oxygen levels at or above those required for optimal fish performance. The relatively small volume of the fish-containing section of the pond enhances the ability to accurately feed the fish, treat for disease and harvest the crop when the fish reach market size.

In-pond raceways have also been employed by catfish farmers and have the potential or have been adopted for the culture of other fish and invertebrate species. Floating raceways are placed in parallel in a pond and provided with flow through them by slow-turning paddlewheels. Alternatively, large volumes of water can flow through enclosed raceways with the use of airlifts. In either case, like the split-pond system, the remaining pond area serves an area for maintaining water quality. Again, harvest of the raceways is easier than having to seine a large pond or reservoir in which the raceways are positioned.

Recirculating Systems

The technique in which effluent water is processed to restore its quality and is then recycled back to the culture chambers is called recirculating or reuse aquaculture. A recirculating system may recycle as little as a few per cent of the water each day (semi-closed system) but, if the vast majority of the water in the system is reused over and over again, it is referred to as a closed system. The home aquarium with an under-gravel or outside filter that treats the water is an example of a closed system with which you may be familiar. In reality, no system is 100% closed. And even in the case of the home aquarium, periodic cleaning of filters is required, which results in the removal of some water from the system that needs to be replaced. Because only a small amount of water is discarded, and that occurs only periodically, the system can be considered closed. We are not considering replacing water that has evaporated as being something that violates the notion of a system being entirely of the recirculating type. Evaporative losses cannot be avoided. When we look at commercial systems, which would include large tanks in public aquariums, some components of closed systems need to be partially drained periodically to remove settled solids. Replacement water then needs to be added and will also be required to replace losses due to evaporation, along with replacement of splash-out water that may occur when fish are feeding actively. Leaks may also occur, which would require repair and the replacement of lost water.

Most recirculating systems are housed in buildings such as prefabricated metal buildings, greenhouses, warehouses or other types of structures. Usually, the amount of natural sunlight that the closed systems are exposed to is minimized to keep algae from growing in the culture tanks. However, at least a few systems have been established in which the culture protocol calls for establishment and maintenance of an algal bloom that can function as a component of the water treatment system, as food for the culture animals or as the only cultured organism in the system – as would be the case in the production of algae used as a nutritional supplement or for manufacture of biofuel. Polyculture systems that combine plant and animal culture in the same system require light for the plants, which may be either artificial or natural light. If artificial lights are used, they should mimic the wavelengths of sunlight.

Designs for recirculating water systems vary widely. Many are designed by the culturists themselves, though there are engineering firms that work with aquaculturists on the design and construction of such facilities, just as there are firms (sometimes the same ones) that work on pond design and construction. Engineering firms do not actually do the construction – that work is contracted out – but they do sometimes oversee it. Public aquariums and government hatcheries, along with aquaculture research laboratories (whether they feature recirculating technology or not), are often designed by engineering firms. The same is true for some, but certainly not all, university research facilities (Box 3.7).

No matter who designs the recirculating system in a particular instance, there are some features of reuse systems that are consistent from one facility to another. Those include the culture chambers (circular tanks or raceways in most cases), an aerobic biological filter of some sort and, commonly, one or more settling basins. There may also be mechanical filters, one or more pumps to move the water from one component to another and protein skimmers. Some systems even employ anaerobic digesters that contain bacteria that convert nitrate to nitrogen gas, a process known as denitrification. A process known as anaerobic ammonium oxidation was discovered several years ago. The process involves chemotrophic bacteria that combine ammonium ions and nitrite under anoxic conditions to produce nitrogen gas. The process has been called anaerobic ammonium oxidation (Anammox) and has been evaluated for some aquaculture systems. Aerobic denitrifying equipment that utilizes aerobic bacteria for denitrification has also been developed. In recent years, filters have been developed that both treat the water and capture suspended solids for removal from the system, so they act as both biological and mechanical filters.

Box 3.7.

Any good engineering firm involved in designing aquaculture facilities should have at least one, and preferably more than one, biologist on its staff. Engineers do a great job of ensuring that water flows through the systems they design, that the plumbing is sized properly and that all components of such things as recirculating systems can be depended upon to do the jobs for which they are intended. What engineers often do not understand are the requirements for survival and well-being of the culture species. The biologist, working with the engineer, can help ensure that the needs of the species reared in the system are properly accommodated.

The basic design of water reuse systems has not changed much since such systems first appeared, though there have been significant improvements in the technology and efficiency. We are not sure when the first reuse systems were developed, but the first experience of R.R.S. with such a system was in 1970 (Box 3.8). Basically, a reuse system functions similar to a human waste treatment plant, except the waste in the case of an aquaculture system is very dilute compared with what passes through a municipal waste treatment plant.

Let us take a walk through a typical recirculating system. We will start with the component that houses the culture animals.

The culture chambers used in recirculating water systems are no different from those described above, with the exception that instead of effluent water being disposed of after one use, some or all of it undergoes treatment and is then returned to the culture tanks or raceways. In most cases one system serves several culture tanks rather than each culture tank having its own filters, settling basins and so forth. Circular raceways are more commonly seen as elements in recirculating systems than linear raceways. In Fig. 3.19, tanks used for the basic components of a recirculating system R.R.S. designed and helped set up at a university in southern Brazil several years ago consisted of cisterns purchased at a plumbing store. Such cisterns are normally used to collect rainwater for domestic use. Every house in the region seemed to have at least one of them. Figure 3.20 shows a row of concrete burial vaults that were plumbed with inflow valves and drains. They have been used in fish growth studies, holding tanks associated with fish harvested from ponds, etc.

Box 3.8.

The first recirculating system R.R.S. ever saw was designed by James W. Andrews, who was undertaking research on channel catfish (*Ictalurus punctatus*) at the Skidaway Institute of Oceanography in Savannah, Georgia, USA. He conducted his PhD research there under Dr Andrews' mentorship, though he was a student at and graduated from the Florida State University (FSU). The recirculating system consisted of a tall culture tank constructed of concrete blocks, and a filter system housed in a home-made plywood box. At the time R.R.S. saw it, the system was holding catfish that averaged at least 1 kg at a density of about 160 kg/m^3, and apparently had been at that density for at least several weeks. The system performed remarkably well until a power failure one night caused a severe drop in DO which stressed the fish to the point that they ultimately succumbed to various diseases (more details can be found in Chapter 5).

The imaginations of aquaculturists around the world have undoubtedly come up with other, even more bizarre, culture chambers. Basically, if it will hold water – whatever it might be – you may be able to adapt it for use in aquaculture.

Water exiting the culture chambers is usually collected in a drainpipe or open drain channel and flowed by gravity or by pumping into a settling chamber. Settling chambers are basically tanks where the water flow rate is slow enough to allow much of the suspended solid material to settle out of the water column. When turnover of the water in the system is rapid, very large settling chambers are required if they are going to be effective. A valve located at the bottom of the settling chamber is opened periodically to allow the accumulated solids to be flushed out of the system. In a modern aquaculture facility that task may be automatically undertaken using computer-controlled valves.

In addition to, or instead of, a settling basin, mechanical filtration can be used to remove solids. Sand or diatomaceous earth filters (Figs 3.21 and 3.22) are often used and are very effective when the solid loads are not too high. Sand filters and particularly diatomaceous earth filters (typically used in swimming pools) tend to clog fairly quickly as the diatom tests are much smaller than sand grains. Once the filter medium begins to clog with particles from the incoming water, the efficiency of the filter will be greatly reduced. Backflushing of the filter to remove accumulated solids is required periodically – sometimes as often as two or more times a day. Backflushing is accomplished by closing a valve to stop water from entering the filter, opening another valve to take the effluent water to a waste drain and pumping water backwards through the filter for several minutes. Again, that process can be programmed into a computer system. It may make the most sense to use a settling tank first to get rid of the large particulate matter and follow that with sand filtration, though sand filters may be alternatively associated with a secondary settling basin as described below. In any case, sand filtration is an

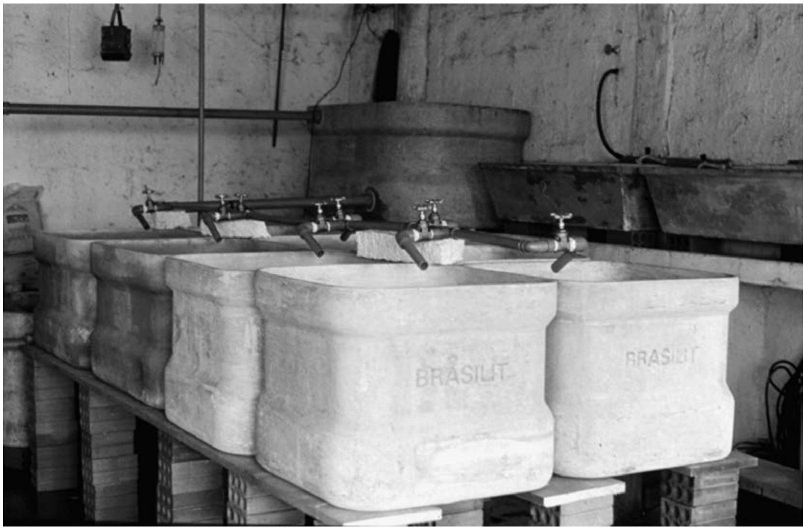

Fig. 3.19. Water system constructed in Brazil with components at a plumbing store.

Fig. 3.20. Concrete burial vaults modified for use as experimental tanks.

option that some culturists use, while others do not. Commercial sand filters are readily available. Swimming pool filters can easily be adapted for aquaculture use, at least at the research level. For large recirculating systems, sand filters of appropriate sizes are available, or can be constructed (Fig. 3.23). Again, settling tanks are recommended to extend the time required between backflushing.

Gravel filters are less efficient than sand filters but will function without backflushing for a longer period of time. Using a gravel filter to remove large particles and then flowing that water through a sand filter can extend the time interval between backwashing the sand filter. Gravel filters also require backflushing when the medium becomes clogged with particulate matter. Various other filter media have also been used. For example, cartridge filters can be used to remove very fine particles from water that has already received prior sand filtration (Fig. 3.24). Cartridges are crafted from various types of permeable materials and are used primarily in systems where suspended solids are at low levels as when the filters are clogged, they need to be replaced rather than cleaned and reinserted.

Fig. 3.21. A swimming pool filter that uses diatomaceous earth as a filter medium.

Bead filters employ small plastic balls as the filter medium (Fig. 3.25). The beads are kept in suspension and constant motion at all times while the bead filter is in operation. Water enters at the bottom of the unit at the rate required to put the medium in suspension. In the case of filters containing beads that float, flow rate does not suspend the beads, but it does agitate them to keep the maximum amount of surface area exposed to the water. Bacteria attached to the medium provide biofiltration. Particulate matter is also trapped. Periodically, the unit is backwashed to flush particulates from the system. While a bead filter can function both as a combination biofilter and particle filter, when used in combination with a rotating bio-contactor (RBC) or other type of biofilter, the primary function of the bead filter will be sediment removal.

Water leaving the settling chamber and/or mechanical filter – if either is incorporated into the water system – next flows to a biological filter

Fig. 3.22. A pair of sand filters.

Fig. 3.23. Large sand filters.

Fig. 3.24. A cartridge filter.

Fig. 3.25. A bead filter.

(biofilter). A biofilter is a device or chamber that contains some type of substrate on which aerobic bacteria will grow. The function of the bacteria is basically to change toxic forms of nitrogen in the water into a non-toxic form.

Aquatic animals excrete nitrogen as a waste product. That nitrogen may be in one of a number of forms, the most common for aquaculture species being ammonia (found dissolved in the water as either highly toxic unionized ammonia (NH_3) or less-toxic ammonium ion (NH_4^+)). The job of the bacteria in the biofilter is to convert ammonia to nitrate (NH_3^-). That is accomplished in two steps. One type of bacteria converts ammonia to nitrite (NH_2^-), which is also toxic. A second type of bacteria then converts nitrite to nitrate.

It has been widely reported that the conversion to nitrite involves bacteria in the genus *Nitrosomonas* and the conversion from nitrite to nitrate involves bacteria in the genus *Nitrobacter*. Other bacterial genera that may convert ammonia to nitrite are *Nitrosococcus*, *Nitrosolobus* and *Nitrosovibrio*, while other genera that may convert nitrite to nitrate are *Nitrococcus*, *Nitrospina* and *Nitrospira*. In any case, the bacteria associated with the reactions are cosmopolitan in nature and will naturally colonize the biofilter medium within a few days to several weeks after water is put in the filter. The process is chemically the same in full-strength seawater as it is in freshwater or brackish water, though bacterial colonization proceeds more slowly in marine systems than in freshwater ones. Also, the two types of bacteria often do not colonize at the same rate. If the bacteria responsible for converting ammonia to nitrite begin working efficiently before the second bacterial population becomes fully established, the conversion of nitrite to nitrate will not occur rapidly enough to prevent a build-up of nitrite to toxic levels. Thus, it is important to have well-established populations of both types of bacteria actively doing their work of converting ammonia to nitrate before the culture animals are stocked at the desired density. In freshwater systems, the bacteria may colonize and begin working effectively within several days, while it can take over a month for the same level of activity to develop in saltwater systems.

The bacteria will not colonize to any extent if there is no source of nitrogen in the system. Development of the bacteria can be encouraged if the culturist stocks a few fish, feed or fertilizer into the system. Any of those nitrogen sources will encourage bacterial development. Commercial mixtures of the appropriate bacteria are available as well, though mixed results with those products have been reported; that is, they may or may not appreciably accelerate establishment of the desired level of bacterial activity in the biofilter. Colorimetric tests can be conducted to measure nitrite and nitrate levels, while colorimetry or an ammonia probe can be used to determine the ammonia concentration. The levels of each chemical that can be tolerated by an aquatic animal species depend on the identity of that particular species. Ammonia tolerance depends on the percentage that is in the less-toxic ionized form. The ratio of unionized to ionized ammonia varies with temperature, DO level, pH, carbon dioxide concentration, bicarbonate alkalinity and salinity. The percentage of ionized ammonia decreases in hard or salty water and with decreasing carbon dioxide level. The percentage of unionized ammonia increases with temperature and pH. An efficiently operating biofilter should keep the levels of both total ammonia and nitrite in the very low milligrams per litre range (e.g. 2 mg/l or less). Nitrate, on the other hand, may be present at several hundred milligrams per litre without causing any apparent stress to many, but not all, culture species.

As the beneficial bacteria build up on the filter medium, they will form mats, pieces of which will slough from the medium and contribute to the level of suspended solids in the water. For that reason, if the culturist only uses one settling chamber and/or mechanical filter in the system, the appropriate location for it is immediately after the water leaves the biofilter.

Various types of biofilter media have been used over the years. In many cases, the media seen today are various types of plastic, though, once again, culturists often use their imagination to innovate or use something that they already have on hand, such as scrap PVC, sheets of fibreglass or even sheets of Styrofoam®. More exotic filter media would include wheat straw and wood chips. The demand for biofilter media is sufficiently high that commercial firms sell products designed specifically for that use. The main things are that the water needs to flow freely through the medium and the medium needs to provide as much surface area as possible.

Water entering the biofilter may flow in at the top and pass over the filter medium and then exit at the bottom (downdraft filter). Alternatively, the medium may be submerged in water (submerged filter), or the incoming water may be sprayed evenly over a filter medium that is basically exposed to the air (trickling filter). Very-large-scale examples of trickling filters can be found in sewage treatment plants where rocks provide the medium on which the bacteria grow. Water may also be introduced from the bottom of the biofilter chamber and overflow near the top of the tank (upwelling filter). Another approach is to flow water in one end of the biofilter chamber and out the other. That is an alternative for a submerged filter design. The medium in a trickling filter must be kept wet to avoid desiccating the medium but has the advantage that the bacteria are constantly exposed to atmospheric oxygen and will not go anaerobic, which can occur in submerged filters.

An RBC is a biofilter design in which the medium (often circular sheets of flat or corrugated fibreglass) is mounted on a rod and half submerged in water. A motor turns the rod at a few revolutions per minute (usually no more than 30 rpm). Examples of RBCs are shown in Fig. 3.26.

Biofilters should be protected from exposure to direct sunlight and bright artificial lights to prevent the growth of undesirable algae. Algal growth can lead to clogging of some types of biofilters and, if certain types of algae – for example, blue-green algae (cyanobacteria) – become established, there is the potential for off-flavours in the flesh of the aquaculture animals that would lead to consumer rejection of the product, or there could be direct mortality of the aquaculture animals from metabolites produced if the undesirable algae are toxic species.

Another type of biofilter similar to previously described bead filters (Fig. 3.25) is fluidized beds (Fig. 3.27). Basically, a fluidized bed filter involves one or more vertical columns that are partially filled with some type of a small-sized medium. Fluidized bed filters most commonly contain sand or very small plastic beads as the filter medium (which is called the bed). Ion-exchange resins, activated charcoal, limestone and crushed oyster shell have also been used in fluidized beds. Water flows through the medium from the bottom of the column(s) at a rate that puts the medium into suspension (hence, the bed behaves like a liquid). Fluidized bed biofilters are used for ammonia removal but do not remove particulates. Anaerobic fluidized beds can be used to remove nitrate by converting it to nitrogen gas. That reaction takes place by certain types of bacteria that thrive in oxygen-depleted environments. While nitrate is usually not a problem in aquaculture systems, it can build up to toxic levels in closed or nearly closed recirculating systems that have been operating for a long period of time, so conversion to nitrogen gas is an option that should be considered under such circumstances.

Well-designed systems typically require only one pump and utilize gravity to flow water between system components. If water is pumped more than once, it is necessary to balance the pumping rates to keep portions of the system from either being pumped dry or caused to overflow. Since achieving such balance is not always a simple matter, in most cases recirculating systems are designed so that only one pump is required. If we were to follow a

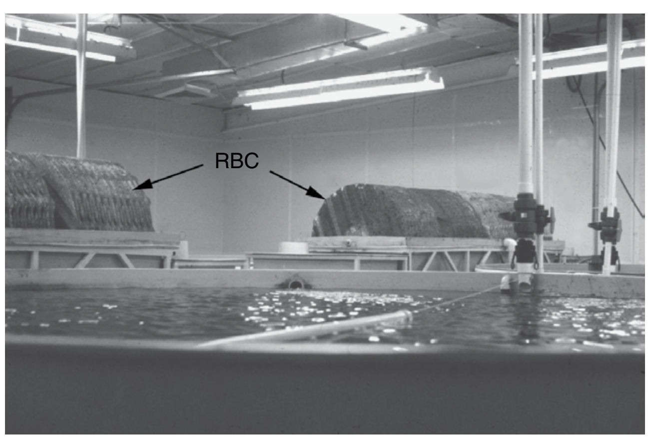

Fig. 3.26. Rotating bio-contractor biofilters (RBCs).

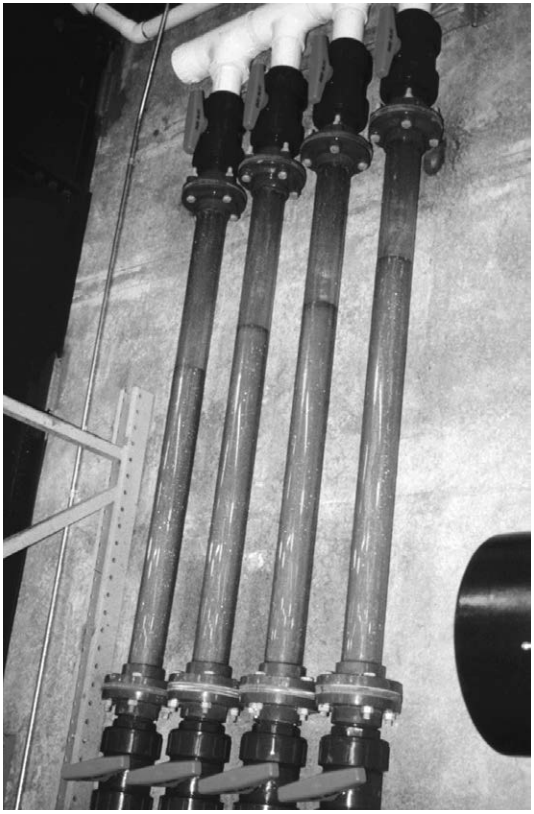

Fig. 3.27. Fluidized bed columns.

water molecule from the lowest point in the system, it would be pumped to the highest component and flow by means of gravity through the other components until it returned to the place where it started, after which the molecule would be picked up to repeat the cycle.

Supplemental aeration is generally provided in closed systems and may also be used routinely in other types of water systems. A variety of aeration devices are available on the market. Included are agitators that mechanically stir up the water surface, compressors that deliver high-pressure air to the system and blowers that deliver low-pressure air. Air from compressors and blowers is delivered through pipes. In multiple small aquarium systems, such as those often used in research and in stores that sell a variety of tropical fishes, air tubes that tap the air hoses are fitted with air stones placed in the small tanks and aquaria that provide air in the form of small bubbles.

Compressed oxygen (as well as liquid oxygen) are options, but they are costly and are not commonly or routinely used in commercial facilities. They may, however, be present as backups in the event of a power or mechanical equipment failure that renders the more standard aeration devices inoperable.

Oxygen is dissolved in water by diffusion. The greater the volume of air exposed to the water, the more rapidly saturation of the water with oxygen is achieved. Agitating the water or delivering millions of small bubbles increases the amount of air–water contact. Aeration is provided to the culture chambers and may also be used in conjunction with the biofilter, particularly if it is a biofilter in which the medium is constantly submerged in water. If the biofilter should go anaerobic, the beneficial bacteria will expire, and the filter will begin to produce such toxins as hydrogen sulfide as anaerobic bacteria colonize the medium. If an anaerobic filter is a component of a reuse system to convert nitrate to nitrogen gas, and if the discharge water from that filter is going to be reintroduced into the aerobic components in the system, that water needs to be aerated in advance of exposing it to either the culture organisms or to the microorganisms in the biofilter.

Sterilization with ozone and/or ultraviolet (UV) radiation is sometimes used in conjunction with recirculating water systems. If the incoming water is from a source that may contain harmful bacteria, sterilization becomes important, but since it is virtually impossible to eliminate pathogens from a water system, no matter what the water source, sterilization can help keep circulating levels of harmful bacteria at low levels and may prevent epizootics. Thus, ozone and/or UV radiation can be used both on incoming new water introduced into the culture system and routinely in conjunction with a recirculating system.

Ozone generators are used to convert molecular oxygen (O_2) to ozone gas (O_3), which is injected into the water. Ozone is highly toxic, so the culture animals and biofilter should not be exposed to that chemical. To avoid exposure, ozonation needs to occur in a separate part of the system into which a side stream of water is flowed. The water is then allowed to stand, with or without aeration, for the time required for the ozone to convert back to O_2. Ozone can also be removed by running the water over activated charcoal. Any ozone that enters the atmosphere of a building needs to be properly vented to the outside as it is also toxic to humans and other terrestrial animals when breathed in at sufficiently high concentrations. The ozone system should be designed by an engineering firm with considerable experience working with aquaculture systems to ensure that it will function properly (Box 3.9).

Commercial UV light systems and ozone generators are available and can be sized appropriately for the culture system for which they are to be employed. Normally, an individual culture system will not employ both approaches.

UV sterilization is considerably safer for personnel and the aquaculture species than ozonation, though it does have some drawbacks. UV sterilizers employ fluorescent UV light bulbs past which a stream of water is flowed. Various designs have been employed and the most effective are those which pass the water by the light in a thin stream. Usually, several bulbs are used within a chamber through which water is flowed. The bulbs are placed inside clear glass or quartz sleeves to separate them from direct contact with the water. Alternatively, the water may be passed through a clear glass or quartz tube that is surrounded by UV bulbs. Microorganisms exposed to the light are killed.

A major drawback of UV sterilization is that the efficiency of UV bulbs deteriorates with time. In addition, particulate matter tends to deposit on the sleeves around the bulbs or on the clear pipe through which the water flows, depending on the type of system used. As the glass becomes increasingly opaque due to particle sedimentation, the effectiveness of the UV light is lost. UV bulbs should be replaced every few months and the material on which deposits form should be cleaned as necessary. A maintenance schedule should be set up that is specifically adapted to each UV system, as each will tend to behave differently due to differences in water quality from one culture system to another, relating to how quickly the particulate matter accumulates on the tubes.

As dissolved proteins accumulate in recirculating systems, they produce foam. Various types of foam strippers have been developed. Some are as simple as skimmers that push the foam into a collection area or even simple platforms placed just at the water surface in areas where foam is produced. The foam will tend to pile up on the platforms and can be cleaned off as needed. Removal of foam reduces the level of dissolved organic material in the system.

One important piece of equipment that should be included in conjunction with any recirculating system, and any other system that depends upon pumped water, is an appropriately sized generator. The generator should be programmed to come on automatically if there is a power failure. It can run pumps, aerators and other types of electrical equipment until power is restored. The generator should be tested periodically to ensure that it is working properly. The culturist should also ensure that there is plenty of fuel on hand for the generator at all times. Aquaculture facilities tend to be located in rural areas where power outages in conjunction with storms can be common. Also, in developing countries, power can be undependable even during fine weather.

Other auxiliary features of recirculating systems include automatic water quality monitoring and computer control. A variety of water quality parameters can now be monitored through the use of sensors. Included are DO, salinity, temperature, pH and ammonia. Knowledge of some or all of those parameters may be critical, depending on the type of system used (see Chapter 4 for details on parameters of importance). You would not need to measure salinity in a freshwater system, for example, and pH may not be of particular interest in a system where the incoming water is of constant pH and the percentage of recirculation being used is very low. Another thing that might be automatically monitored is water flow in various parts of the system. All the data can be captured on a computer and displayed in real time on a monitor. They can also be archived so the culturist can look at fluctuations that occur over any given period of time. The computer can be programmed to increase or decrease the rate of aeration depending on DO

Box 3.9.

One of the large government salmonid hatcheries on a river in the Pacific Northwest of the USA (the states of Washington and Oregon) obtains its inflow water from a river that has already been used by another hatchery. If the upstream hatchery experiences a disease epizootic, fish at the downstream hatchery will likely be exposed to the disease organism. To resolve the problem, the downstream hatchery will need to expose all the water that passes through the hatchery to ozone treatment.

level, adjust the rate of chemicals being used to do such things as dechlorinate incoming municipal water, adjust pH, turn on or off heaters or chillers to maintain water temperature within set limits, adjust water flow rates, backflush mechanical filters, turn on and off feeders, and perform various other tasks. One of the most important things a computer can do is send out an alert (e.g. by mobile phone) to one or more of the personnel who are affiliated with the facility if there is a power failure, a pump fails, water quality falls outside the normal range for any critical parameters or something else goes awry with the system. If telephonic alerts can be sent from a computer, it is not necessary to have a person at the facility to monitor the system 24 h a day. The computer should be set up to operate on emergency power if normal electrical service fails and should be programmed to activate backup systems automatically. Computerized systems are expensive, but the money may be well spent if a disaster is averted.

Materials used in the construction of any type of water system should be non-toxic to the aquatic animals and, in the case of recirculating systems, the beneficial bacteria in the biofilter. Exposed metal should be avoided as much as possible because of potential toxicity. This is particularly important in saltwater systems where metal corrosion occurs very rapidly, and toxic levels of trace metals may be present as the metal ionizes (Box 3.10).

A variation of recirculating water systems involves outdoor ponds that recirculate their effluent water. An example of that approach was developed by the shrimp-farming industry in Texas, USA, in response to criticism over the release of nutrients and suspended solids into public surface waters. The shrimp farmers, who had been pumping extremely large volumes of water through their ponds on a flow-through basis, responded by expanding their drainage canals, placing weirs or baffles in the canals to provide settling areas for suspended material, reducing stocking densities and reducing the protein level in the feed. Some farms also developed constructed wetlands with the idea that the plants would absorb nutrients, thereby acting as biofilters (Box 3.11). Similar types of systems have been used for various other cultured species. Another variation on the same theme involves flowing effluent water through a pond where algae provide treatment. The water can then be returned to the culture ponds, though it may be necessary to filter out the algae first. Another option might be to use seaweeds in the treatment pond in seawater systems or rooted aquatic plants in freshwater systems.

Box 3.10.

A colleague of ours was conducting research on freshwater shrimp (*Macrobrachium rosenbergii*) in a recirculating water system and was faced with significant mortalities in his hatchery. Water quality conditions were appropriate for the larvae, including the salinity level required for their development. Ultimately, our colleague discovered that the submersible plastic pump he was using to move water through the system had an exposed metal screw on it that was obviously being corroded from exposure to the saltwater. Once he eliminated the issue with the screw, the mortality problem associated with toxic metal levels was resolved.

Cage and Net Pen Systems

Cages and net pens are culture chambers designed to confine aquaculture animals, usually finfish (but also shrimp or other invertebrates in some cases), in large water bodies (lakes and reservoirs, as well as coastal and open ocean marine areas). If the animals were not confined in such a water body, they would be difficult to harvest and, in the case of the marine environment, might leave the area entirely. Basically, cages and net pens are floating, or submerged units placed in open water. Cages are sometimes used in large ponds that cannot be drained or are difficult to seine for one reason or another. Cages have also been used in smaller ponds for rearing catfish (as in partitioned aquaculture systems described above). The standard type of

Box 3.11.

Sometimes the best intentions of an aquaculturist to resolve an issue can lead to unintended consequences. One shrimp farmer who developed a large wetland to treat his effluent water prior to recirculation ended up attracting large numbers of waterfowl that probably introduced more nutrients to the wetland through their excretory products than were being produced by the shrimp.

cage will have a rigid frame on all sides (Fig. 3.28), while traditional net pens have rigid frames only at the top (Fig. 3.29). The netting, which may extend down into the water for 20 m or more, hangs from the frame of the typical marine net pen. Sea cages are usually much larger than cages used in freshwater. Some of the models currently in use have volumes of thousands of cubic metres. Feed distribution in small cages is typically done by hand (Fig. 3.28), while automatic feeding systems are often used in conjunction with large net pens (Box 3.12). Feed is stored in bins on shore or in association with the net pens. Air under pressure may be blown through plastic pipes to convey the feed into net pens at intervals under computer control or dropped into the water from an overhead feed bin (Fig. 3.30). The open ocean net pen system shown in Fig. 3.30 was a design developed in Scotland that could withstand 6 m waves. While the one shown is near the shore, the fetch of the wind was so long that such waves were sometimes experienced. The long legs are partially filled with water to submerge part of the system. The large bin at the top contains feed that is released automatically. The bin holds several days' worth of feed.

The part of a freshwater cage that holds the culture animals may be made of hardware cloth, plastic-coated wire, plastic mesh or stretched nylon netting. The frame may be made of metal, wood (including bamboo) or rigid plastic including PVC pipe. Saltwater cages are typically much larger than their freshwater counterparts. The mesh material is usually some type of netting stretched over the cage frames. Happas are small cages with small mesh that are often used to hold small fish for a period of time before they are released into a pond for growout (Fig. 3.34).

In the harsh offshore environment, it is often desirable to submerge cages at all times, though in some cases cages are maintained at the surface most of the time and are submerged only when wave conditions warrant. In standard coastal net pens, large nylon mesh bags are suspended below the floating frames. The framework is provided with flotation devices to keep the upper part of the cage or net pen at or above the water surface. A walkway is provided so workers can go about their business. Predator nets of strong mesh that cannot be chewed through by toothy animals can be placed around cages to keep marine mammals from rending the nets that retain the fish.

Cages used in freshwater are usually small, ranging in volume from less than one to a few cubic metres. Freshwater cages have been used for the culture of channel catfish (*I. punctatus*), tilapia (*Oreochromis* and *Tilapia* spp.), carp (primarily common carp, *C. carpio*) and various other species. Marine cages, which range from a few cubic metres to up to thousands of cubic metres in volume, are being used in conjunction with research or

Fig. 3.28. A small ridge-framed cage.

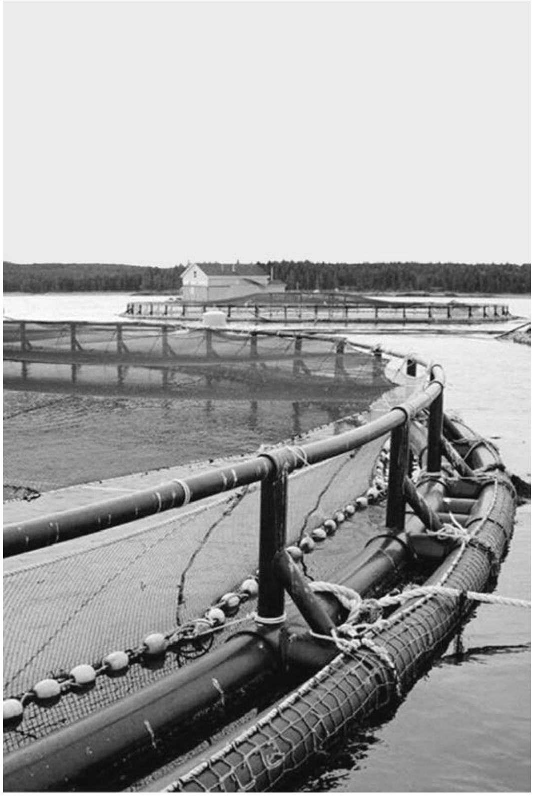

Fig. 3.29. A large Atlantic salmon net pen in Maine, USA.

commercial production of such species as Pacific threadfin or moi (*Polydactylus sexfilis*), red drum (*Sciaenops ocellatus*), red snapper (*Lutjanus campechanus*), European sea bass (*Dicentrarchus labrax*), sea bream (*Sparus aurata*, *Pagrus major*), yellowtail (*Seriola quinqueradiata*), striped bass (*Morone saxatilis*) and hybrid striped bass (*M. saxatilis* × *Morone chrysops*). The lists presented are not meant to be complete as many additional fishes have undoubtedly been produced in cages and net pens commercially or for research.

For cages at the surface, some type of flotation material needs to be provided. This may be in the form of blocks of Styrofoam®, some other type of

Box 3.12.

Feeding small ponds and small to relatively small cages (Figs 3.31 and 3.34) is usually done by hand, while large ponds are fed often using trucks or tractor trailers that are equipped with feed bins and blowers that distribute the feed over a major portion the pond surface. The feed is often stored in a silo bin (Fig. 3.32), or it may be poured into the bin by hand from 50 lb (22.7 kg) bags. Boats may also be used to feed cages in large ponds, reservoirs or lakes (Fig. 3.33).

Fig. 3.30. Net pen in Scotland with automated feeding system. The system is designed for operating in the open ocean.

foam material, sealed metal cans such as oil or grease drums, and various other appropriate items or materials. Cages may be anchored in place or, commonly, they may be tied to a dock that provides access to the culturist (Fig. 3.31).

The topics of feed types and feed manufacturing are discussed in some detail in Chapter 8 but, basically, most fish in production facilities are fed pelleted feeds. The pellets are of various sizes, depending on the species and life stage being fed. Because of the way they are manufactured, pellets may float or sink, and they may be dry and hard, or they can be moist, or semi-moist and soft. Floating pellets are most commonly fed to fish in floating cages. A feeding ring at the top of the cage may be used to contain the pellets while the fish rise to the surface to feed. An alternative to a feeding ring is a layer of small-mesh netting that can be placed around the upper several centimetres of the cage to keep floating feed from drifting out of the cage before the fish can consume the pellets. Having the feeding ring or mesh that contains the feed extend above the water line is important because feeding activity commonly involves a lot of splashing. In the absence of a barrier to prevent them from being ejected, the feed pellets may be carried from the cage due to the splashing. Sinking feed is used in offshore cages and in net pens as they are much wider and deeper than most freshwater cages so the pellets can often be consumed before they drift out of the pen, though settling feed pellets do escape, often through the bottoms of both cages and net pens.

As previously described, feeding systems have been developed for use in floating cages that involve a central feed storage bin and a computer-controlled distribution system of pipes through which dry pelleted feed is distributed by air pressure. It is common to feed salmon several times a day so such a feeding system greatly reduces the amount of labour involved in that activity, though, as we will see in Chapter 8, the aquaculturist should check to ensure that fish are feeding actively because if they go off feed it is a good sign that they have been stressed (due in most cases to water quality issues or the onset of disease). It is a good

Fig. 3.31. Cages, such as those shown in Japan, are often fed by hand.

Fig. 3.32. Trailers equipped with feed blowers are often used for feeding large ponds.

Fig. 3.33. A line of catfish cages, which are fed from a boat full of feed.

Fig. 3.34. Small cages (happas) stocked with young tilapia in a pond in the Philippines.

idea to observe the fish in each culture unit at least once daily when they are being fed. In many salmon cage and net pen operations one or more video cameras that monitor feeding activity on the surface and/or under the surface are placed in each culture unit. The individual cages or net pens can be monitored centrally. Feed is offered as long as the fish are actively feeding and discontinued when the fish are satiated, or the equipment can be programmed to introduce a specific weight of pellets at each feeding, with that amount being adjusted over time to meet the demands of the growing fish. Those adjustments would be largely based on previously obtained data and experience. The approach greatly reduces wasted feed and provides the culturist with the opportunity to more easily observe behaviours that may be indicative of disease. There is more on this later in this chapter and also in Chapter 8.

According to the Maine Aquaculture Innovation Center (www.maineaquaculture.org, accessed 10 December 2021), net pen culture began in the state of Maine, USA, in 1970. By 1992 there were about a dozen commercial salmon net pen facilities in the state of Washington, USA, and a similar number in Maine. In the meantime, the industry became dominated by Norway, and it is in that nation that modern net pen designs were developed. Net pen salmon culture has also been developed in Scotland, Chile, Japan, New Zealand and a few other nations. The industry in Chile grew rapidly beginning in the early 1990s, and Chile became the second largest commercial salmon-producing nation in the world by 2006, with Norway leading by a small margin. A disease hit the Chilean industry in 2007, which led to near collapse by 2009. New regulations and modifications in management practices, along with use of antibiotics, allowed recovery to begin in 2011. Norway produces Atlantic salmon exclusively, while Chile produces both Atlantic and Pacific salmon.

The use of cages in the marine environment is a commercial activity that is now a few decades old. With the move towards offshore culture, the scale of cage culture is likely to change dramatically. Visionaries in Japan have envisioned floating offshore cities that would produce part of the food needs of residents through the culture of marine organisms in large sea cages. There has been some research on cage culture in association with offshore oil and gas platforms in the Gulf of Mexico, but commercial operations have not been realized to date.

While the vast majority of the salmon cultured around the world are Atlantic salmon (*Salmo salar*), there is at least some net pen production of Pacific salmon species such as coho (*Oncorhynchus keta*) and chinook (*Oncorhynchus tshawytscha*) salmon in British Columbia, Canada. Pacific salmon are also grown in net pens in Japan. Rainbow trout (*Oncorhynchus mykiss*) are cultured in net pens in North America, Great Britain, Scandinavia and a number of other nations. Japan has used net pens for many years to rear red sea bream, yellowtail and other species. Sea bream and sea bass are sometimes cultured in cages in Europe. Net pens can also be used to grow flatfish such as Atlantic halibut (*H. hippoglossus*).

The number of net pens that can be accommodated by a particular site depends to a large extent on water circulation. If a site is well flushed, waste feed and faeces will be rapidly diluted and removed from the immediate vicinity of the cultured fish. In locations that are not well flushed, the wastes can accumulate at the bottom, leading to anaerobic sediments. Those accumulations can also lead to significant water quality problems in and around the net pens. The accumulation of wastes under and around net pens has led to a phenomenon known as self-pollution, which was a serious concern in Japan until limitations were placed on the number of net pens that could be established in the various bays where net pen culture is practised. The IMTA approach (discussed in the next section) appears to be a good way to mitigate the problem.

In Japan it is has been common practice to catch low-value fish (sometimes called trash fish) and grind them up as feed for fish in net pens. The low-value fish are captured and ground up daily and may be mixed with 10% or so of one or more dry ingredients such as soybean meal and supplemental vitamins. The material is fed to the caged fish within hours of preparation. Because of the nature of this type of diet, it breaks up quickly in the water and is not nearly as efficiently utilized as dry pellets, which usually remain intact in the water for at least several minutes. The result of trying to produce too many fish in a limited area will be water quality deterioration, so controlling the number of fish within each bay in which aquaculture is practised is critical. Similar problems can occur in protected waters where pelleted feed is used, but the carrying capacity of an area where wet feed is offered is undoubtedly reduced compared with the same area if dry pellets are used.

Integrated Multi-trophic Aquaculture

IMTA combines the culture of (most often) fish or shrimp in conjunction with organisms that obtain nutrients from the waste products generated by the primary culture species. Salmon cage and net pen culture are good examples. Seaweed grown outside salmon cages or net pens will remove dissolved nutrients from the water while one or more benthic species (typically molluscs) will feed on solids (waste feed, faeces). The approach is aimed at improving water quality, and thus can mitigate some stress on the salmon, reduce environmental impact (bioremediation) and improve the social acceptability of aquaculture. IMTA is not limited to marine aquaculture, but can be adapted to aquaculture in ponds, lakes and hydroponics by employing appropriate species at each of the various trophic levels.

Various Forms of Mollusc Culture

The technique for producing most molluscs generally involves growing them on a substrate in bays and estuaries as has been done for hundreds, or even thousands of years. In many cases, this approach is not much different from hunting and gathering. Various modifications have been made in terms of how molluscs are cultured, but in most cases, they involve open areas rather than the types of culture systems described earlier in this chapter. An exception to this would be in the hatchery production of various molluscan larvae which eventually are moved to production areas for growth to market size. Based on these different means of culturing molluscs, this section describes various ways in which several different molluscan species are cultured. A mollusc culturist can take the next step up in culture intensity by growing the animals off-bottom. That can be accomplished in a variety of ways depending on the species being reared and the location. Molluscs may be placed in bags, socks, lantern nets or attached to ropes and suspended from rafts, longlines at the water surface supported by floats, poles or some other structure. A method that was developed in one country and perhaps used for decades may not be found in any other nation. On the other hand, some methods have become widely adopted and modifications of them can be seen in various places around the world.

With the exception of providing food for larval molluscs produced in hatcheries, culturists rely solely on natural primary productivity to provide food for the molluscs once the animals have been stocked in nature. There is, to our knowledge, virtually no large-scale mollusc production in onshore confinement facilities (Box 3.13), with the exception of abalone in some cases. It is not practical to produce algae in an indoor or outdoor culture facility to feed molluscs stocked in the natural environment for growout.

Oysters

At its simplest, an oyster farmer might just go out to a natural oyster bed and do no more tending of the bed than removing predators such as oyster drills and starfish to reduce predation. While that activity would meet the broadest interpretation of the definition of aquaculture (semi-extensive culture), it might be more appropriate to call it oyster management. The next step up, which is also more management than actual farming, would be to enhance the natural environment in some way to make it more conducive for oyster growth. The simplest thing to do would be to spread oyster shell (cultch) at the bottom in a location where natural oyster beds are sparse or do not occur in order to provide substrate for oyster larvae (spat) to settle on, attach to and grow to harvest size (extensive culture). That approach has a long history in parts of Europe, Asia and the USA, among others.

Aquaculture scientists learned to spawn oysters in captivity during the last half of the 20th century. The late Winston Menzel, a professor at Florida State University, USA (and the major professor of R.R.S.), was one of those who made major breakthroughs in oyster spawning and larval rearing. In recent years, commercial oyster farmers in some places have begun spawning their own oysters. Large companies with oyster hatcheries can often produce enough spat to meet their own needs with enough left over to sell to other oyster culturists. Hatchery production provides an opportunity for selective breeding to improve the stock; for example, one objective might be to breed oysters for disease resistance. The hatchery personnel will typically grow the algae required to feed the spat and will then provide cultch material for the spat to settle on and attach to. The cultch will then be distributed on the oyster beds. Hatcheries are sometimes used in North America and elsewhere to produce cultchless oysters – oysters grown unattached to any cultch material, thereby producing single oysters rather than clumps. Cultchless oysters are often grown in trays off the bottom.

Oyster farmers who purchase their oysters from a hatchery may concentrate spat in baseball- or tennis-ball-sized packages (each of which will contain several million individuals) wrapped in fine-mesh netting. The spat can be sent by air freight virtually anywhere in the world packaged in that way. Alternatively, settled spat on oyster shell cultch and packaged in mesh bags may also be made available for shipment to nearby buyers (Box 3.14). Sending settled spat on oyster shell cultch long distances would greatly increase the cost to the buyer due to the amount of weight that would be involved.

Bottom culture is one of the many forms of oyster farming that is commonly seen. While spat collection in nature is widely practised, spat can be,

Box 3.13.

R.S.S. has seen molluscs stocked in ponds or channels associated with fish culture ponds to remove algae and other organic particulate matter from the pond effluent. Some research using that approach, for example, was conducted in Israel in conjunction with gilthead sea bream (*S. aurata*) culture several years ago. Other examples can undoubtedly be found if one looks hard enough.

Box 3.14.

We are not sure where it originated, but oyster spat and other types of invertebrate larvae, as well as the early life stages of finfish, are often referred to by aquaculturists as seed. Our objection to that characterization is that seeds come from plants, not animals. As a result, you will not see any mention of seed except as related to plants, and in most cases those instances will be associated with things such as cottonseed meal or other oilseed meals.

and are, produced in hatcheries as well, as previously described. One of the problems with bottom culture of oysters is predator control. Oyster drills (predatory snails) and starfish are major predators of oysters. There has also been a problem with burrowing or ghost shrimp in the Pacific Northwest of the USA (discussed under the section headed 'Pests and predators' later in this chapter).

Off-bottom culture of oysters is practised in many parts of the world. Rack and hanging-rope culture are common methods. Rack culture in France is a good example of the former method. The racks comprise metal horizontal pipes attached to the tops of other poles driven into the substrate. The horizontal pipes are placed in pairs to form trestles about 0.5 m above the bottom on which bags of spat are placed. As the oysters grow, they are thinned and spread out to additional racks.

Hanging-rope culture in Europe apparently originally involved cementing 1-year-old oysters individually to ropes suspended in the water column. Longline culture that involves suspending horizontal ropes between buoys or fixed structures to which the oysters are attached is also practised in Europe. Longline and raft culture are used in subtidal areas, while intertidal culture depends on naturally produced spat that attach to various types of substrates, including concrete, stone, wood and bamboo.

Cultchless oysters can be produced on trays suspended above the bottom. The spat may be collected on flexible sheets of metal or plastic from which they can be removed by bending the cultch material and popping loose the oysters when they are only a few millimetres long. The individual oysters can then be reared on trays or cemented to a rope or pole for growout. The result is nicely shaped oysters that enter the half-shell trade.

Before leaving the subject of oysters, the production of pearls deserves some attention. Pearls occur naturally in oysters, with the best-quality ones being from pearl oysters (*Pinctada* spp.). Some species of mussels from at least two families also produce pearls. In nature, pearls are found in oysters and mussels only occasionally, so techniques have been developed to encourage pearl production.

A pearl is formed by the laying down of many layers of mother-of-pearl (nacre) over a foreign body, such as a sand grain, that becomes lodged within the mantle cavity of the mollusc. It is speculated that the foreign body acts as an irritant, and because the mollusc cannot eliminate the foreign body, covering it with nacre is seen as a defence mechanism.

To produce cultured pearls, a small, polished round bead made from a piece of mussel shell (called a nucleus), along with a small piece of mussel mantle tissue, is inserted into the gonad of a pearl oyster. The mantle tissue apparently acts as a catalyst to get the oyster to lay down nacre on the nucleus. To develop a pearl in a mussel, only a piece of mantle tissue is required, and it is inserted into the mantle cavity of the host mussel. Pearls from oysters are perfectly spherical, while mussel pearls are irregular in shape. Various colours may be exhibited in pearls, both those from oysters and mussels. Pearls from oysters are most commonly white or cream-coloured but can also be black or some pastel shade. Mussel pearls range widely in colour.

Japan is perhaps the nation best known for cultured pearl production from oysters, but China is also a major pearl-oyster-producing nation. Those two countries are also major sources of cultured pearls from mussels.

Mussels

China is a leading nation in the production of mussels, while Spain – in particular the Galicia rias in the north-western part of that nation – is the centre of the industry in Europe. Rias are sunken river valleys, akin to the fjords of the Scandinavian countries. Spain began culturing mussels using pole culture methods similar to those described below for France, but now has focused on raft culture. The rafts are wooden structures from 100 to 500 m^2 anchored in place and kept afloat with various types of buoys. The mussels are grown on ropes suspended from the rafts. The rafts are placed where the water is about 11 m deep at low tide and the ropes are about 9 m long so that they do not come in contact with the substrate at any time during the tidal cycle. If the ropes were to make contact with the sediments, predators would be able to climb on to them and prey upon the mussels. A single raft may hold as many as 700 ropes, and the Galicia region supports thousands of rafts. Mussels are also grown on longlines from which individual socks or sleeves containing the animals are hung. That approach is one also used in Canada where it has been shown that the distance between socks affects production, as one might expect. The same is undoubtedly true of other forms of mussel (and other mollusc) culture techniques as well. The animals are filter-feeders, and there is only so much phytoplankton density present at any given time, so overstocking can deplete the food supply, thereby slowing mussel growth.

Small mussels are either allowed to attach by their byssal threads to the culture ropes in the growout area or are collected at a size of a few millimetres shell length at a distant location where heavy spatfall occurs and transported to the growout site. The small mussels are wrapped on to the ropes with rayon netting that will disintegrate within a few days. By then the small mussels will have attached to the ropes. The mussels are thinned after a few months and those that are removed are reattached to new ropes. Harvest is from October to March and is accomplished by lifting the ropes with a crane and placing them on a vessel where they are shaken to dislodge the mussels. Undersized mussels may be put back on ropes and returned to the raft for further growout. A single raft with 700 ropes suspended from it can produce as much as 60 tonnes of mussels per harvest.

The location of a rope under a raft in relation to other ropes has a bearing on mussel growth. This is also true of hanging culture of other molluscan species and for the location of fish culture cages in arrays as well. Mussels on ropes near the edge of the raft are exposed to better water quality and are the first to have an opportunity to filter out the food from the water column. In addition, mussels higher up in the water column will grow faster if light is limiting photosynthesis deeper down and if there is a drop in temperature with depth due to the establishment of a thermocline.

In France, Thailand and the Philippines, pole culture is a commonly used method for rearing mussels. In Thailand and the Philippines, 6–8 m long bamboo poles are driven into the sediment and ropes to which the mussels are attached are either attached to the poles or strung between poles in what is called a rope-web configuration. A modification of that approach is used in parts of the Mediterranean Sea where pairs of metal poles are used as uprights and a wooden horizontal pole is mounted between each pair of uprights. Ropes are then strung between the crossbars to create what is known as the hanging park system.

The French system is called bouchet culture. It involves suspending ropes horizontally between poles in natural spawning areas and allowing the mussel larvae to settle on and attach to the ropes by their byssal threads. The growout areas are some distance from the spawning area. In the culture area, poles made of oak are driven into the substrate. The poles are 4–7 m long and 12–25 cm in diameter. In the past, the ropes were fastened to the vertical poles for the entire growout period. However, today, after a few months on the ropes, the mussels are removed and placed in mesh tubes that are wrapped around the poles and nailed at each end to hold them in place. The mesh bags will disintegrate with time, but not before the mussels become attached to the wooden poles.

Scallops

China has assumed the leading role in the world in terms of scallop production, followed by Japan. In Japan, scallop spat are collected and placed in small mesh bags, where they are retained until reaching a size of 5–10 mm shell height. They are then transferred to larger mesh bags called pearl nets. Once they reach a length of about 5.5 cm, they may be hung by the ear of the hinge on a rope for suspension culture, placed in lantern nets or grown in baskets tied to a rope that is suspended from floats. Shell hinge hanging is the most labour-intensive as a hole needs to be drilled in one ear (the protrusions that can be found on each side of the hinge) of each scallop after which a string is threaded through the hinge and tied to the rope from which the scallop will be suspended. Scallops are strung one above the other along the length of the rope. All stages of growout are conducted on horizontal longlines that are kept near the surface of the water column with floats. The various types of nets and the ropes from which scallops are hung are suspended from the longlines.

In China, the early stages of scallop rearing also take place in net bags but, instead of longlines, the bags are suspended from rafts. Lantern nets are used to suspend the larger life stages from longlines as was described for Japan. Thinning is required prior to the time the scallops reach market size.

A small number of scallops were introduced to China from the USA in 1982. The species, which was not indigenous to China, now represents a significant portion of the scallops produced in that country, many of which find their way to US seafood markets as imports.

Clams

China dominates the world in the culture of clams. Malaysia, Taiwan, Korea, Italy and the USA also produce significant numbers of clams. Manila clams have been introduced from Asia to North America and northern Europe where hatcheries are now used to produce young clams. Following a nursery phase, the clams may be placed in nature in trays until they are 10 mm or so in shell length. The clams can then be put out on the bottom in the intertidal zone under a net, which keeps crabs and birds from preying upon them. The nets should be cleaned and checked for holes periodically. Any predators that do get under the nets should be removed. Most clam farmers use mechanical harvesters pulled behind tractors. In France, two layers of netting are used with the clams located between them so the net forms an envelope. Harvesting is facilitated because, when the nets are raised, the clams come up with them and can easily be collected.

Abalone

Abalone culture has been developed in a number of nations, including China, Taiwan, the Philippines, Japan, Korea, Australia, Chile, Canada (British Columbia) and the USA (California and Hawaii). Various methods have been used to spawn the separate sexes of abalone and to rear the larvae. Several methods are also used to grow the juveniles to market size. For example, in China some areas grow abalone suspended in cages from rafts, while in other areas abalone cages or other types of enclosures are placed in the intertidal zone. There is also tank culture on land. Abalone are herbivores and the juveniles need to be provided with seaweed, which may be cultured or harvested from nature.

The red abalone (*Haliotis rufescens*) was introduced to Chile in 1977, followed by the ezo abalone (*Haliotis discus hanna*i) five years later. Chile has since become a major abalone-producing nation with most of the production being attributed to the red abalone. Hatcheries and land-based growout occur in the northern part of Chile, with growout in the natural environment dominating in the southern part of the country. Algae are the primary foods used, though prepared feeds have been developed and are used, particularly in land-based growout operations.

Geoducks

Recall that the correct pronunciation of geoduck is 'gooey duck'. The information presented here relates to *Panopea abrupta*, the geoduck that is found along the west coast of North America and fished commercially in British Columbia, Canada and in Washington, USA. Geoducks were first produced in hatcheries by the state of Washington for enhancement stocking in intertidal areas in 1991. Once the hatchery technology was developed, commercial hatcheries and production of geoducks began in British Columbia and the state of Washington, USA, later in that decade. There is also some hatchery production in Oregon, USA, and other nations have become involved with geoduck research and/or production.

Geoducks reproduce in the spring. Female geoducks are multiple spawners that typically release one to two million eggs at a time, though larger numbers have been reported. The planktonic larvae settle after 2–7 weeks in the water column. They remain at the sediment surface for several weeks until their siphons develop, after which they burrow into the sediments. The sedentary adult form of the geoduck can live for up to at least 160–170 years. Adulthood is reached after 3 years at a weight of about 0.7 kg. The largest geoduck ever found so far weighed 3.7 kg. Adults bury 60–90 cm deep, with their siphons at the sediment surface. The siphon, resembling an elephant's trunk, can be retracted somewhat, but cannot be entirely pulled into the shell.

After the adults in the hatchery have spawned and the larvae have settled, they are maintained in tanks or ponds for at least a year before being planted in intertidal sand flats. Two methods of growout are commonly practised. One involves driving approximately 30 cm long pieces of 10 cm diameter PVC pipe into the substrate, with a few centimetres protruding above the surface, and adding three or four geoducks, each of which is about 10 mm in size. The pipes can be spaced 30–40 cm apart and are removed after 2 years. The second method is to plant 25 mm geoducks directly into the sediment. Mechanical planting devices have been developed for that purpose. The direct planting method is used where currents would cause PVC pipes to be displaced. Once the geoducks are stocked in nature, no feeding is required, as the animals will filter naturally occurring phytoplankton.

Growout requires up to 6 years. Harvesting can be done by hand digging but that is time-consuming and labour-intensive. The preferred method is to wash the geoducks from the sediments. Gasoline-powered water pumps are used in conjunction with a handheld water jet inserted into the sediment next to the geoduck siphon. The jet of water fluidizes the sand, allowing extraction of each geoduck. Spotting geoducks is easy. Just look for the tip of the siphon at the sand surface.

Seaweed Culture: The Nori Example

A previous section was devoted to algae culture. That section involved primarily single-celled species. This section looks at macroalgae (seaweed) culture which takes place in the marine environment. Multiple varieties of seaweeds are produced by aquaculturists around the world (see Table 1.1). Brown, red and green algae are all grown. Seafood markets in Japan feature a wide array of seaweeds for human consumption (Fig. 3.35).

Nori (*Porphyra* spp.) is extensively cultured in Japan. Ariake Bay in southern Japan, for example, is dedicated to nori rearing. The algae produce spores (called conchospores) that are derived from what is known as the conchocelis phase of the nori reproductive cycle. One method of culture is to allow conchospores from adult plants to attach to nets in static raceways in indoor facilities (Fig. 3.36). The conchospore-covered nets are then taken to the bay for growout.

To prepare the bay for receipt of the nets, thousands of long poles are driven into the sediments (Fig. 3.37). The nets are fitted with rings in the corners and at intervals along their sides, and the poles are spaced so that each ring will fit over a pole in a manner that will keep the net flat at or just below the water surface. Initially, several nets are stacked on top of one another, but as the nori grows the nets are spread out so that eventually there is only one net in each location. Figure 3.38 is a view of some nets shortly after they were placed in the bay. The nets are washed periodically to remove fouling organisms (Fig. 3.39). Having the nets stacked during the early phases of nori growth makes the washing process go much more quickly than later on when the nets have been separated. When the nori plants are about 15 cm long, the first cutting is taken. The nets are left in place until a second cutting is obtained once the plants grow back to the 15 cm harvest length. The original nets are removed after the second cutting and new spore-covered nets that had been kept in cold storage are used to replace them. Using the process described above, four cuttings per year are obtained.

Biofloc Systems

Biofloc technology as a concept has been around for a few decades and has been adopted by some

Fig. 3.35. A typical fish market in Japan features a variety of fish, invertebrates and macroalgae.

Fig. 3.36. Nori nets are placed in static raceways (shown dry here) where nori fronds shed spores that attach to the nets.

Fig. 3.37. Thousands of poles in Ariaki Bay are spaced to hold nori nets when they are moved from the raceways to the bay.

Fig. 3.38. Close-up of nets showing one of the rings of the poles that allow the nets to remain just below the water surface as the water level changes with the tides.

Fig. 3.39. Workers washing nori nets to remove fouling organisms.

aquaculturists located in North and South America, Europe, Asia and Australia, primarily for the production of shrimp and tilapia. The technology has been employed in plastic-lined ponds and indoor closed systems. In outdoor pond biofloc systems, plastic liners have been found to reduce disease problems. The technology involves producing aggregates of bacteria, fungi, algae and other microorganisms in conjunction with organic particles (faeces and feed particles) in a culture system to produce particles upon which the culture species can feed. Bioflocs dominated by heterotrophic bacteria typically are produced through addition of carbon in the form of soluble carbohydrates along with strong agitation of the water. Nitrifying bacteria in the biofloc convert ammonia released by the culture species to nitrite, which is converted to nontoxic nitrate as previously discussed.

Biofloc systems for marine shrimp were adopted primarily for biosecurity after the appearance and spread of several diseases occurred in the 1990s. Such systems can lead to better growth and reduction in the requirement for prepared feeds. In closed systems there are also the advantages of reduced water requirement, year-round production, maintenance of good water quality and very high density of culture animals. Disadvantages are the threat of total loss of the culture species in the event of a power failure and the complexity of developing and maintaining the biofloc (requiring a specially trained staff).

Dr Tzachi Samocha was with the Texas AgriLife Research Mariculture Laboratory in Flour Bluff, Texas, USA, for several years, and conducted research on the use of biofloc with respect to the Pacific white shrimp, *Litopenaeus vannamei*. The water in the system is anything but clear due to the biofloc, but the quality of the water is more than suitable for rapid shrimp growth (Fig. 3.40).

Some Challenges, Particularly for Mariculturists

Management of any aquaculture system presents a number of challenges, but marine systems are somewhat more difficult to manage than their freshwater counterparts. Having an available source of freshwater is important in some situations, fouling can be a significant problem, and corrosion is often an issue.

A source of freshwater is important in conjunction with saltwater facilities, particularly those that are static in nature (most ponds), which draw upon ocean salinity or hypersaline sources of incoming water or are of the closed recirculating type. There are also instances where growth of euryhaline species is accelerated when salinity is reduced or where some protection against predators or disease organisms that cannot tolerate low salinities is provided.

The most common need for freshwater is to provide dilution when the salinity becomes too high in a static saltwater pond or closed recirculating system. As we have seen, one source of water loss from ponds is through evaporation. When saltwater evaporates, it leaves the salt behind, thereby causing an increase in salinity. Adding seawater of the same salinity as that which was used to fill the

Fig. 3.40. Biofloc raceway. (Photo courtesy of Tzachi Samocha.)

pond will reduce the salinity to some extent, but because the amount of salt left behind from the water that evaporated is still present, the final salinity will be higher after additional saltwater is added than when the pond was filled (Box 3.15). As the process is repeated a number of times, the salinity may eventually become high enough to adversely affect the performance or even compromise the survival of the culture species. To deal with the problem, replacement water of low salinity – preferably freshwater – needs to be available in sufficient quantity to deal with the problem. Evaporation will also occur in closed recirculating systems, so the situation in the marine systems of the closed variety is the same as that in ponds, though the rate of evaporation may be less, particularly if the system is inside a building.

The brown mussel (*Perna perna*) is among the species of interest to aquaculturists. It is a large mussel native to Africa, Europe and South America. Brown mussels were introduced to the USA in 1990, probably through ballast water, and were first found at Corpus Christi, Texas. It is an invasive species that has been known to develop populations of such weight that they can sink navigation buoys. They are edible, which could be of some interest to culturists; however, one of the negatives of their use is that they would colonize pipes, cages and other culture system components. To date, brown mussels don't appear to have become a major issue in aquaculture, unlike the freshwater invasive zebra mussel (*Dreissena polymorpha*), which has caused significant problems in the USA with respect to displacing native mussels, clogging intake pipes to water treatment and industrial plants, growing on aquatic plants and various other surfaces, and being transported from one place to another on recreational fishing boats. Such invasive and harmful species, whether edible or not, should not be cultured as the negatives greatly outweigh the positives, particularly the potential of aquaculture of those species to exacerbate the environmental problems they create.

We haven't had any experience with zebra mussel fouling, thankfully, but while R.R.S. managed the Aquaculture Research Center (now the Aquacultural Research and Teaching Facility) at Texas A&M University in the late 1970s and early 1980s we had a flow-through raceway system fed by surface water from a reservoir. We learned the hard way that the incoming water contained freshwater bryozoans and sponges. When those animals colonized the inflow pipelines, they clogged the pipes to a considerable degree, thereby reducing water flow. As the invaders grew, they also depleted the oxygen in the incoming water and ultimately died and decayed in the pipes, leading to the production of toxic hydrogen sulfide gas. That problem only occurred during the summer (and for one year); whereas, in the marine environment, fouling can be, and often is, a yearly problem. Also, there are many more types of fouling organisms in the marine environment than are encountered in freshwater systems. Sponges, bryozoans, tunicates, sea anemones, mussels, oysters and barnacles are among the fouling organisms that are commonly seen in marine systems. They have been known to block the flow of water through cages completely or nearly completely within a few weeks after the cages are placed in the water and, like the freshwater fouling organisms previously mentioned, marine fouling can be a major problem in conjunction with plumbing. The problem is particularly severe in low-temperate, subtropical and tropical waters, and is exacerbated when there is a high level of primary productivity upon which many of the fouling organisms feed. Frequent cleaning of culture units and pipes is required when fouling occurs. The problem is not common when municipal or well water is used, or if water from surface sources is properly filtered and/or sterilized. Colonization of culture tanks by algae is possible in any water system when there is sufficient light to support those organisms.

Box 3.15.

Salinity is discussed in some detail in Chapter 4, but since a specific salinity level is mentioned in the paragraph that refers to Box 3.15, some explanation is needed for readers who may not know how salinity is measured. Traditionally, salinity has been presented in parts per thousand, which is abbreviated ppt or ‰. A part per thousand is one-tenth of a per cent (%), so seawater with a salinity of 35 ppt would have a salt content of 3.5%. However, oceanographers are now indicating that salinity is a unitless number, so 35 ppt becomes merely 35. The situation with respect to whether salinity can be expressed with a unit or is unitless doesn't appear to be settled, so in this book we have opted to keep it as a measurement with some sort of unit (i.e. ppt).

With respect to small cages, the culture animals can be moved from a fouled cage to a clean one, after which the fouled cage can be removed from the water to allow the fouling organisms to be scrubbed from the cage with a stiff bristle brush. For larger cages and net pens, it may be necessary to have scuba divers scrub the mesh while the cages and net pens are in the water. A silicone-based compound (Netminder®) has been developed that is said to reduce the ability of fouling organisms to attach to the mesh of net pens. Cleaner fish such as wrasses (family Labridae) have been used in some cases to reduce fouling.

Closed cages that can be rotated every few days have been stocked with the idea of reducing the fouling problem. Rotation exposes one side of the cage to the atmosphere, allowing desiccation to kill any fouling organisms that are present. Once the organisms are no longer alive, they can be scrubbed off the cage after which it is rotated to expose another fouled side. If the fouling is not too severe and the proper rotation schedule is maintained, it should be possible, with a minimal amount of cleaning, to keep the cage mesh from becoming clogged. Automatic cleaning equipment and the use of existing chemicals, as well as further development of compounds that discourage the attachment of fouling organisms to cage and net pen mesh, may reduce the need for divers at some point in the future. That may be a good use for the development of specialist robots. However, divers are also needed to repair any tears that are found in the mesh of cages and net pens. They are also often required during harvesting, so the need for their services is not going to disappear.

Net pen operators may maintain a second set of nets that can be placed over the nets that are first in use when those nets become fouled. The fouled nets can then be removed without letting fish escape. The removed nets can then be dried, cleaned and used again when the replacement nets become fouled. Antifouling chemicals have been used to coat nets and, in the case of tributyl tin, have been incorporated into paint used for net pen support structures. Antifouling agents may be directly toxic to the culture animals or may be taken up and deposited in their flesh, after which they could enter the human food chain. Therefore, such chemicals are not recommended for use in conjunction with aquaculture facilities and, in fact, are banned from use in some countries.

Shore-side marine aquaculture facilities should be constructed with paired inflow pipelines. One of the pair is used to bring water into the facility while the other is filled with freshwater to kill fouling organisms. When the pipeline in use becomes fouled, it is filled with freshwater and the second pipeline is flushed out to eliminate the dead fouling organisms as well as the freshwater before being put into use to supply saltwater to the facility. Once the fouling rate is known, the switching interval between one pipeline and the other can be put on a set schedule that leads to changeover before the problem becomes so severe that water quality or flow rate is significantly altered. Having a fine screen over the seaward end of the intake line will eliminate many fouling organisms, but their planktonic stages will be able to get through, so secondary filtration will be needed to avoid fouling of raceways. That does not eliminate the problem in the pipeline that runs from the intake screen to the filter.

In cases where a dual inflow system has not been installed, it is still possible to deal with fouling organisms. This can be accomplished by forcing a solid object through the pipe with a diameter slightly smaller than that of the interior of the pipe to clean off the fouling organisms. Objects used to clean pipes are known as pigs. Pigs of various sizes are shown in Fig. 3.41. Pigs also come in handy for cleaning pipes in dual systems.

Metal should be avoided in association with saltwater systems because of the corrosion issue and the possibility of heavy metal toxicity, as

Fig. 3.41. A group of pigs of various sizes used to clear fouling organisms from pipes.

previously discussed. There are some exceptions. For example, galvanized metal is widely used in the framework and walkways of salmon net pen systems. Stainless steel is also found in various types of equipment, such as heat exchangers. Galvanized metal and stainless steel are fairly resistant to corrosion and can be made more so by painting them with epoxy paint. Any exposed metals, including net frames, tools and the walls of metal buildings, are subject to corrosion when exposed to saltwater. The water does not have to come directly in contact with the metal as aerosols containing corrosive salts will be in the atmosphere around marine facilities. Metal that does come in contact with saltwater should be rinsed in freshwater, dried and, if possible, stored away from potential interaction with salt-laden aerosols. The interior of metal buildings and such things as light fixtures and various types of equipment can be shielded from the sources of corrosion in various ways. Foam insulation has been used to cover the exposed metal in buildings; plastic plumbing should always be used instead of metal; generators and other equipment can be housed in separate rooms in a building to keep them away from the water in the culture rooms, or such equipment can be located in a storage building in conjunction with a saltwater pond facility. Light fixtures can be fitted with waterproof plastic covers.

We have seen that even a small amount of metal in a seawater recirculating system can cause problems. However, that issue is primarily a potential problem in recirculating systems. Metal pumps are appropriate for use in freshwater facilities and can be used to pump saltwater in raceway and pond systems where the levels of trace metals will not become concentrated enough to produce toxicity.

Personnel Considerations

Personnel needs vary with both the size of aquaculture operations and their complexity. Nearly anyone with any level of education can learn to rear fish like tilapia or invertebrates such as shrimp in ponds from juvenile to growout. Much of the world's production of many species is overseen by small-scale farmers who may tend one or a few ponds or a handful of cages in a lake or reservoir. A minimal amount of training is required for culture at the artisanal level so long as stocking densities are kept relatively low to avoid water quality problems. Similarly, methods for growing molluscs do not require a great deal of technical expertise, except for captive spawning and larval rearing, which are not activities with which the majority of artisanal aquaculturists would be involved.

Large pond systems and flow-through raceways are stocked at much higher levels, so some water quality monitoring is required, as is some engineering knowledge. The level of expertise that should be available on an aquaculture facility increases with culture system intensity, with closed biofloc systems being arguably the most sophisticated, though ocean net pen and cage culture have been adopting a great deal of modern technology in the past few years as well. Add a hatchery, and even more varied expertise is required. If the facility uses polyculture and hydroponics or aquaponics (the multi-trophic approach to aquaculture), even more skills and background knowledge will be needed.

At a large-scale intensive culture facility, it will be virtually impossible for one skilled individual and a number of unskilled labourers to keep the facility functioning at maximum capacity. Some of the disciplines required to conduct modern aquaculture were discussed in Chapter 1, and it should be clear that a cadre of people will be required to keep a major facility operating smoothly. While those who have an educational background in aquaculture at high school, undergraduate or graduate university level will often have some credentials in a variety of the involved disciplines, it is best to have a group of individuals working on the facility, each of whom brings a particular strength to the operation. An engineer can keep water systems functioning but should not be expected to know much about developing feed formulations. Similarly, a salmon hatchery operator might not have the experience required to dive into a net pen and repair a tear that has been found. Of course, a variety of skills can be honed and perfected over the course of time, and it is a good idea to have people sufficiently skilled in a variety of disciplines so they can provide backup when necessary. One of us (R.R.S.) saw that concept at work in Israel several years ago on a kibbutz where tilapia were being raised. The culturists rotated periodically from one job to another so they would become familiar with all aspects of the operation. That was a pond facility, so the activities were fairly straightforward and could be learned quickly, which is not always the case with respect to other types of systems.

In the final analysis, the level of education required to be a successful aquaculturist depends upon the nature of the facility, though the culture species is also a consideration. In most cases, large facilities will have a few people with a high level of training and a number of skilled labourers who are responsible for most of the day-to-day activities (feeding, collecting water samples for determining water quality, checking for potential signs of disease, mowing grass in conjunction with pond facilities, being engaged in carpentry or plumbing, harvesting, assisting in the hatchery and a variety of other tasks). While the level of education may vary significantly, each person is critical to the success of the operation and the contributions made by each should never be discounted.

Other Issues

Before leaving the general topic of water systems and turning to water quality, a couple of other issues need to be addressed. Those are disposal of effluents from water systems and the important topic of pests and predators.

Effluent disposal

Whether a water system is static or flowing, at some point the water will need to be totally removed from the system – the obvious exceptions being culture systems in large bodies of water like cages and net pens in lakes, reservoirs or the ocean, and installations such as mollusc farms in subtidal areas. In many cases, when draining of a facility happens it will be necessary to dispose of that water in an environmentally responsible manner. Regulations on water disposal vary greatly from nation to nation and even in different jurisdictions within nations. There are also variations with respect to water system type. For example, an open ocean cage system may be exposed to currents that rapidly remove and distribute fish wastes and unconsumed food without measurably affecting local water quality. In that type of operation, there may be little or no regulation imposed other than periodic water quality monitoring to ensure that the situation does not deteriorate. Constant releases of water from a raceway system and intermittent releases from ponds or recirculating systems may, on the other hand, be carefully monitored and highly regulated, particularly if the effluent enters public waters such as a bay, estuary, stream, lake or reservoir. If the effluent is used for irrigation, there is usually no need for pre-treatment before it is applied to crops.

In some cases, treatment of effluent water may be required. That can take the form of constructing and utilizing settling ponds, filtering the water mechanically, releasing it into a sanitary sewage system or passing it through a constructed wetland for treatment. One form of treatment that can be used to improve wastewater quality is chitosan, which is a chemical derived from chitin. Chitin makes up the exoskeleton or shell of crustaceans such as shrimp. Chitosan has been shown to reduce the levels of turbidity, chemical oxygen demand, and nutrients such as nitrogen and phosphorus in effluent water. It has also been found to remove some types of harmful bacteria.

Another method of treating effluent water involves membrane filtration. Membrane filtration is a pressure- or vacuum-driven separation process through which particulate matter larger than 1 μm is separated from the water by a membrane. Forms of membrane filtration include microfiltration, ultrafiltration, membrane cartridge filtration and reverse osmosis. Research has indicated that membrane filtration coupled with chemical precipitation using magnesium chloride ($MgCl_2$) and alum ($KAl(SO_4)_2.12H_2O$) is effective in treating effluent from recirculating water systems.

Effluent water from saltwater pond systems or raceways can also be cleaned up by passing it through a culture unit stocked with molluscs (to filter out particulate matter) and/or seaweed (to reduce the levels of nutrients in the water). This can lead not only to improvement in effluent quality, but also to the production of valuable secondary crops.

If the water is used for irrigation as an alternative to flowing it into a surface water-receiving area, the nutrients in the effluent will help fertilize the land. Typically, aquaculture permits require no more than primary treatment (filtering the water or flowing it into settling ponds before release), though some regulators require secondary treatment (biological filtration such as passing the water through a sewage treatment plant that has a trickling filter or a lagoon system, or that uses the activated sludge process). Constructed wetlands are thought to be useful in settling solids, as well as eliminating nutrients, due to uptake by the plant community in the wetland. In rare situations, tertiary treatment may be required. That involves nutrient removal and can be a very expensive proposition, one that could eliminate the potential for profitability.

Pests and predators

If an unwanted organism is in the vicinity of an aquaculture facility, it is a safe bet that it will find its way into the culture units. There is such a thing as biosecurity, which means that you have taken every precaution to make sure the cultured species will not escape (though it can also be applied in conjunction with attempts to prevent the establishment of invasive disease organisms). Escape-proof facilities are required in some places when exotic species are being reared or when GMOs are being produced. One would think that biosecurity would work both ways; that is, if you can keep something in, perhaps you can keep other things out. That probably does work to a point, but unless you maintain a biohazard-type facility with air locks, highly filtered air and strict controls on who enters and what they are wearing (personnel may have to wear special clothing when in the facility, sanitize their footwear in iodine baths when moving from room to room and take other precautions to prevent contamination in addition to escapement), some types of unwanted organisms will probably find their way into the facility. Some of those are merely pests, but others can lead to significant losses through disease and predation. Even biofloc systems have sometimes become infested with pathogenic bacteria.

The use of surface waters for aquaculture provides excellent opportunities for unwanted species to enter a facility. Water from springs and wells is typically sterile as it leaves the ground and, unless it is stored in a reservoir prior to entering the aquaculture facility, water from those sources does not present a significant threat for introducing undesirable waterborne species into a culture system. Disease organisms such as viruses and bacteria, as well as many parasites, can be eliminated through sterilization of the water. As we have seen, ozone and UV light are methods suitable for application in aquaculture. In outdoor facilities, water sterilization is often not practical; nor will it be effective, as airborne pathogens can still enter the system and become established. A combination of ozonation followed by UV irradiation has been used effectively in some facilities. Maintaining an environment for the culture animals that is not stressful is the best course of action to avoid disease and parasite problems. This is discussed in more detail in Chapter 5.

Small organisms can survive passage through pumps and the associated plumbing to enter ponds and other types of culture chambers. Unwanted fish and invertebrates entering a culture system with incoming water can have a significant impact on production by preying on the culture species, competing for food and impacting water quality. Because it is not often possible to selectively remove such species, filtration of the incoming water is often employed. This can be done by passing the water over a fine-mesh screen or through fine-mesh netting. Screens and netting should be cleaned frequently because they tend to become clogged quickly, resulting in significant reduction or cessation of water flow.

Net pens and cages will frequently contain a number of species in addition to those that were initially stocked. Small finfish and invertebrates can enter cages and net pens through the openings in the netting, compete for feed and then grow too large to escape. If they grow large enough quickly enough, they may actually not only compete with, but could in some cases also prey upon, the culture species.

Marine mammals have been known to rend net pen netting, after which they may prey directly upon the culture species in addition to providing an avenue for escapement. Marine mammals are protected by law from being killed, harmed or even harassed by humans in the USA and various other nations. In the USA, it has been illegal to be in possession of bones or other collected body parts of marine mammals beginning sometime in the 1970s. Stiff fines and jail sentences can be imposed for violations. Predator nets, as previously mentioned, are typically used in areas where marine mammals are likely to interact with culture facilities. Such nets should not have the potential to entangle marine mammals.

Dolphins and whales are not the only mammalian predators a culturist might encounter. River otters, raccoons and other four-legged mammals have been found to prey upon aquaculture species. Muskrats and other mammals that burrow can cause pond levees to leak or even fail, though they might not be predatory on the aquatic animals in the pond.

Turtles and water snakes are common in freshwater culture ponds. Most turtles are harmless to people, though snapping turtles pose a definite threat. Many snakes that one finds in and around culture ponds are non-poisonous, though venomous snakes are common in some areas. One example is the cottonmouth water moccasin (*Agkistrodon* *piscivorus*) in parts of North America. Water snakes, such as the northern water snake (*Nerodia sipedon*) in North America, are common in aquaculture ponds. That snake will consume a variety of animals inhabiting the water, including fish. Water snakes are very aggressive and will give a human who attempts to handle them a nasty bite, though fortunately they are not venomous. A pond facility in the Philippines with which R.R.S. was involved (yes, it is the one mentioned elsewhere in this book) was constructed in an area that previously contained rice fields. The aquaculture pond facility was constructed with the objective of producing fish for rice–fish culture. During the time when the topsoil and vegetation were being removed prior to pond construction, the bulldozer operators reported killing at least a few pythons and a large number of Philippine cobras (*Naja philippinensis*). Fortunately, when R.R.S. was at the construction site, the snakes that had not been killed had found other habitats. Keeping pond levees mowed will help workers locate snakes before being bitten. Destroying turtles and snakes is permissible in most places. The culturist needs to determine if permits are required. Some species of both turtles and snakes will prey upon aquaculture species, so it is a good idea to control their numbers.

Aquatic insects such as dragonfly larvae can also take a toll on aquaculture organisms, particularly larval and early juvenile fishes. There are very few marine insects, but there are plenty of other predatory invertebrates as well as vertebrates to contend with in mariculture ponds and in conjunction with cages and net pens.

Burrowing shrimp, or ghost shrimp as they are often called, are natural inhabitants of coastal waters in many regions, and are normally not an issue for aquaculturists. They have caused significant problems for Manila clam and Pacific oyster farmers in the states of Washington and Oregon, USA. These soft-bodied shrimp (*Neotrypaea californiensis* and *Upogebia pugettensis* in this case), which have no commercial value, are found in very large numbers on the intertidal mudflats used for culturing molluscs in the two states. Their burrowing activity destabilizes the mud flats, leading to shellfish mortality because the molluscs sink into the mud and suffocate. The pesticide carbaryl (Sevin) has been used effectively in the past to control burrowing shrimp since they are highly sensitive to that compound. Sevin has been shown to have little or no long-term environmental impacts and its use by oyster farmers has been approved as part of an integrated pest management programme that involves monitoring of burrow density and allows pesticide application only when that density reaches a certain threshold of burrows per square metre. Sevin continues to be controversial as there can be collateral deaths induced in other species, such as the Dungeness crab (*Cancer magister*), with the larvae being more sensitive than the juveniles or adults of that species. The use of direct electrical current (DCP) on unstocked oyster beds has been shown to hold the possibility for ghost shrimp control, though once again unintended impacts on other species are of concern.

Wading birds can do significant damage in ponds and shallow tanks and raceways. Great blue herons (*Ardea herodia*) have been a source of predation in catfish ponds in the southern USA. There have been reports that a great blue heron takes an average of 12 catfish fingerlings (10 cm long) daily. That does not mean great blue herons restrict themselves to fish of that size. I (R.R.S.) have found catfish broodstock weighing as much as 4–5 kg floating in their pond with a hole through their bodies where a heron suffering from that age-old problem of its eyes being bigger than its stomach had attacked. Double-crested cormorants (*Phalacrocorax auritus*) have also been a significant problem for the catfish industry in the USA. Rapid growth of the industry in Mississippi appears to have led to the expansion of the wintering range of that bird in association with the expansion of prey availability as fish ponds have been constructed and stocked. On the other hand, cormorant populations have also increased in the state of Arkansas where catfish production levelled off many years ago but other species such as various bait minnows are produced.

Pelicans (*Pelecanus* spp.) invaded the trout-farming area of the north-western USA a few years ago and reportedly consumed a significant portion of the crop. Other birds considered problems on aquaculture facilities around the world include families of birds that encompass ibises, gulls, terns, kingfishers, hawks, eagles and grebes.

Most of the bird species that cause problems in the USA are protected under law from control by lethal means except under permit. Depredation permits have been granted to take such species as double-crested cormorants, great blue herons and some types of egrets. Local regulations should be consulted before lethal means are employed to reduce or eradicate birds around culture facilities.

Sometimes birds can actually be useful when they eat cultured fish. Should a fish kill occur, vultures and other carrion-consuming species, including eagles, can do a nice job of cleaning up the mess (Box 3.16). Fish farmers are not too interested in attracting birds for such tasks because the avians only serve as reminders about how much of the crop, and the potential profit, has been lost.

Not all birds suspected of preying on farmed fish lead to significant levels of mortality. It has been found that great crested grebes (*Podiceps cristatus*) in the Netherlands exert only marginal influence on fish mortality in culture ponds. The impact of black-crowned night heron (*Nycticorax nycticorax*) and little egret (*Egretta garzetta*) predation on common carp (*C. carpio*) and tilapia (*Oreochromis* spp.) farms in Israel showed that the presence of the birds actually contributed to improved growing conditions for the fish by, among other things, consuming uncontrolled fry production and eliminating diseased fish.

In addition to being predators, birds can also be vectors of various disease organisms. Such shrimp diseases as white spot syndrome virus (WSSV), taura syndrome virus (TSV), yellow head virus (YHV) and infectious hypodermal and haematopoietic necrosis virus (IHHNV) can be transmitted via seabird droppings.

Noise cannons have been widely employed to scare off birds, but they are generally ineffective after a few hours or days when the birds get used to the explosive sounds that are produced at intervals of a few minutes. Stringing wires over culture chambers, such as raceways and relatively small ponds, has worked well in some cases against birds such as cormorants which require a rather large landing area; and bird netting will work, though it can be expensive and is a bit of a nuisance to work around. Dogs trained to chase away birds from ponds, raceways and even net pen facilities are preferred by some culturists and appear to be quite effective. The dogs do not seem to tire of chasing birds.

Box 3.16.

R.R.S. discovered a fish kill in a small farm pond one morning due to oxygen depletion. The word soon got out to the turkey vultures in the area and by noon there were over 50 of them, along with a heron or two, scavenging around the edges of the pond. Within two days, all that remained were a few skeletons.

Human predators, or poachers, can also pose a significant threat. Some farmers hire watchmen to guard against poachers, but there is always the possibility that the watchmen will see how easy it is to obtain a meal and become the fox that guards the henhouse, so to speak. Hiring watchmen adds to the expense of operating an aquaculture facility, though having 24 h presence by one or more employees has the benefit of allowing water quality (in particular, DO levels) to be checked and ensuring equipment is operating efficiently in the absence of computer oversight. High fences and perimeter lighting can be used to dissuade poachers, but those are expensive alternatives and still require the presence of humans or dogs as a further deterrent. Many net pen and cage culture sites, as well as pond systems, are not manned 24 h a day and are subject to poaching and vandalism. The poacher of a cage or net pen may damage the unit, providing fish beyond those that are stolen an opportunity to escape. Sometimes vandals rend nets and allow fish to escape for no apparent reason. Poachers at pond facilities may use hook and line or some other type of gear (seines, cast nets, luring the fish with feed, perhaps dynamite followed by dip nets) to capture their booty. Not having any relationship with poachers, at least as far as we know, our thoughts on their techniques are largely speculative. We would suggest that if they use dynamite, they should check that there are no watchmen or other personnel at the facility who might disrupt their activities, or who might call the authorities.

Angling in a net pen or culture pond is also often very productive for poachers. Dip nets provide a handy way to remove fish from raceways and there tend to be plenty of those nets lying around a culture facility. Poachers are generally not considered to be ruthless criminals, except by the aquaculturists who experience poaching. The threat of relatively insignificant punishment by the courts in many nations does not offer much by way of deterrence.

Summary

Aquaculture systems vary in intensity from basically a form of hunting and gathering, where only a minor amount of environmental manipulation by humans is involved (extensive aquaculture), to very intensive aquaculture systems in which virtually every aspect of the culture environment is controlled by the aquaculturist, often with assistance from computers. Culture systems can be established in both freshwater and saltwater. Most systems involve some rate of water exchange, which can range from natural currents in large freshwater bodies or the marine environment, to pumped water. Static or nearly static systems may be required in hatcheries, particularly in conjunction with the hatching and larval rearing of species that are particularly delicate at those life stages.

Finfish and shrimp can be grown to market size in ponds, raceways (circular and linear being the most common forms of raceways) that may or may not involve recirculation, cages or net pens. Many species of finfish and shrimp are produced in hatcheries that employ raceways for rearing the larvae to stocking size, though others are spawned and complete their early life histories in ponds. Shrimp are most commonly reared to market size in earthen ponds, though culture in biofloc systems has developed in recent years. Shrimp have also been cultured in polyculture systems.

Various methods are used for rearing molluscs. Oysters and clams are most commonly grown at the substrate in shallow water or intertidally. Pole culture, raft culture and longline culture are among the most common systems found around the world for mussels, while scallops are also often grown on longlines. Abalone are grown in cages intertidally or hung from rafts, and in some cases are produced in tanks on land.

Various approaches are used for seaweed culture. The nori example provided in this chapter involves allowing spores to settle on nets that are then placed in the environment for growout. The nets are spread out on, or just below, the water surface and held in place by poles so the nets can ride up and down with the tide.

Aquaculturists need to be particularly aware of the types of materials used for culture chambers and other parts of their facilities in order to keep corrosion to a minimum and reduce the possibility of trace metal toxicity, both of which can be significant problems in certain types of saltwater systems. Predation by various species of birds and mammals is a problem that needs to be dealt with effectively. Snakes can also be a problem, both for the culture species and, if poisonous, pose a threat to personnel. Poaching by humans can also be significant.

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4 Understanding and Maintaining Water Quality

The Range of Variables

Aquacultured animals perform best when they are not subjected to stressful environments. Part of the secret of controlling stress is found in maintaining good water quality. What is considered good water quality for one species may be inappropriate or even lethal to another, so a large amount of research has been conducted over the years to identify what the optimum water quality conditions are for a wide variety of individual species. This type of research will continue as additional new species are considered for commercial or hatchery/enhancement production. Small-scale aquaculturists are often innovators who try to culture a new species while much of the information on their water quality, nutritional and other aspects have not been studied in detail. Large-scale aquaculturists may have researchers on their staff who can conduct studies aimed at refining information on a variety of topics, with the intent in both cases being to provide a hospitable culture environment for the new species and thereby increase the chances of profitability with that species. Part of that process will require test marketing to determine if consumers will find the product acceptable if it is not already available from the wild or is not a species familiar to potential consumers.

One way to gain insight into the question of the tolerance a species has for water quality is to look at where, in nature, that species seems to perform best. Sometimes tolerance for a particular water quality variable is obvious. For example, a fish species that is only found in the open ocean, such as tuna (*Thunnus* spp.), cannot survive in low salinity, let alone freshwater systems; and most species that occur only in freshwater cannot tolerate full-strength seawater – exceptions are euryhaline species that can tolerate a wide range of salinity, perhaps even the ability to live in a salinity range from freshwater to hypersaline. Some species of tilapia and hybrid tilapia are examples. Optimum water quality conditions may change depending on the life cycle stage of the animal, so that aspect needs to be taken into consideration as well. An example is flatfish such as summer flounder (*Paralichthys dentatus*) that spawn at sea near the shore and migrate into estuaries as post-larvae. They ultimately penetrate upstream, in some cases into freshwater springs, and then move back to coastal bays and estuaries as advanced juveniles.

Water is home to literally hundreds of thousands of ions, elements and chemical compounds. Most people recognize that the elements sodium and chlorine (in the form of sodium and chloride ions, Na^+ and Cl^-) are the primary contributors in making the ocean salty. Those elements can also be found in most freshwaters, but at very low concentrations. But both freshwater and saltwater routinely contain a variety of other elements and ions, many of which are required for good health and performance of both plants and animals. Minerals in seawater are abundant and can be absorbed into marine animals when they drink the water. Freshwater animals obtain most of their required minerals from the food they ingest because the levels of required minerals in freshwater are very low, or even absent.

Well water can present the culturist with some interesting quality issues often not of much concern when other water sources are used. Well water can include significant levels of carbon dioxide (CO_2), iron in the reduced, ferrous form (Fe^{2+}) and/or hydrogen sulfide (H_2S). We have even seen ammonia in well water, though that is rare. As seen in Table 4.1, CO_2 and H_2S can reach toxic levels. When oxygen-depleted well water containing ferrous iron reaches the surface and is oxidized due to exposure to the atmosphere, it combines with hydroxyl ions (OH^-) to form ferric hydroxide ($Fe(OH)_3$), which precipitates. If the level of $Fe(OH)_3$

DOI: 10.1079/9781800621145.0004

Table 4.1. Desirable levels of various water quality parameters in aquaculture systems.

Parameter	Desirable level or range	Species type and example(s)
Temperature (°C)[a]	15–20	Coldwater (trout, salmon, halibut)
	20–25	Coolwater (walleye, zander)
	26–30	Warmwater (tilapia, channel catfish)
Dissolved oxygen (mg/l)	5.0	All species tend to thrive; below 3.0 is considered marginal for many species
pH	6.5–8.0	Freshwater fishes
	>7.5	Marine species, particularly molluscs
Ammonia (mg/l)	0.1–1.0[b]	Tolerance varies among species
Nitrite (mg/l)	<0.1	May be toxic at very low concentration
Nitrate (mg/l)	<50	Some species tolerate hundreds of mg/l
Salinity (ppt)	0–10	Most freshwater fishes
	0–35	Highly euryhaline species[d]
	30–40	Stenohaline marine species
Alkalinity (mg/l)	≥20[c]	Freshwater species
Hardness (mg/l)	≥20[c]	Freshwater species
CO_2 (mg/l)	0	Can range from 0 to ~50 mg/l in wells
H_2S (mg/l)	0	Can occur in well water
Iron (mg/l)	<5	Sometimes found in well water

[a]Survival temperature range may be much broader. The ranges shown promote good growth.
[b]Range is for total ammonia.
[c]Tolerance range is typically broad, but the minimum level should be maintained to support the carbonate–bicarbonate buffer system.
[d]Some species may tolerate much higher salinities (e.g. certain species or hybrid tilapia can tolerate as much or more than 100 ppt).

is sufficiently high, it can clog the gills of aquatic animals. The precipitate also settles on hard surfaces, such as pipes, and can for example cover white PVC with a coating that looks like rust. It may be necessary to filter the water to remove $Fe(OH)_3$. That can be done using sand filters. Aeration can be used to drive off CO_2 and H_2S, though not having them present in the first place is the most desirable way to avoid potential problems. In any case, the water from a new well needs to be checked for the presence of any of the chemicals mentioned and appropriate steps need to be taken if one or more of them are present at unacceptable levels.

Geothermal water can contain high levels of sulfides as well as unacceptable levels of trace metals. There are notable exceptions where geothermal water of very high quality and the required temperature can be flowed directly into culture chambers. In other cases, when you are bound and determined to use poor-quality geothermal water, it may be necessary to pass it through a heat exchanger that will elevate the temperature in adjacent culture units without contaminating them. The water in the culture chambers would obviously need to come from a different source, and the geothermal water would only be used as a source of increasing the temperature of the water in the culture system by passing it through heat exchangers.

Water also typically contains a wide variety of chemicals that are not required by the aquaculture species cultured in it. In many cases, those chemicals are toxic when present at sufficiently high concentrations. High levels of even required elements, such as copper (an element that is especially required by invertebrates as a component of their respiratory pigment), will produce toxicity. The situation with trace metals and other chemicals is compounded by the fact that some of those substances, when present individually at some levels, are not of concern; but, when present with other metals that would individually cause no problems, there may be an additive effect. On the other hand, sometimes when two or more chemicals are present at certain levels their potential for toxicity is diminished. In some cases, the ratio of the chemicals to one another is an important factor in whether there will be toxicity. The cadmium:zinc ratio is one example where the level of each individual element may be sublethal, while in combination there may be a synergistic effect that could lead to toxicity.

Petroleum and its various fractions or related substances (natural gas and gas hydrates, for example) are present in many places in the world's oceans as naturally occurring substances through seeps into the water from the sediments. It is commonly believed that all the oil found on beaches or forming slicks in the sea is from oil spills or blowouts associated with drilling operations. In fact, most of that oil is from natural seeps, not spills, though of course there are local notable exceptions such as the Gulf of Mexico oil spill in 2010 and a pipeline rupture leading to a significant spill off the coast of California, USA, in 2015. Petroleum is also the source of a myriad of organic chemicals that are used for everything from plastics to pesticides. Each of those compounds finds its way into the water where many of them can be absorbed and concentrated in the tissues of aquatic organisms, sometimes leading to direct toxicity. Alternatively, they may be passed up the food chain where their concentration increases from one trophic level to another through a process called biomagnification (Box 4.1). Microplastic contamination of the marine environment and its impact on various organisms have received much greater attention in recent years. Humans are the intended ultimate consumers with respect to the species that are the focus of this book, so it is important that toxic chemicals do not become concentrated in the flesh of the species that are being raised by aquaculturists. The problem is not only one of concern to consumers of aquaculture products but can also be an issue that occurs in nature, for example mercury in tuna.

The Minamata Bay mercury problem in Japan that led to serious human illness and death from methyl mercury poisoning of some 3000 people who consumed fish from the bay is a good example. Over a period of many years, starting in 1938, a manufacturing company dumped tonnes of mercury into the bay and large numbers of people were ultimately poisoned by methyl mercury that built up in their bodies – primarily in nervous tissue – through consumption of seafood captured from the bay.

Many public health authorities routinely monitor the water for toxic chemicals and distribute health alerts as necessary. Those alerts are not restricted to chemical contamination but are more commonly seen in conjunction with the presence of bacteria in the water or in shellfish that can be transmitted to humans. This is particularly an issue with oysters and other shellfish species in many locations at some times of the year, though not always annually in the same location. There are also instances of the occurrence of toxic algal blooms that may not kill shellfish that consume the algae but can sicken and even kill people who eat the shellfish. That problem can occur both in natural and cultured shellfish populations. Immunocompromised people need to be particularly careful. In addition, a significant percentage of people develop shellfish allergies that can be serious or even fatal.

Having a source of high-quality water should be, as previously indicated, a top priority for the aquaculturist. Not only does the culturist need water of high quality for the organisms being reared, but also to market products of the quality that consumers expect and demand.

How does one determine if the water is of acceptable quality for aquaculture? There are basically

Box 4.1.

A copepod may, for example, consume phytoplankton cells that contain a small amount of a compound such as a PCB. The zooplankton will, as a result, have a higher concentration of the PCB in its body than was in any single phytoplankton cell. A small fish consuming several PCB-containing copepods will further concentrate the chemical. If several of those contaminated fish are then eaten by even larger fish, the body burden in the latter will, once again, be higher than in any of the individual prey fish it consumed. This is a phenomenon called biomagnification. And so it goes, up the food chain, with the level of chemical deposited increasing at each step until a human consumes the top predator and, potentially, suffers the consequences. Health advisories often mention that certain tuna species should not be consumed by pregnant or nursing mothers, or children under a certain age, because of high mercury levels in the flesh. Some warnings about eating more than a specified amount of tuna at a specified period of time have also been promulgated. Tuna are top carnivores that obtain the mercury burden from the food they ingest, not from the water. The above information also applies to the multi-billion introduced salmon species in the Great Lakes of the USA. Severe limits on eating those fish have been developed. Recreational fishermen are encouraged to catch the fish but should severely limit consumption. The best approach might be to take a photo and release the fish!

three ways. The most thorough of the three is to run a complete chemical analysis of the water to screen it for both desirable and undesirable elements or compounds that may be present. Such a screening should, in some situations, include microbiological evaluation. That would certainly be worthwhile in the case of a proposed oyster culture facility in a bay that could be contaminated, and from surface waters that may be contaminated from pesticide or sewage runoff, for example. Routine monitoring of shellfish-growing areas for toxins and disease organisms that could be transferred to humans is recommended, particularly during certain times of year and prior to harvest.

While it is unreasonable to test for every possible chemical individually – that could include hundreds of thousands of chemical entities – sometimes more detailed analysis of certain chemicals may be warranted. As an example, tumours were found on various species of fish (particularly flatfish) in Puget Sound, Washington, USA, in the latter quarter or so of the 20th century. A vast array of organic compounds in the Sound were found, many of which could have been causative.

The second way to determine if the water is suitable for aquaculture is to take a sample of the water, place it in an aquarium or some other suitable container, and introduce a few individuals of the species you intend to rear. Provide aeration and allow the animals to remain in the water for a period of several days. If they survive and do not show signs of disease, the water can at least tentatively be considered safe. While such a bioassay test will not reveal the identity of any toxic compounds that might be present in such low concentrations that they would not elicit even a behavioural response, if there is a high level of mortality, you might be dealing with one or more chemicals that cause acute toxicity; that is, something that would kill at least some of the animals within a period of 96 h or less. You might also have put some highly stressed or diseased animals in the water and the deaths may have not been directly related to the presence of a toxic compound. Dissection and microbiological testing of the mortalities would certainly be warranted, followed by chemical testing of the water to verify the cause of the problem if no obvious disease problems are found.

The third approach is to determine if there are other aquaculturists in the area who use the same source of water that you intend to use and, if you find one or more, speak with them. Ask if they have had any unusual problems that might be related to the presence of contaminants in the water and, if they have water quality problems, determine how they are dealing with them. If there are no aquaculturists in the vicinity, information may be available from government agencies and well drillers. The third option would be a good place to start, because well drillers keep good records of water quality in various water tables and the variability within the region where the new facility is planned. If any red flags arise, you could follow up with appropriate chemical analyses and/or toxicity tests on live animals. Those data may also be available from the government agency that oversees water quality in the area.

Once it has been determined that the water can be used to support the life and health of the aquatic species of interest, there are a relatively small number of important water quality parameters that need to be routinely monitored. Some of them may require obtaining and analysing samples frequently, while others may need to be sampled only periodically (monthly, every few months or at even longer intervals when the levels have not changed appreciably over time). We will first look at water quality variables that should be monitored routinely and then discuss those that tend to be relatively stable over time.

Variables to Measure Frequently

There are nine variables (including three discussed below under the subheading of ‘Plant nutrients’) that should be measured routinely in most, if not all, water systems, though the frequency with which those measurements should be taken will vary to some extent. The variables which are influenced by biological activity are classified as non-conservative in nature; whereas those that are not influenced by biological activity are classified as conservative. At the beginning of most of the following subsections, there is a Box that provides an indication of which types of water systems require monitoring for the variable to be discussed. A summary of desirable levels or suitable ranges for various parameters was presented in Table 4.1. That information will vary in many instances depending on the species being cultured. Some indication of that variability is also provided in Table 4.1.

Temperature (Box 4.2)

The metabolic rate of poikilothermic (cold-blooded) aquatic animals and aquatic plants is controlled by

Box 4.2.

Temperature should be monitored routinely in all water systems whether the temperature changes seasonally or is maintained by heating or cooling the water. (If the source for heating or cooling the water should be disrupted, you would certainly want to know that.) For many systems, daily or even constant monitoring will provide useful information. Less frequent monitoring would be required when large volumes of constant-temperature water are flowed through raceways that have high rates of exchange. Ponds in tropical environments change only marginally in temperature seasonally, so it may not be necessary to monitor temperature daily in those systems.

water temperature. Each aquatic species has a temperature range within which growth is optimal so long as other conditions are appropriate and sufficient food of the proper quality is available. The optimal temperature range is generally only a few degrees wide. Water that is either warmer or colder than optimum leads to reduced growth, though most species are relatively eurythermal; that is, they can tolerate a relatively broad range of temperature and survive, but performance is negatively affected at temperatures outside the optimum range and disease or even death may occur as the range violation increases. For aquatic animals, there are warmwater, coldwater and mid-range species, as described in Chapter 1.

Many warmwater species, such as channel catfish (*Ictalurus punctatus*), can survive in freshwater that approaches freezing and will live at temperatures a few degrees above 30°C. However, channel catfish are classified as warmwater fish because their optimum temperature range for growth is from 26 to 30°C. Tilapia (*Oreochromis* spp.) have a similar optimum temperature range for growth, but they cannot tolerate even moderately low temperatures. Those very hardy fishes tend to be fairly disease resistant until the temperature drops to about 20°C, after which they begin to develop various disease problems and will typically die if the temperature drops below about 10–12°C. Trout and salmon, like catfish, can survive in very cold water, but begin to perform poorly when the water temperature approaches about 20°C. The temperature ranges given here are generally applicable, but there will be some variation among species.

You may be wondering 'how do fish survive in water bodies that freeze in the winter?' The fact is that unless the water freezes to the bottom of the water body, overwintering is not a problem for species that live in climates with harsh winters (it has been said that common carp (*Cyprinus carpio*) have even been known to survive after being frozen in ice, though we cannot confirm that). Freshwater has its highest density at 4°C, which is as cold as the water below the ice in a lake or pond gets. The fish may be lethargic, but survival for many species is not an issue. They certainly must eat or continue to strike at objects that appear to be food during the winter, or ice fishing would not be very popular or productive.

Because there is a strong relationship between water temperature and growth rate, there is also a linkage between temperature and the amount of feed that should be provided when prepared diets are fed (see Chapter 8). There is also a direct relationship between the abundance of natural food (primarily phytoplankton and zooplankton) and temperature, particularly in temperate regions. The species composition in the plankton communities will change seasonally and productivity may be quite high during periods when the temperature is out of the range for optimal growth of the cultured fish or shellfish species. Bloom cycles of the plankton communities are controlled not only by temperature, but also by nutrient availability (primarily nitrogen and phosphorus levels). Spring and autumn blooms are common in nature in association with rising or falling temperatures. As discussed in a later section of this chapter, the culturist can control plankton blooms to a large extent through fertilization of the water.

Higher aquatic plants (macrophytes) also grow in tune with water temperature, so the culturist who depends on such plants to feed his or her animals should use plants that grow best within the same temperature range as the culture animals. The problem with feeding macrophytes is that few aquaculture species will consume them, so they do not play a significant role in aquaculture except when grown as a primary or secondary vegetable crop in hydroponic, polyculture or IMTA systems. Grass carp (*Ctenopharyngodon idella*) are one of the few animals produced in aquaculture that directly consume aquatic macrophytes and even that species is selective in what it will eat.

Reproduction is another activity commonly controlled by water temperature (though other factors, such as photoperiod, trigger spawning in some species, particularly tropical species where temperature varies little during the year). Most temperate aquatic species spawn during a particular season of the year, so when those animals are spawned in a controlled hatchery environment, spawning time can often be manipulated by making the appropriate changes in temperature and/or light regime. Off-season or even year-round spawning can be achieved with some species (see Chapter 6). In many instances, the optimum temperature range for growth is quite different from the optimum temperature range for spawning. For example, many finfish species spawn in the spring or autumn but may grow most rapidly at summer water temperatures.

Temperature is one of the easiest variables to measure. The tried-and-true method is with a glass thermometer (mercury-in-glass or alcohol-in-glass), though electronic thermometers have been around for many years and are very precise; in fact, much more precise than is needed for routine measurements. Glass thermometers are easily and frequently broken. Given the concern about allowing mercury to enter the environment or cause direct poisoning of people through inhalation, mercury-in-glass thermometers are not used nearly as widely today as they were in the past. Such thermometers have even been banned for certain uses in some countries. In addition to alcohol, various other liquids have been used in thermometers by manufacturers as replacements for mercury.

Glass thermometers typically measure temperature to the nearest degree Celsius or Fahrenheit. That is generally sufficient for aquaculture purposes. Electronic thermometers, many of which are relatively inexpensive, often measure accurately to the nearest 0.1°C or even less. The aquaculturist may wish to adjust the feeding rate as the temperature falls or climbs out of the optimum range (see Chapter 8). Temperatures outside the optimum range, whether above or below, can act as stressors. When stressed, fish will not feed as actively as when in a non-stressful environment, so some of the feed will be wasted if the culturist continues to feed at the same rate when temperature is above or below the optimum range for growth. In culture systems where waste feed can accumulate, it will decay and place additional demand on the DO level in the water, which is the next variable discussed. Decaying feed can also support fungal and bacterial growth, and there have been instances under marine cage and net pen culture facilities where anoxic conditions have developed due to the accumulation of waste feed and faeces (see Chapter 3).

Temperature is often measured daily by aquaculturists. The time required to determine that variable is very short, so individual pond temperatures are easy to obtain. Electronic thermometers can be linked to recorders that produce a continuous record or they can be used in conjunction with computer programs that not only provide a continuous record but can show high, low and average temperatures over any time period you might want to examine. Recorders can produce graphs of the information and also monitor various other parameters at the same time.

In raceways, closed systems and cage or net pen systems, temperatures tend to be uniform in culture chambers that are in proximity to each another. In the case of closed systems, temperature should be similar among culture tanks unless there are temperature differentials within a greenhouse or other type of building that are related to the position of the various tanks relative to exposure to sunlight, as opposed to tanks lit only by artificial lights. If high-intensity lights are used, water in tanks directly under them could be warmer than those not directly exposed. Generally, that is not an issue, however. If the facility is heated with appropriate air conditioning, there may be differences in temperature among culture units related to their proximity to the source of the air conditioning unit. You might think of other reasons why one culture unit might vary in temperature from another. How about proximity to doors that might be opened and closed periodically or might even be kept open for relatively long periods of time? That could become important when the temperature outdoors is significantly warmer or colder than that in the culture building.

As with other water quality variables, temperature should be recorded for future reference every time a measurement is made (that information is even handier to obtain and store if it is taken automatically in conjunction with computerized systems). Each culture unit should have a numeric or alphanumeric designation so the temperature in each individual culture chamber where measurements are made will have its own record. In ponds, measurements may be taken at different depths. When that is the case, the depth should also be recorded. Most commonly, the temperatures in ponds would be recorded just below the surface and at the bottom of the water column.

Culture animals should not be exposed to rapid changes in temperature such as might occur during transfer from a hauling truck to a culture pond or when a pond is drained during harvesting in warm weather (Box 4.3) – whether the purpose is for redistribution of the animals to other ponds or for live-hauling to market. If the temperature differential between the two water sources is more than 2–3°C, the temperature should be adjusted gradually. This is a procedure known as tempering. Slowly exchanging water from the receiving water source with water in which the fish are being held is an effective way to achieve the desired result when the fish are in a hauling tank and going to be transferred into a pond or some other type of culture unit. Using pond water to fill the hauling tank and then running new water in the harvest basin to keep the shallow water in the basin from warming excessively during the harvest process is effective at eliminating or at least reducing the time needed for tempering during the harvest process. The rate of tempering should be no more than about 5°C/h.

Observation over the years has led us to the conclusion that fish are less stressed when being moved from a temperature higher or lower than their optimum temperature for growth towards the optimum range than when they are being moved from the optimum range to water that is warmer or colder than optimum. It stands to reason that fish outside their optimum range are already experiencing stress and that the stress level is reduced as they are tempered in the direction of the optimum range.

Box 4.3.

Even after repetitive seining while the water level is being reduced in a pond, there will be culture animals remaining when there is only a small amount of water left in the pond, even when there is a harvest basin. In other words, you never catch them all, even with repetitive seining. Those fish or shrimp can be picked up by hand or in dip nets. While that is occurring, the water temperature can rise quickly on a warm day, so the animals will often be exposed to quite a different temperature when they are placed in another pond or into a hauling tank on a truck. R.R.S.'s students once drained a tilapia pond and harvested all the fish we could see – many were found in the mud after the water was drained, even though we had pulled the seine several times. After completing the process, we showered and left the research farm for the day. The next morning, we checked the pond and found dozens of tilapia – still alive – that had apparently dug themselves out of the mud after we left the evening before. We washed them off and put them in a tank of water, after which they showed no ill effects from their night in the mud.

The water temperature, and thus the animals therein, may undergo rapid changes during the passage of cold fronts. Such fronts may alter the temperature so significantly that death can occur. The problem can be significant in pond culture systems, particularly in temperate regions. In some cases, temperature tolerance can be increased by changing the salinity of the culture water. One example is red drum (*Sciaenops ocellatus*), which, when being reared in freshwater, can tolerate temperatures colder than what would normally be lethal during the winter if the salinity of the water is increased by several parts per thousand.

Dissolved oxygen (Box 4.4)

The earth's atmosphere contains about 20% oxygen by volume or 200,000 parts per million (mg/l). Contrast that with the saturation level of oxygen in water, which is never above about 10 mg/l unless the water is supersaturated. In the case of supersaturation, a high level would still be no more than about 30 mg/l, which is still extremely low compared with the atmospheric level. As salinity (discussed below) increases, the oxygen-holding capacity of the water decreases, so seawater holds less oxygen at saturation than freshwater. The same is true with respect to temperature. Cold water will hold more oxygen at saturation than warm water.

The oxygen story

The amount of oxygen that can be dissolved in water at saturation depends on three primary factors.

Box 4.4.

DO needs to be maintained as near saturation as possible in all culture systems in which aquatic animals are being reared to avoid the imposition of stress. The culturist should attempt to maintain a DO level of no less than 5 mg/l at all times.

Two of those – temperature and salinity – were mentioned above. The third is altitude. As the level of each of the three variables increases, the amount of oxygen that the water can hold at saturation is reduced. Warm, salty water at high altitude would hold the least amount of oxygen at saturation, while cold, freshwater at sea level (or below sea level, which would be an unusual situation) would hold the most oxygen at saturation. Because aquatic animals are adapted to the normal oxygen concentrations in the waters they inhabit, they can perform well when the water is saturated, and will often perform well at levels somewhat below saturation, though there are definite lower limits.

In general, aquatic animals with gills – which includes nearly all the species cultured for human food – will survive and grow without apparent stress so long as the DO level is maintained at 5 mg/l or higher. That level can usually be found even in warm seawater. Hypersaline warm water may exhibit DO levels below 5 mg/l, however. At the other extreme, some high mountain lakes may have oxygen levels too low to support aquaculture organisms.

Oxygen can be measured in various ways. The first method, Winkler titration, has been around since the late 1800s and involves wet chemistry. A certain chemical is added to a water sample resulting in the development of a straw-yellow colour. A titration procedure is used to determine how many milligrams per litre of oxygen are in the water sample by adding another chemical until the yellow colour disappears. Tables are available to convert the amount of titrant used into the milligrams per litre of oxygen present in the sample. Portable test kits are available that use titrant, in at least one brand with which we are familiar, which translates each drop into 1 mg/l, so if five drops are used to effect the colour change, the sample DO content is 5 mg/l. That test is conducted on small water samples, while the standard Winkler titration uses biochemical oxygen demand (BOD) bottles (they contain a few hundred millilitres) and measures DO to within 0.1 mg/l. Most commercial aquaculturists are more interested in knowing whether the DO is 2 or 5 mg/l, not whether it is 4.9 or 5.0 mg/l. The Winkler titration method takes a few minutes per test and involves fragile glassware, plus there is the need to purchase chemicals periodically. For at least the past few decades electronic DO meters have been available, and their popularity has been such that they can now be obtained relatively inexpensively. Most are temperature-compensated, and thus measure temperature and DO. Some are also compensated for both temperature and salinity. DO meters not only have the advantage of making rapid measurements; many can be combined with recording devices or linked with computers so that long-term continuous monitoring can be accomplished. That type of monitoring can be very important as it will show daily cycles in DO level and can provide an indication to the culturist that a period of dangerously low oxygen may be approaching. The subject of oxygen depletions is discussed below.

While saturated DO is desirable and 5 mg/l is acceptable, most aquaculturists begin to worry when the DO level falls to about 3 mg/l. For salmonid culturists, that level may in fact be the cause for considerable concern as the DO level for salmon and trout should be at or above 5 mg/l at all times. Warmwater fishes tend to tolerate lower DO levels, so 3 mg/l appears to be the point where culturists of warmwater species begin to take remedial action.

Scientists who are studying hypoxic areas that occur naturally in various places around the world have decided that hypoxia exists when the DO level is <2.0 mg/l (Box 4.5). Therefore, taking steps to increase the DO level in an aquaculture system makes sense when the 3.0 mg/l threshold is reached, and the animals can be considered stressed or close to becoming stressed at that DO level.

There are some species or groups of aquaculture species that can withstand hypoxic conditions, sometimes for relatively long periods of time. When low-oxygen stress occurs, many fish species will appear to gulp at the surface. Shrimp have reportedly climbed grass stems to bring their gills into contact with the surface as well. The reason is that it is at the air–water interface that oxygen is transferred from the atmosphere into the water. The microlayer at that interface is always saturated, so when the fish surface they are trying to extract oxygen from that oxygen-rich microlayer. For most species, including shrimp, the technique should be considered a last-ditch effort to survive as the animals are severely stressed when they come to the surface and they are not efficient, with at least one exception (tilapia, *Oreochromis* spp.), at obtaining oxygen at the surface. Unless something is done immediately to increase the DO level in the water, mass mortality will typically be the result. We have seen tilapia survive, without subsequent negative impact on their health or growth, for at least a few hours when the DO concentration was 1 mg/l or

Box 4.5.

Seasonal hypoxia events are being reported in increasing numbers along the coasts of many nations, particularly in areas that receive high rates of freshwater inflow from river basins that contain large amounts of fertilized farmland. There are various theories about the reasons for hypoxia development. One of them places the blame on high nitrogen levels in the runoff water due to the contained nutrients from fertilizer applied in upstream areas, primarily from farmland. Another does not discount the involvement of nitrogen, but also associates the development of hypoxia with the presence of a freshwater lens over the top of the saltwater when the two waters are not mixed. Freshwater is less dense than saltwater, so it will tend to form a top layer when it enters the sea unless there is sufficient wind turbulence to mix the water column. The freshwater lens serves to block the diffusion of oxygen into the saltwater, so respiration by marine organisms can lead to depletion of the oxygen. Finfish and other motile species are usually able to move to areas with sufficient DO, but sessile invertebrates may be killed in large numbers due to the low-oxygen conditions. Hypoxic areas of several thousand square kilometres have formed in some places, usually in the summer, and may persist for several months when they do form. If the oxygen level drops to zero, the areas become what is known as anoxic.

less (also see Box 4.3). Few other cultured species have the same ability to effectively extract oxygen from the oxygen-rich microlayer. That does not mean other species cannot survive low-oxygen events. Walking catfish can utilize atmospheric oxygen, while oysters and other shellfish can close their valves and survive for extended periods (perhaps several days) in hypoxic waters. Intertidal species are also able to survive out of the water during low tide using the same technique.

Because of their design and operational characteristics, fluctuations in DO from hour to hour or day to day tend to be small, if they occur at all, in flow-through raceway systems with rapid exchange rates. In warmwater raceways with relatively slow flow rates and in recirculating water systems, aeration is usually required. Agitators, blowers, air compressors, bottled air or oxygen, and liquid oxygen tanks are among the types of apparatus that are commonly or sometimes used by aquaculturists.

Other systems are also susceptible to low DO under some circumstances. While DO problems are not very common in cage and net pen systems, there are exceptions in the cases of cage culture in ponds or other small water bodies where hypoxic conditions can develop. DO problems can also occur in coastal marine systems, for example, if the culture site is in a region that is susceptible to hypoxia (as described in Box 4.5). Quiescent coastal areas, particularly shallow ones, that have very limited tidal exchange may experience declines in DO as well (Box 4.6). Open ocean systems and well-flushed coastal areas are unlikely to experience significant fluctuations in DO level except when significant temperature changes occur. In any case, ponds remain an excellent example of temporal DO dynamics, so that is where we will focus our attention.

Box 4.6.

Tidal range varies from place to place around the world. It can be virtually zero. Such places (the island of Puerto Rico in the Caribbean is one of them) are known as amphidromic points. At the other extreme are places where the tidal range can be several metres. The Bay of Fundy in eastern Canada has the highest tidal range on earth, about 15 m. Tidal range varies from day to day depending upon the phase of the moon, with the highest ranges occurring during new and full moons (spring tides) and the lowest during the first and third quarters of the moon (neap tides).

Supplemental oxygen is not usually provided in cage, net pen or hanging culture situations. An exception would be cages in ponds, in which case the same approach described for open pond aeration would apply.

Oxygen in ponds

Oxygen enters the water from the atmosphere through a process called diffusion. The water surface acts as a semipermeable membrane and the oxygen will move from the region of higher concentration (the atmosphere) across the membrane (the water surface) to the region of lower concentration (the water). The process is expedited, and the oxygen becomes distributed through the water column more rapidly, when there is wind blowing across the water so that the water is mixed with the atmosphere. When pond water is mixed by wind, it basically moves in a circular pattern from surface to bottom and back up. If we were to follow a parcel of water, it would become saturated at the surface and then move down where respiration would reduce the oxygen level in the parcel as it moved along the bottom to the opposite end of the pond where it would rise with the current. When the parcel reached the surface again, it would become saturated again. The wind stirs up waves and creates currents that both increase the amount of water surface that is in contact with the air at any instant and help mix the oxygenated water throughout the pond.

There is a second process by which oxygen is dissolved in water. That process is photosynthesis. In the presence of light and chlorophyll, plants convert CO_2 and water into sugar and molecular oxygen.

The photosynthetic reaction continues throughout the daylight hours. Photosynthesis can also be promoted under artificial lights of the proper wavelength but installing the appropriate lighting system over a pond facility is not something that we have seen. In most cases, the primary source of photosynthetic oxygen in a pond is the phytoplankton community. Rooted aquatic plants are also sources of pond oxygen, but in most cases aquaculturists try to avoid having such plants established in their ponds.

As a result of photosynthesis, the DO level in a pond will begin to increase not too long after sunrise and may continue to rise throughout much of the day before the photosynthesis rate declines as the afternoon progresses. Photosynthesis stops shortly before sunset. The rate of increase will be highest when the sun is high in the sky and less when the sun is at an acute angle to the pond because light penetrates deeper when it shines directly on the water from above. Overcast conditions (and associated precipitation) interfere with photosynthesis.

All aerobic (oxygen-dependent) species of plants, animals and microorganisms consume oxygen through respiration, which involves combining the sugar glucose ($C_6H_{12}O_6$) with oxygen to produce energy for metabolism. The by-products of that process are CO_2 and water.

Respiration is continuous both day and night. If there is a well-established phytoplankton community in the pond, daytime photosynthetic production of oxygen by that community, in conjunction with diffusion from the atmosphere, will add oxygen to the water more rapidly than it is being removed through respiration. At night, on other hand, all the aerobic organisms will continue to respire in the absence of photosynthesis and the only source of additional oxygen will be from diffusion. The result is that the DO level will normally increase during the daytime and decrease at night.

In most cases, the culturist can expect the DO to be within the acceptable range for the culture animals throughout the night, but there are often instances when DO can fall to critically low levels. That will often occur after a period of cloudy weather that limits the amount of light reaching the phytoplankton community and when there has been little or no wind to help mix atmospheric oxygen into the water. Cloud cover will typically reduce, but not eliminate, photosynthesis and while DO will rise during the day, the increase will be less on day 2 than on day 1, less on day 3 than on day 2, and so forth, if the cloud cover persists and wind mixing continues to be insignificant. After several days of such a pattern, the early-morning DO levels may fall to ≤3.0 mg/l. It is at that point that warmwater pond culturists typically develop a concern that the animals are under stress. Should the cloudy conditions continue to persist in the absence of a strong wind, the pond DO level could become critically low, leading to mass mortality.

A second cause of a declining pattern in minimum daily DO would be collapse of the phytoplankton bloom, which would severely limit photosynthetic oxygen production and add to the BOD as the phytoplankton decay. That result can occur because of a lack of sufficient nutrients to maintain the bloom but can also be associated with the cloudy weather that reduces the amount of light penetration and the lack of proper mixing of the water, which in turn limits the exposure of individual cells to the light if they are not periodically brought into the photic zone. Phytoplankton that are no longer in the photic zone will die, and their decomposition will compound the problem of declining photosynthetic oxygen production.

These problems occur most commonly during the summer and early autumn when primary and secondary productivities are at their highest levels. The culturist should, at least during those portions of the year, monitor DO daily during the predawn hours at a minimum. Usually, it is just before dawn that the DO level is the lowest for the day. If the culturist is not monitoring DO in the hours before dawn, and instead shows up to check out the situation after the sun has come up, what he or she may face is one or more ponds full of dead or dying fish. Having a continuous monitoring system in place is a well-justified expense as such systems can sound an alarm by telephoning one or more personnel when a problem is detected. Otherwise, someone needs to be present during the predawn hours to take routine DO measurements in each of the ponds (Box 4.7). On a large facility, and in the absence of an automatic monitoring system, two or more personnel may be required to go around and take DO measurements on something like an hourly basis in each pond.

When the culturist determines that the approaching DO level could be considered unacceptably low, action needs to be taken immediately to aerate the water. That can be accomplished in a number of ways, including adding new well-oxygenated water to the pond, spraying water from the pond into the air with a pump and allowing it to splash back into the pond, or using some type of mechanical aeration device. The latter option is the most commonly employed one in use today on large commercial culture facilities, with paddlewheel aerators such as those shown in Fig. 4.1 being very popular throughout the world. The aerator shown in Fig. 4.1 is permanently installed in the pond. In many cases, the paddlewheels used are operated by the power take-off of a tractor (Fig. 4.2). Because not every pond might require aeration on a given morning, paddlewheel aerators on wheels can be towed to ponds that need them, eliminating the need for an aerator in every pond.

Box 4.7.

Some say, 'If you have seen one pond you have seen them all.' And while that is true at some level, the statement that no two ponds are alike is also true. One earthen pond looks like any other in terms of it being a constructed basin that holds water. However, the dynamics of the water chemistry in each pond varies because of perhaps even minor differences in the composition and size of the various communities of organisms present, turbidity, depth and various other factors. If you were to fly over a large pond facility, you would typically see that the colour of the water is often variable from one pond to the next. Because the photosynthetic rates among ponds vary, you might have a DO depletion in only one or a very few ponds on a given morning; you may have several ponds affected; or you may have none. The only way to know for sure is to measure DO in each pond near dawn during warm weather and particularly during periods of warm and cloudy weather.

Paddlewheel aerators not only increase the amount of water surface area in contact with the atmosphere to enhance diffusion of oxygen into the water through the splashing that occurs; they also create a current that continuously brings new oxygen-depleted water to the surface where it can be enriched in oxygen due to diffusion. A variety of other aerator types are available, including the fountain variety (Figs 4.3 and 4.4), which throws water into the air. However, fountain aerators do not create a current across the entire pond, so the effect is localized, with basically the same water being cycled through the aerator repeatedly. One type of aerator which looks like it would not be very functional is shown in Fig. 4.5. The example in Fig. 4.5 is a small floating electric motor equipped with a slowly rotating wheel – revolving at perhaps 60 rpm or less. While it circulates the water in a pond in the same way a paddlewheel aerator does, the slowly rotating type does the same job with little or no visible indication that it is contributing to aerating the water. Such units are quite effective and efficient with respect to cost, both of the aerator itself and also with the cost of its operation.

It is well established that feed intake and energy metabolism of fish are optimized when DO is not limiting. Thus, in attempts to obtain as much production from ponds as possible, a significant percentage of shrimp and fish farmers now have one or more dedicated paddlewheel aerators or some other type of aerator in each of their ponds. In some cases, the respiratory demand becomes so high, due to heavy stocking rates, that aerators are operated 24 h a day, though that is quite expensive in terms of energy use. However, it may be necessary, particularly during the latter part of the growout period, when biomass becomes extremely high due to high stocking densities, to provide supplemental aeration at least during part of the year.

Fig. 4.1. A large paddlewheel aerator at the end of a pond causes the water in the pond to circulate.

Fig. 4.2. A tractor pulling a paddlewheel aerator.

Fig. 4.3. A series of small ponds, each with its own fountain aerator.

Fig. 4.4. A fountain aerator.

When in constant or part-time daily use, aerators are run by electric motors or by either gasoline or diesel engines. It is usually not practical to have a tractor available for paddlewheel aerators for every pond, though we have seen examples of aquaculture pond systems where 20 or more tractors were in evidence, which was probably one for every two or three ponds on the facility. It would have been

Fig. 4.5. A slowly rotating pond circulator.

less expensive to put dedicated paddlewheel aerators in each pond.

If the biomass in the ponds leads to only nighttime oxygen depletions, the aerators may be set to come on only during the critical hours of the day. Again, that could be completely automated so when a predetermined minimum in DO is reached, the computer system will activate the aerators. With the technology available today, it is physically possible and economically feasible to have an oxygen probe in every pond and have them all connected to a computerized control system. The probes need to be checked frequently to make sure they are calibrated correctly (computer readouts from probes in the ponds can be verified using portable DO meters or Winkler titrations). Some DO probes have membranes in them that can fail, and in any case need to be replaced periodically. In recent years optical DO electrodes have been developed that eliminate the need for membranes; though, if left in the water, they may require frequent cleaning, and daily calibration may be recommended by the manufacturer. Optical DO meters may also be salinity compensated. Figure 4.6 shows an optical DO meter.

pH (Box 4.8)

The parameter known as pH is defined as the negative log of the hydrogen-ion concentration in a water sample. The pH scale runs from 0 to 14 with a value of 7 being neutral. Values below 7 are

Fig. 4.6. An optical DO meter.

Box 4.8.

The extent to which water is acidic or alkaline is the pH of the water. Routine monitoring of pH – at least weekly – is a good idea when recirculating systems are used.

acidic, while those above are basic. The range of pH in most freshwaters is between 6 and 9, while saltwater pH is above 7. Since the pH scale is a log function, the differences between consecutive whole numbers are an order of magnitude. That is, for each increase in one unit of pH (e.g. an increase from pH = 6 to pH = 7), the water becomes one-tenth as acidic (or ten times more basic, depending upon how you want to look at it).

In recirculating water systems, the accumulation of organic acids from substances such as tannins in the feed, along with the accumulation of CO_2 due to respiration, will lead to a reduction in pH over time. For freshwater aquaculture systems the pH should be maintained between 6.5 and 8.5. Marine systems, particularly those in which molluscs are being reared, should be maintained at a basic pH (above 7.0). This is because the calcium carbonate ($CaCO_3$) shells of molluscs will begin to dissolve under acidic conditions. If the pH approaches or begins to fall below 7.0 in a marine system or 6.5 in a freshwater system, a buffering compound should be added. This can be done by providing a source of carbonate or bicarbonate ions. The simplest way of doing that is to introduce crushed limestone or oyster shell into the system. Both are composed of $CaCO_3$, which will slowly dissolve and buffer the water. The resulting carbonate anions (CO_3^{2-}) will then combine with free hydrogen ions (H^+) to produce bicarbonate (HCO_3^-). Removal of the free hydrogen ions will result in an increase in pH. Adjustment of pH can also be achieved by adding sodium bicarbonate.

When the water is soft (contains a low level of calcium and/or magnesium) or has low alkalinity (a measure of the levels of carbonate and bicarbonate ions), certain conditions can cause the pH to rise or fall dramatically, as discussed later in this chapter. In some instances, stressful and even lethal pH levels can occur. The pH of any water source should be determined before it is used for aquaculture, and ponds should be monitored if the conditions are right for the possibility of a dramatic change in pH.

Water pH can be measured with a colorimetric test, litmus paper test strips, a portable pH pen (Fig. 4.7) or a pH probe connected to a pH meter. Such meters can be purchased relatively inexpensively and should be a standard item in the water quality laboratory of an aquaculture facility.

Nitrite (Box 4.9)

Rare in natural waters because it is an intermediate that is quickly transformed by bacteria to nitrate, nitrite sometimes occurs in high concentrations in aquaculture systems. Nitrite may reach toxic levels in recirculating systems if the bacteria required to transform nitrite to nitrate are not present or are present in insufficient concentration for one reason or another. The problem has occurred in flowing water systems and in ponds when very high densities of animals are being maintained. For example, channel catfish (*I. punctatus*) farmers in Mississippi, USA, have experienced nitrite toxicity during the spring or late summer/early autumn when temperatures fluctuate and the nitrogen cycle becomes disrupted. This can be particularly problematic in the early autumn when fish biomass levels are at or near their highest of the year, the water is warm and the amount of feed being introduced to the ponds each day is high.

Nitrite is measured through a colorimetric test. The proper reagents, along with a spectrophotometer or colorimeter, are required. Water chemistry test kits are readily available from aquaculture equipment suppliers. Various individual test kits

Fig. 4.7. Portable pH and salinity pens.

Box 4.9.

Nitrite should be measured at least once weekly in high-density culture systems, such as those of the closed or mostly closed recirculating type, and more frequently, if there is an indication that a problem is imminent. Nitrite can also reach toxic levels in heavily stocked ponds, so they should be checked periodically towards the end of the growing season.

are available, as well as kits that provide everything needed to make ten or more different types of measurements. Such kits may come complete with a colorimeter. Nitrite probes have been developed in recent years. A search for 'water test kits' and 'nitrite probes' on the Internet will reveal sources. Tolerance to nitrite varies considerably by species, even the genetic strain of the animal, as well as with life stage. Further, other water quality parameters, such as salinity, ammonia level, nitrate level and temperature, will affect nitrite tolerance.

When nitrite is present in the water, it will combine with haemoglobin in the blood of finfish to produce methaemoglobin. Haemoglobin is the chemical in the bloodstream that carries oxygen throughout the body of the fish, and in other vertebrates including humans. Methaemoglobin, on the other hand, will not combine with oxygen, so the fish will become asphyxiated when its haemoglobin is converted to methaemoglobin. If nitrite toxicity is suspected, a fish should be sacrificed, or blood should be drawn and examined. Chocolate-brown-coloured blood is a sign that methaemoglobin is present. Channel catfish (*I. punctatus*) that succumb to nitrite toxicity die with their mouths open and their opercula closed. Nitrite toxicity was a significant problem in the US channel catfish industry for several years until research showed that increasing the chloride-ion concentration in the water mitigates the transfer of nitrite across the gill membrane of that species. The same technique should work with other species that experience nitrite toxicity. Adding table salt (NaCl) at 25 mg/l for each milligram of nitrite present is an effective treatment for the condition known as methaemoglobinaemia. Increasing the level of vitamin C (ascorbic acid) in the diet may also help protect fish against nitrite toxicity. The vitamin apparently acts to reverse the conversion process from haemoglobin to methaemoglobin. Research has also indicated that in addition to chloride, nitrite toxicity is affected by pH, sulfate, nitrate, phosphate and calcium.

Salinity (Box 4.10)

Salinity has historically been defined as the *total amount of solid material in grams contained in 1 kg of seawater when all the carbonate has been converted to oxide, the bromine and iodine replaced by chlorine, and all organic matter completely oxidized*. That is a mouthful, but more simply, salinity is basically the amounts of elements and ions in the water after the organic matter and suspended particulate matter have been removed. Because the original definition produced a result that was in grams per kilogram, salinity has been considered to be a variable, with units presented in parts per thousand (also written as per mille, ppt or ‰). Salinity has also sometimes been reported in milligrams per litre or parts per million (ppm). A salinity of 35 ppt would be equal to 35,000 ppm or 35,000 mg/l. In 1978, oceanographers came up with the practical salinity scale, in which salinity began to be reported in practical salinity units (PSUs). A PSU is defined as the conductivity ratio of a seawater sample to a standard potassium chloride (KCl) solution. Basically, a sample of 35 ppt salinity would contain 35 PSU, so the relationship between ppt and PSU would seem to be 1:1. However, in recent years, oceanographers have been involved in a debate as to whether salinity has units or is a unitless number, as previously

Box 4.10.

The frequency with which salinity should be measured will depend on the source of the water and the type of water system that is used. Naturally, there is no need to measure that parameter in freshwater systems. For saltwater pond systems there should be freshwater available to replace evaporative losses, as has been discussed in Chapter 3. Ponds with a water source that fluctuates in salinity need to have the salinity measured routinely before water is added so the proper salinity can be maintained.

mentioned. The conventional wisdom became that a ratio is unitless, so salinity is also unitless. So, those who accept that argument report salinity with no units. What used to be a salinity of 35 ppt is now just a salinity of 35 using that approach. We find the argument somewhat strange since salinity was first measured by determining how much material remained after 1 litre of water was evaporated (g/kg), which is clearly not unitless. Having been trained to present salinity in ppt, we are torn between accepting the new unitless unit convention (which when you think about it is not a problem with pH, which is also unitless) and sticking with the old one. In looking at the aquaculture literature, we have not found instances where PSU was selected over ppt and have yet to see any instance where salinity was presented as a unitless number in an aquaculture paper (though that doesn't mean they aren't out there). Because most aquaculturists are still familiar only with the notion that salinity is measured in ppt, and the oceanographers might change their collective minds again in the future and revert to one of the earlier ways of expressing salinity – or possibly come up with yet another idea, we have elected to use the ppt convention in this book. Be aware that ppt is also used as an abbreviation for parts per trillion, which is often the level at which chemicals like pesticides are found in water.

Salinity can be measured in a few ways. The original method of determining it was by titration. By knowing the density and temperature of the water, salinity can be calculated, and tables were developed to assist in the process. The electrical conductivity of a water sample also relates to salinity and, in fact, can provide a very precise measurement, so it is widely used by physical oceanographers who want to know salinity down to a fraction of whatever unit (or lack of unit) they have adopted. The level of precision sought by oceanographers is high because they are interested – at least sometimes – in following certain water masses that may vary in salinity by a very small amount. Knowing that the salinity is 35 ppt (or 35) is not sufficient to the physical oceanographers. They are sometimes interested in knowing if it is 35.00 or 35.01. Aquaculturists are not that picky, nor do they need to be.

Perhaps the easiest method of determining salinity is by measuring the refractive index of the water. This can be accomplished rapidly using a refractometer (Fig. 4.8), and those can be purchased with a built-in salinity scale. When refractometers were first used to measure salinity, they used something called the brix scale, which is used to determine the weight of sugar per volume of a solution at a given temperature. Conversion tables were developed to convert brix to salinity, but those are no longer required. A drop of water is placed on a glass plate and a transparent plastic lid is lowered over the water drop to spread it over the glass. The observer looks through the eyepiece and will see a salinity scale. A distinct shadow falling on the scale, perceived as a change from white or light grey to darker grey, indicates the salinity of the sample. The measurement requires only one drop of water, as indicated, and the reading requires only a second or so to complete. Accuracy is more than sufficient for aquaculture purposes as it is within ±1 ppt. Similar to pH pens, salinity pens also are relatively inexpensive and readily available (Fig. 4.7).

While oceanography is a stickler for precision, the aquaculturist just wants to get some idea of the salinity of the water. Certainly, accuracy within 1 or 2 ppt is sufficient. However, knowing the salinity within 2–5 ppt would be sufficient in many cases.

Freshwater is defined as having a salinity ≤0.5 ppt. Human taste buds can begin to detect saltiness in water when the salinity reaches about 2 ppt. Tasting the water will not tell a person its salinity with any degree of accuracy.

Marine waters are those with salinities ≥30 ppt and <40 ppt (mean ocean salinity is about 35 ppt), while hypersaline waters or brines are waters of ≥40 ppt salinity. Estuaries – regions where rivers enter the sea and the water is measurably diluted by freshwater (Box 4.11) – have salinities ranging between freshwater and seawater (>0.5–30 ppt).

Most freshwater species can tolerate a few ppt of salinity (typically as much as 10–12 ppt). In fact, adding sodium chloride to the water to increase the

Fig. 4.8. A refractometer for measuring salinity.

Box 4.11.

This section defines estuaries (regions where rivers enter the sea and the water is measurably diluted by freshwater) as occurring where freshwater inflow exceeds evaporation, so those situations are actually more accurately referred to as positive estuaries. There are also negative estuaries, such as the Laguna Madre of Texas and Mexico, where evaporation exceeds freshwater inflow, often leading to hypersaline conditions. Salinity in the Laguna Madre often exceeds 50 ppt and can be well over 100 ppt in embayments with little or no circulation. The Mediterranean Sea also acts as a negative estuary, only it is a big one! Theoretically, there could be such a thing as a neutral estuary in which freshwater inflow is perfectly offset by evaporation. We can't provide an example of that type, but it is theoretically possible.

salinity from 2 to 5 ppt has been used as an effective treatment against the parasite Ich (*Ichthyophthirius multifiliis*) in various freshwater fish species (see Chapter 5). Strictly marine fishes (those that spend their entire lives in offshore waters) require oceanic salinities. Species with narrow tolerance ranges with respect to salinity are called stenohaline. Species that live in estuaries where there is a wide range of salinity, or which inhabit estuaries as part of their life cycle, along

Box 4.12.

Anadromous species are those that spawn in freshwater and migrate to the ocean to mature (e.g. salmon, and steelhead trout – the sea-run strain of rainbow trout, *Oncorhynchus mykiss*), while catadromous species do the opposite; that is, they spawn at sea and migrate to freshwater for the majority of their lives. American eels (*Anguilla rostrata*) and European eels (*Anguilla anguilla*) are good examples. The term diadromous is inclusive of both anadromous and catadromous species.

with anadromous and catadromous species (Box 4.12), generally have a wide tolerance of salinity. Those species are called euryhaline.

The blood of a fish has a similar mineral composition to that of ocean water; it is certainly not identical, as it has a lower salinity. Fish blood has a salinity that is typically around 10–12 ppt (leading to the question of whether the tolerance of 10–12 ppt salinity by many freshwater fishes, and the salinity of the typical fish's blood being the same, is coincidental).

The skin of a fish acts as a semipermeable membrane, which means that water will pass through it in the direction of the higher salt concentration. In effect, the water will move through the membrane until the concentration of salt is equivalent on both sides of that membrane. In the case of a freshwater fish in its natural environment, the external salt concentration is, under most circumstances, considerably lower than that in the tissue fluids and blood. Thus, water constantly enters the fish. To maintain the internal salt concentration and keep the animal from blowing up like a balloon, the freshwater fish must continuously eliminate water from its body. This is the job of the kidneys. Freshwater fishes do not drink water as their bodies are continuously taking it in. Instead, they produce copious amounts of dilute urine that does not contain much in the way of the minerals required for proper growth and metabolism. The main source of those minerals in freshwater fish is their food, so depending on the food composition, some minerals may be excreted if they are present at levels higher than needed to meet the requirements of the animal.

Marine fishes are just the opposite from their freshwater counterparts when it comes to dealing with water balance. In their case, the salt concentration in the water is higher than that in the tissues, so the movement of water is from inside of the fish to the outside. To compensate for the water loss and keep from dehydrating, saltwater fishes drink a lot of water, which means they also take in excessive amounts of minerals, including some that are required. Again, it is the job of the kidneys to help maintain the proper salt levels in the tissues. Saltwater fish produce small volumes of urine, but it is highly concentrated in minerals. Adjusting and maintaining the tissue composition with respect to minerals is called osmoregulation. As we will see in the nutrition chapter (Chapter 7), prepared feeds for freshwater fishes need to be supplemented with various minerals, while those designed for saltwater fishes generally need less mineral supplementation.

Theoretically, an estuarine fish could move around and seek out places where the salinity of the water matched or nearly matched the salinity in its cells and blood. Because salinity at a particular location in an estuary can change nearly constantly due to dilution by freshwater inflow, either increase or decrease depending upon the direction of tidal flow, increase due to evaporation, decrease due to rainfall, change in association with wind-generated currents and possibly other factors, fish movement probably does not relate to a search for a particular salinity but is more likely to be associated with the search for food. Recall that estuarine organisms are predominantly euryhaline and can readily adapt to salinity changes.

Anadromous and catadromous species must obviously be able to transition between osmoregulating like a freshwater fish to osmoregulating like a marine fish during the life stages when they move from one type of water to the other. Switching from freshwater to seawater or vice versa requires significant physiological changes. In the case of salmon, the process of adjusting from their natal freshwater environment to being able to enter seawater is known as smoltification. Salmon smolt – that is, they undergo smoltification – at different ages depending upon species. They may reside in freshwater for a few weeks to as much as one year before entering the ocean depending on species. Young salmon have dark vertical bars along their sides, which are called parr marks, and that part of the life cycle is known, not surprisingly, as the parr stage. When smoltification occurs, the fish lose their parr marks and become more silver coloured in appearance. At the silvery stage they are ready to enter the sea and are called smolts. The change in coloration is the primary visual sign associated with the process. Significant hormonal changes are also associated with the smoltification process. Smoltification in salmon has been studied intensively and details of the process are now well understood. With respect to Atlantic salmon (*Salmo salar*), smolting occurs when the fish are several months old and are about 40 g in weight. That is when culturists move them from freshwater rearing facilities to marine facilities (cages, net pens, saltwater ponds, etc.).

Some euryhaline species can tolerate a remarkable range of salinities. For example, the Mozambique tilapia (*Oreochromis mossambicus*) is a species found naturally only in freshwater, but it will tolerate hypersalinities up to several times the salinity of seawater. There is speculation that tilapia evolved in the ocean and invaded freshwater, though it remains a mystery why no tilapia species opted out of making that transition. Hybrids among various species of tilapia (including some three- or four-way crosses of species) are currently being reared in seawater in various places around the world. The fish will not spawn at oceanic salinities, but performance of some species and hybrids is as good as when the same fishes are reared in freshwater. The tolerance of other tilapia species is not nearly as high.

Marine shrimp and various fish species thrive in the Laguna Madre of Texas, USA, and its continuation along the upper north-east coast of Mexico, during periods when very high salinities occur. Salinities of >50 ppt are not uncommon in the Laguna Madre and can be much higher in areas of extremely high evaporation, yet a number of animal species, including finfish, are found apparently under little or no stress when hypersaline conditions exist.

Variables to Measure Periodically or Under Certain Circumstances

There are a few water quality variables that should be measured at frequencies of once a month or longer because their levels tend to be stable over time. More frequent samples for measurement should be taken if there is a significant change in environmental conditions that could impact their levels, however. The two variables discussed here are alkalinity and hardness; both are related but are, in fact, quite different. Others that should be investigated initially when a water source is being considered for use in aquaculture include H_2S, iron and CO_2, which may be elevated in well water. It is incumbent upon the culturist who uses municipal water to continuously monitor the system after treatment to remove chlorine or chloramines to make certain the treatment method being employed to remove either of those compounds is working efficiently.

Alkalinity

The buffer system in water has already been discussed to some extent in the pH section of this chapter. Alkalinity is the capacity of water to resist changes in pH by the buffer systems comprising various chemical reactions that occur in the water. The carbonate–bicarbonate buffer system is virtually the only one present in freshwater and is also dominant in saltwater where there is also a borate buffer system and a phosphate buffer system. Normally, only carbonate–bicarbonate alkalinity is measured by aquaculturists.

Alkalinity is commonly measured through a simple titration technique that involves determining how much dilute sulfuric acid is required to change the colour of a water sample to which two indicator chemicals (phenolphthalein and methyl orange) have been added. The colour changes occur at specific pH levels. The methyl orange end point provides the total alkalinity value, while the phenolphthalein end point indicates the bicarbonate alkalinity. The difference between the two is the carbonate alkalinity. The results are reported in milligrams per litre or ppm as $CaCO_3$. Digital titration cartridges are commonly used for measuring alkalinity (Fig. 4.9). Scientists have found that the pH levels at which the end points in the titration occur may not be at 10.4, 8.3 and 4.5 as once thought, but may, in fact, be at higher or lower pH levels. For example, the bicarbonate portion of the titration is supposed to occur at a pH of 4.5, but actually it may occur over a range of pH levels from about 4.3 to 5.4. However, for purposes of aquaculture, the standard titration method continues to be suitable for use, so we do not need to delve further into the chemistry.

Fig. 4.9. A digital titrator for measuring alkalinity.

When CO_2 is added to water (largely through respiration in aquaculture systems), it forms carbonic acid. Carbonic acid can then dissociate to form hydrogen ion and bicarbonate. The release of hydrogen ions will drive the pH down (make the water more acidic), but if there is an adequate pool of carbonate ions present, the free hydrogen ions will combine with carbonate to form bicarbonate. The result is that the pH will not change until the carbonate pool is exhausted.

Aquaculturists like to see freshwater alkalinity levels between 30 and 200 mg/l, though water sources with higher and lower levels have been used in many instances. The minimum recommended level is 20 mg/l. Below that level the water has very little capacity to resist changes in pH. As previously mentioned, some source of carbonate, such as limestone or oyster shell which are composed of $CaCO_3$, can be added to water systems to provide a source of carbonate.

Hardness

The concentration of divalent cations in a water sample provides the value for a parameter called hardness. The dominant divalent cations are calcium and magnesium. Like alkalinity, hardness is determined through a titration process and is also reported in milligrams per litre or ppm of $CaCO_3$. Because both alkalinity and hardness are reported with respect to $CaCO_3$, many consider the two to be the same thing, which they are clearly not. Alkalinity focuses on how anions behave with changing pH, while hardness is associated with the concentrations of certain cations. It is quite possible, and routinely happens, that one is high while the other is low.

There are many instances, however, where both alkalinity and hardness in a water sample are either very high or very low. Where they are both high, if the hardness is due to a high concentration of calcium (which is common), a reaction will occur that produces $CaCO_3$ which will precipitate. Precipitation of $CaCO_3$ can and does occur in natural waters as well as in aquaculture systems. We have seen the compound cloud the glass of a flow-through aquarium system within a few days after the aquaria were exposed to hard, highly alkaline water. A weak acid, such as carbonic acid (weak hydrochloric acid), can be used to dissolve the precipitate but it will reform again within several days after the glass is exposed once again to the same type of water.

Soft water is defined as having a hardness of 0–55 mg/l. Very hard water has a hardness ranging from 201 to 500 mg/l. Values between 55 and 201 mg/l are called slightly hard (56–100 mg/l) or moderately hard (101–200 mg/l). Anything above 500 mg/l is extremely hard.

Some estuarine fishes perform well in freshwater, particularly when the water is somewhat hard. An example is the red drum (*S. ocellatus*), also referred to in some places as redfish or channel bass. Some marine species can also adapt well to water of very low salinity, even to freshwater if the hardness is sufficiently high. It appears that the ability of such species to osmoregulate is enhanced in hard water. Some species of marine shrimp, for example, can be reared in freshwater that has sufficient hardness. Studies have shown that some species or their certain life stages require low hardness levels, while others may need to be exposed to relatively hard water.

Typically, freshwater fishes should be reared in water that has a hardness of 20 mg/l or higher. Other species, such as those found only in estuaries or have life cycles that involve one or more stages associated with low-salinity water, may require much harder water for acceptable performance and survival. Strictly marine species live in water that has high levels of hardness at all times, so measurement of hardness is not required in those environments.

One way of increasing hardness, as well as alkalinity, is to add crushed limestone or oyster shell (comprising $CaCO_3$ as previously indicated). Because those sources of calcium carbonate are not required in water of high pH, only increased hardness may be required. To do that, lime (CaO) can be added. To determine the amounts of chemicals to add, the culturist should consult published information such as the book by Claude Boyd (1990). The reference to that book can be found in the 'Additional Reading' section at the end of this chapter.

Ammonia

Most of the nitrogenous waste aquaculture species produce is in the form of ammonium ion (NH_4^+), also called ionized ammonia, which is excreted through the gills. The source of the ammonium ion is the amino acids in proteins that are being used for energy rather than growth, so ionized ammonia is a by-product of metabolism.

Ionized ammonia in the form of ammonium is relatively harmless, but if transformed to unionized ammonia (NH_3), very low levels can be toxic. At a minimum, elevated levels of unionized ammonia can lead to poor growth and gill deformities. Adding the two types of ammonia together provides a measure of total ammoniacal nitrogen (NH_3-N). That can be determined in various ways, with a common method in use today being an ammonia probe coupled to an ammonia monitor to electronically measure the level of ammonia. Colorimetric tests for ammonia have been around for many years, but again they require glassware, so a handheld monitor with a probe is more convenient and provides the necessary level of accuracy. A wide variety of other water quality parameters can now be measured with probes or by colorimetric methods with a spectrophotometer (Fig. 4.10). In most cases such devices can be obtained at what we think are reasonable prices, though the prospective user should determine the precision of the probe(s) of interest before making a purchase.

Saltwater interferes with the colorimetric ammonia test, though the problem is eliminated if the samples are distilled prior to being measured. Distilling water samples increases the time and effort involved in obtaining a value, so once again

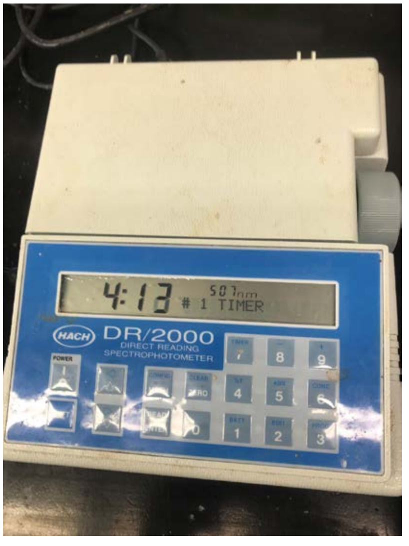

Fig. 4.10. A spectrophotometer for measuring ammonia and a variety of water quality characteristics.

an ammonia probe is preferred. Both ammonia probes and colorimetry can be used to measure total ammonia, but tables are available from which the fraction of unionized ammonia or NH_3-N can be determined. In order to use the tables, one needs to know at least the temperature and pH of the water. Salinity also plays a role, so salinity becomes an additional factor in saltwater culture systems. Other components of water quality that can affect the form in which ammonia occurs are DO, CO_2, hardness and bicarbonate alkalinity, though their impacts are less important than temperature, pH and salinity so they can typically be ignored. The percentage of unionized ammonia in a water sample increases with increasing temperature and pH, and decreases as salinity, CO_2 and/or hardness increase.

Measurement of ammonia in every type of water system is not necessary, but aquaculturists who operate closed systems are well advised to routinely monitor the ammonia levels in their system. Data on ammonia tolerance can vary considerably with respect to the species under culture and the history of ammonia exposure experienced by that species. In a study conducted by one of R.R.S.'s graduate students, we learned that the level of ammonia that was tolerated by blue tilapia (*Oreochromis aureus*) was higher in fish that had been previously exposed to sublethal ammonia levels than by fish of the same species that had not been exposed to elevated ammonia levels. The conclusion was that blue tilapia can develop an increased tolerance to ammonia based on prior exposure; in other words, it can adapt to some extent. Similar results have been shown in other species, including some invertebrates.

Because temperature, pH and other water quality parameters (including DO) influence ammonia tolerance in aquatic animals, the total ammonia concentration that may be perfectly safe under one set of conditions could be stressful or even lethal under a different set of conditions. To be safe, it has been suggested that such coldwater species as trout and salmon should be exposed to total ammonia levels no higher than 1.0 mg/l, while the level of total ammonia to which warmwater fishes are exposed should not exceed about 2.5 mg/l.

Plant nutrients

There are three nutrients of primary interest to the aquaculturist who wishes to establish and maintain a plankton bloom in a pond or is involved in culturing algae as a food for other aquatic species, such as invertebrates, finfish larvae or the small zooplanktonic animals that are being grown to feed to those larvae (see Chapter 6 for more information on culturing live food). Those primary nutrients are nitrogen, phosphorus and silicon. The latter is only important if the desire is to promote the growth of diatoms. Diatoms are benthic algae species with a sort of skeleton composed of silicon, known as a test. When the diatoms die, their tests settle to the ocean bottom and accumulate over millions of years. Diatomaceous earth, which is often used in swimming pool filters, is mined from ancient diatom marine deposits.

The nutrients phosphorus and nitrogen promote algal growth, which in turn promote the growth of zooplankton in ponds or in culture concurrently with, but separate from, the algae. Either or both types of plankton are often used as first foods for aquaculture animals. It is common practice to establish a bloom in a pond prior to stocking early life stages of culture animals, such as the larvae or post-larvae of fishes or invertebrates. Later stages, such as fry fish or post-larval shrimp, will also benefit from having plankton available upon which they can feed. Even species that will accept prepared feeds, when they begin to feed, forage on plankton and can benefit from having the live food present, particularly during their early days in ponds. Because plankton are often distributed more evenly throughout the pond than prepared feed that is thrown into the water, the young animals do not have to exert as much effort and consequently burn less energy to obtain a meal than they do when searching for prepared feed. Zooplankton will be distributed pretty much evenly throughout the water column or at least throughout the photic zone during the daytime when they are feeding, while prepared feed either quickly sinks to the bottom or floats at the water surface (see Chapter 8). That is a significant advantage of plankton; but having prepared food available as well is a good idea as the animals need to transition from natural to prepared feed as they grow. The culture species can also quickly grow too large to consume the live foods that are typically provided by aquaculturists.

It is not common practice to measure the levels of any of the three nutrients in pond water, though that is certainly possible in the cases of nitrogen (in the forms of nitrate and nitrite) and phosphorus (in the form of phosphate) using available water test kits or electronic probes. In most cases the culturist monitors the plankton bloom indirectly by measuring the clarity of the water. That measurement is most easily done through use of a Secchi disc, which is a circular piece of metal on which alternating black and white pie-shaped sections are painted. A nylon string or light rope is tied to the middle of the disc, which is then lowered into the water with the black-and-white painted side facing the surface. At the point that the Secchi disc disappears with depth, the length of string from the water surface to the top of the Secchi disc is measured. This is called the Secchi disc depth. A healthy plankton bloom in water with low clay turbidity should have a Secchi disc depth of approximately 30 cm. An alternative to the Secchi disc is for the culturist to put one arm in the water with the hand parallel to the surface. In this case, the hand should disappear at about the depth of the elbow, which is approximately 30 cm in most adults. Either measuring method will produce different results on sunny as opposed to cloudy days, as well as the time of day that the measurements are made, because of changes in the ambient light penetration due to the position of the sun. However, unless the readings are taken close to dusk or in the early hours after dawn, they should be reliable. Time of day and weather conditions, particularly with respect to percentage of cloud cover, should be recorded each time a reading is taken. Taking the readings at the same time of day also makes sense. Of course, light penetration will be reduced due dark overcast skies, rain and wind that will affect depth visibility.

Fertilization

Plankton blooms should be established and maintained through fertilization. Organic fertilizers can be used to induce both phytoplankton and zooplankton blooms, while inorganic fertilizers are primarily used to induce phytoplankton blooms.

Organic fertilization

Organic fertilizers can be in the form of either animal wastes or plant constituents. Freshwater culturists have used such plants as hay, lucerne (alfalfa), rice bran, cottonseed meal and a wide variety of other readily available plant materials (often in the form of post-harvest wastes) as organic fertilizers. Cottonseed meal has also been used in saltwater ponds as have various other plant materials. It is often a matter of what is readily available and least expensive. Fertilizers contain nutrients that promote plankton blooms upon which larval and post-larval aquaculture animals can feed. Nutrients dissolved in the water from plants also promote zooplankton blooms. The question then arises: if a zooplankton bloom is induced in the absence of a phytoplankton bloom, will DO problems be more likely to occur? The answer is that DO problems are not necessarily a result because zooplankton blooms are typically associated with feeding the early life stages of the aquaculture animals, which, while they may be present in high numbers, do not have much biomass. Thus, there is not the respiratory oxygen demand on the system that exists in a growout pond where biomass is often orders of magnitude higher than in a larval and post-larval nursery pond. Typically, zooplankton are basically eliminated by the growing aquaculture animals within a few weeks, after which the species of interest will have been converted to prepared feed. One precaution needs to be mentioned, however, and that is the decay of the plant material that was used to induce the plankton bloom. If a large amount of plant material is added to a pond, it may be necessary to remove as much of it as possible once the zooplankton bloom has been established. Decaying vegetation can create a large oxygen demand and lead to hypoxic conditions.

When animal wastes are used as fertilizer, the intent is to primarily produce a phytoplankton bloom. Duck and geese, chicken, swine, cattle and even human wastes have been used as sources of organic fertilizers. The birds and four-footed animals may be reared over or adjacent to culture ponds so their wastes are constantly added to the water (Figs 4.11 and 4.12), though care must be taken to avoid overdoing a good thing. There are places in the world where outhouses have been erected over ponds to fertilize ponds as well. Excessive waste levels will, of course, lead to anoxic conditions.

Disease transmission is a concern with respect to using animal, including human, wastes as fertilizers. That is especially the case with respect to those who harvest and process the culture species, particularly if they have open sores or are cut when handling the animals, which may have bacteria on their body surfaces at the time of processing. Consuming raw fish grown in manured ponds could also be a serious health risk. Manure is not an issue in most developed countries where the practice is probably rare. In developing countries where inorganic fertilizer is often not readily available, and when it is available tends to be quite expensive, the use of manure is common.

Fig. 4.11. Pigs over a pond.

Fig. 4.12. Chickens over a pond.

A better approach than rearing animals over ponds may be to add known amounts of manure on a fixed schedule. Research has indicated that maintaining 4000 laying hens/ha over ponds will promote good tilapia (*Oreochromis* spp.) growth in the absence of prepared feed. Interestingly, in studies one of R.R.S.'s former graduate students conducted using laying hens over ponds for fertilization, he found the best stocking density of hens was one that would yield something between 70 and 140 kg/ha of dry manure daily. When the alkalinity of the water is high, the lower end of the range for dry poultry manure was recommended, while the higher level has been recommended in low-alkalinity water. Most of the research to date has been conducted in freshwater ponds, but there is some evidence that manure can also be successfully used in conjunction with tilapia grown in saltwater.

If you were particularly interested, I (R.R.S.) could also tell you how many growing-finishing pigs to stock per hectare over ponds to get good tilapia growth. Those numbers were generated by research conducted by another of my graduate students. I do not want to discuss how disgusting it was to wade into a pond under a hog pen to pick up tilapia that were flopping in the mud after the swine ponds were drained, but I had first-hand experience and it was not much fun.

Inorganic fertilization

There are many inorganic fertilizers on the market today including liquid and granular forms. Liquid fertilizers disperse rapidly when applied to water, while granules release their nutrients over a period of time as they dissolve. Some dissolve quickly and release their nutrients shortly after application, while others dissolve slowly (usually within several hours to a few days). Granular formulations have been developed for use on lawns or agricultural crops so even the water-resistant form dissolves quite rapidly in water. This is because it was designed to dissolve when exposed to intermittent rainfalls or irrigation water, which may be applied on a schedule, but not continuously. Crops like rice that are grown in water are an exception to intermittent exposure.

Each formulation of inorganic fertilizer has a composition that is revealed through a system that employs three numbers. Those numbers, always in the same order, refer to the percentages of nitrogen, phosphorus and potassium in the formulation. This is also known as the N:P:K ratio. In freshwater ponds, the recommended application rate for phytoplankton blooms is 50 kg/ha of 16:20:4 fertilizer. When there is already sufficient potassium present in the pond soil, as is frequently the case, blooms can be promoted with a fertilizer with the composition of 16:20:0.

If 16:20:4 or 16:20:0 compositions are not available, some other formulation with the same relative ratios of four parts nitrogen to five parts phosphorus, and either one or zero potassium can be used. Examples are 100 kg/ha of 8:10:2 or 8:10:0, or 25 kg/ha of 32:40:8 or 32:40:0.

The treatment should be repeated every 10–14 days until the desired Secchi disc reading is obtained. This may take a few applications, but if a bloom is not established within a few weeks, the culturist may be stimulating the growth of unwanted plants, which may be rooted, floating or in the form of filamentous algae. In that case the aquaculturist should stop introducing fertilizer. Should the wrong type of plant growth be initiated, herbicide may be used to kill the plants. Depending on the extent of the problem it may be necessary to drain and refill the pond before once again attempting to develop a phytoplankton bloom. Because herbiciding the pond will lead to release of nutrients from the dead plant material, it may not be necessary to add more fertilizer to stimulate a phytoplankton bloom if the pond has not been drained. Draining a pond that has been treated with herbicide will flush a considerable portion of the nutrients out of the system, so it may be necessary to apply fertilizer once the pond is refilled in order to stimulate a bloom. Plant seeds and algal spores can enter a pond by being carried by the wind and, if surface water from a reservoir, lake or stream is used to fill the pond, the water will often contain seeds and spores in abundance. In any event, it is not necessary to inoculate the pond with phytoplankton.

It is assumed that the attempt to establish a phytoplankton bloom precedes the introduction of aquaculture animals into the pond. Otherwise, if it is necessary to herbicide the pond to eliminate aquatic plants (including algae), you stand a high risk of killing the desired aquaculture species unless you treat only one portion of the pond at a time (usually not more than a quarter of the infested portion at a time). That can be a slow process. If the entire pond is treated simultaneously, however, you run the risk of direct toxicity to the culture animals from the herbicide and/or a greatly increased BOD as the vegetation decays that results in the development of hypoxia or even anoxia. More on this can be found in the next section.

If, after becoming established, a successfully initiated phytoplankton bloom begins to decline (the Secchi disc reading is greater than the desired 30 cm), additional applications of fertilizer may be required. When the culture animals become accustomed to prepared feed, fertilization can be discontinued, though maintaining a phytoplankton bloom is still desirable. One reason is that phytoplankton can shade out unwanted plants that might otherwise re-establish in the pond. A phytoplankton bloom will also provide a source of DO, as previously discussed. Plankton blooms can continue to exist after fertilization is discontinued because other sources of nutrients are being supplied from the metabolic waste products of the culture animals and nutrients that leach from any waste feed that is present.

In some cases, plant communities other than phytoplankton are actually desirable. For example, various rooted aquatic plants are the primary source of nutrition for grass carp (*C. idella*) and the culturist who is rearing that species may want to promote the growth of plant species that are readily consumed by that fish. We would rather feed grass carp terrestrial waste vegetation that they will eat, or use them for weed control, rather than actually introduce rooted aquatic plants.

Another example where plants other than phytoplanktonic algae are encouraged is in conjunction with milkfish (*Chanos chanos*), where culture occurs in South-East Asia. One common method of milkfish pond culture involves introducing water until it is a few centimetres deep and then adding fertilizer. The goal is to develop algal mats and associated animal communities on the pond bottom. Once the algal mat is established, the pond is filled and stocked with milkfish, a species that will feed on the algae and animals associated with the algal mat. The algal mat communities are called lab-lab in Asia. The more technical terms are periphyton and *Aufwuchs* (Box 4.13).

Box 4.13.

Aufwuchs is a German word that refers to the plant and animal communities found attached to surfaces in the aquatic environment. If you have ever slipped on a rock while wading in a stream, you will have had an intimate personal contact with *Aufwuchs*. The term periphyton refers to the plant portion of the *Aufwuchs* community.

Controlling Undesirable Plants

Undesirable aquatic vegetation may appear after fish have been stocked in a pond that may initially have had a good plankton bloom that died off, was largely consumed by the culture animals or both. When a bloom declines and undesirable plants become established, some type of control measure should be employed. The methods available are biological, mechanical, environmental and chemical.

Biological plant control

By biological plant control, we do not mean putting a biologist in the pond to pull weeds, though we have used that technique on several occasions and don't recommend it. We are including the biologist-in-the-pond approach under mechanical plant control, which is where we think it belongs. What we are referring to primarily by biological plant control involves a variety of herbivorous animals that can be stocked to control aquatic vegetation. The most popular of those are finfish of one species or another, some of which – such as grass carp (*C. idella*), the most popular among them – are also marketable. Some species of tilapia (e.g. red-bellied tilapia (*Oreochromis zillii*) may reduce the growth of macrophytes; blue tilapia (*O. aureus*) consume filamentous algae) along with the Java barb (*Barbonymus gonionotus*), tambaqui (*Colossoma macropomum*) and giant gourami (*Osphronemus goramy*) have been used as weed control agents. Common carp (*C. carpio*) have also been used, though the most voracious plant consumer among finfish and the strictest herbivore is the grass carp. Common carp do not consume aquatic vegetation except, perhaps, incidentally, but they do root around on the pond bottom and submerged portions of the levees causing increased turbidity which can lead to a reduction in the amount of light reaching the plants and will thus reduce plant growth rate or even cause the plants to die back. The rooting around the bottom by common carp can also cause considerable damage to levees, leading eventually to their deterioration, so we do not recommend the use of common carp as that may make the life of the aquaculturist even more difficult.

Some species of turtles and birds, along with manatees, nutria and muskrats will also control aquatic vegetation. Muskrats burrow in levees and are usually not welcome on fish farms. Turtles and birds would be more difficult to contain in and around culture ponds than are fish. Plant-eating domestic ducks with clipped wings could be used, but even if they could not fly, you would have to put a fence around the pond to keep them from walking off. The idea of having an adult manatee or sea cow (genus *Trichechus*) weighing 700–800 kg in a culture pond seems unrealistic and would be illegal in the USA, where native manatees (which occur only in Florida) are on the endangered species list. Like the Florida manatee, the West Indian manatee is listed as endangered throughout its range. The same may not be true of Antillian and West African manatees, but we are not aware of anyone promoting the idea of stocking manatees for biological plant control.

There are species of snails and insects that eat aquatic vegetation and there has been at least a limited use of them by aquaculturists. Their best use might be to impair the establishment of unwanted plant populations. Unless they are present in very large quantities, they would probably be hard-pressed to control a heavy infestation of plants due to their small size and limited capacity to ingest plant material.

The use of grass carp (*C. idella*) is widely accepted, though use of the species has been controversial in some places. Native to the Amur River in Russia – and often called the white amur – grass carp are exotics in most regions where they are used for vegetation control. Fears that grass carp would eliminate aquatic vegetation in natural water bodies and have dramatic impacts on habitat, including at least the upper reaches of estuaries where the salinity is low, prompted the promulgation of strict laws associated with prohibiting or regulating the stocking of grass carp in as many as 30 states in the USA during the 1960s and 1970s. There was also fear that grass carp would spawn and displace other, more desirable fish species. The suitability for stocking grass carp will vary from country to country, based not only on regulations involving the species, but also on the species of aquatic plants that need to be controlled. Grass carp prefer some species of plants and avoid others.

Re-evaluation of the use of herbivorous grass carp in many places where the fish were once prohibited has taken place in recent years as the result of the development of techniques for developing sterile hybrids (grass carp (*C. idella*) × bighead carp (*Aristichthys nobilis*) being the most common). Techniques have also been developed to produce fish, including grass carp, which contain three pairs of chromosomes in their cells (triploid) instead of the normal two pairs (diploid). Both hybrid and triploid grass carp are assumed to be sterile, thereby supposedly eliminating the chance of reproduction should they escape from an aquaculture system. Based on that assumption, many jurisdictions have modified their regulations on grass carp and will approve stocking of hybrids and/or triploids, and in many instances not diploids, as the projections of negative impacts on native habitats from the latter were found to be less disastrous than anticipated.

However, grass carp appear to have become familiar with the concept, if not the famous line from the film *Jurassic Park*: 'Nature will find a way.' The 'way' found in the case of grass carp is that the techniques used to produce triploids are not 100% effective and some diploid fish have been found in supposedly triploid populations; thus, those fish can spawn and produce viable offspring. Some jurisdictions now require that each grass carp stocked must be certified as triploid. That requires examination of a properly prepared tissue sample under the microscope to ensure that the cells do, indeed, have three pairs of chromosomes. More simply, the blood can be examined. The cells in triploids are larger than those in diploids because of the extra set of chromosomes, and that can be determined microscopically or with certain instruments that can make the measurements. Methods for manipulating the number of chromosomes in fish are discussed further in Chapter 6.

Stocking rates for grass carp vary from location to location. In many instances, the maximum stocking rate is regulated by government agencies, typically state fish and wildlife departments. More hybrids are often stocked per unit area of pond than non-hybrid grass carp because the hybrids are not strict herbivores and do not consume as much vegetation as non-hybrids. In the case of hybrids, plant consumption rates do not seem to be particularly influenced by water temperature. Stocking rates can also vary depending on the species of aquatic plant or plants that is/are targeted for control. It has been suggested that it might be necessary to stock twice as many hybrid carp to achieve the same level of vegetation control as from non-hybrids. The appropriate stocking rate for grass carp also depends on the size of the fish stocked and the amount of vegetation they are expected to control. Stocking a few small fish before plants become well established may be effective, while larger fish in much greater numbers would be appropriate if a heavy plant infestation is present at the time of stocking. Typical stocking numbers for grass carp for aquatic weed control are in the range of 15–100/ha.

Preferred stocking densities for the other aquatic-plant-eating species mentioned above as potential vegetation control agents, as is the case with grass carp, will vary depending upon plant density. Local regulations with respect to stocking exotic species such as other plant-eating fish to control aquatic vegetation need to be consulted before any of those species are introduced.

Mechanical or environmental plant control

Mechanical plant control typically involves physical removal of aquatic plants from the culture system, though alterations to the system to discourage aquatic plant growth also fall under this designation. We were not being facetious when indicating that one method is to put a biologist in the pond to pull weeds. It does not really take a degree in biology to pull weeds, of course, but if just a few plants are present, the most convenient method of removal might be to pull them or, in the case of floating plants, collect them by hand or in nets. One doesn't have to be a biologist to perform the task; a chemist could also serve the purpose, as could an engineer, graduate student … you get the idea (see Box 4.14). Actually, anyone who can be convinced to jump into a weedy pond and start pulling up plants and tossing them up on the levee road is a suitable candidate. The plants need to be hauled off and disposed of because if they are left on the pond levee they will decay and become malodorous.

Pulling weeds by hand becomes increasingly more difficult and time-consuming as the extent of the problem increases. Mechanical plant harvesters are available, but those are most commonly used in large water bodies such as lakes and reservoirs. Also, mechanical harvesters often do not uproot plants but merely mow them down, so regrowth can occur quickly.

Box 4.14.

R.R.S. had been managing the Aquaculture Research Center at Texas A&M University for only a few months in 1975 when he got word that the Dean of Agriculture was planning an inspection visit on a Saturday. He went out to the lab early to make sure things were not in disarray. Shortly after arriving there, his department head also appeared. He looked around the lab building, then walked out to the ponds, with R.R.S. in tow. One of the ponds had cattails growing at one end. He said, 'You need to get in there and pull those weeds.' R.R.S. quickly changed into his bathing suit and did as he was told. R.R.S. was still in the pond pulling, or at least trying to pull, cattails when the dean arrived. He took one look and asked R.R.S., 'Why are you pulling those plants? That's not your job!' He then completed his inspection and said he was satisfied with what he saw. R.R.S. and his department head never discussed the situation thereafter, and R.R.S. was more interested in making a positive impression on the dean with respect to the appearance of the fish culture research facility than in not acting professorially. In any case, the department head and R.R.S. developed a very positive relationship and remained good friends for the nine years that R.R.S. oversaw the facility.

Dyes that are not toxic to animals have been developed for use in aquaculture ponds. While the method could be discussed under chemical control, the purpose of dyes is not to directly affect the plants, but to alter the environment to discourage plant growth. Use of dyes to darken the water and restrict light penetration and limit photosynthesis is not a new concept. Aniline dyes have been used for that purpose as early as the 1940s. A common commercial dye product in use today turns the water a deep-blue colour, thus reducing light penetration and shading out the plants. The dye is a combination of two active ingredients, acid blue #9 and acid yellow #23, along with inert ingredients. The recommended dose rate is 1 mg/l. Dyes should not be applied in turbid ponds (where the effect of the turbidity, if sufficiently high, should restrict or eliminate rooted plant growth in any case). Dye should be applied before plant growth reaches the water surface in the spring.

Establishing a phytoplankton bloom will be difficult once the undesirable plant biomass has been reduced, because the shading effect of the dye is not selective. However, if lack of a phytoplankton bloom is acceptable, using a dye before plants become established in the first place, if possible, provides a good solution. Zooplankton blooms will also be impeded from the shading because they are dependent upon the availability of phytoplankton.

Lining ponds, as discussed previously with respect to controlling seepage losses, will also help keep rooted aquatic plants from becoming established. The plants will not be able to take root in the liner, though if there is a layer of sediment on the pond bottom – perhaps associated with a high suspended solids load that has settled out over time – plants can take root and grow. Pond liners will have no effect on reducing the establishment of floating aquatic plants or algal mats.

Chemical plant control

Regulations on the use of chemicals to control aquatic vegetation in ponds will vary greatly from one country, or region within a country, to the next. Some nations strictly control the use of herbicides in ponds, or limit herbicide application to products specifically designed for application on water bodies. Some countries, on the other hand, have very liberal or no policies on regulating the use of herbicides in the aquatic environment. In some cases where regulations do exist, they may not be enforced to any degree. Certain chemicals in the USA require the applicator to have a licence which can be obtained after the individual has taken a class and passed an examination on the use of specific herbicides and pesticides that can only be purchased and applied by a licensed applicator. The process to obtain a permit is not particularly onerous. A typical class in the USA involves one day of lectures followed by an examination. Similarly, the types of vegetation present will vary from region to region and the appropriate herbicides to control local types of vegetation that commonly occur will also vary. Applicator courses focus primarily on chemicals that are used on agricultural crops, so very little mention of applying chemicals to treat aquatic plants may be included, unless a class on aquatic vegetation is available in your area. Naturally, it can be easier to find such a class in a region where aquaculture is a common activity.

Herbicides must be used carefully as they can be toxic to the culture animals if improperly applied – which usually means being applied at too high a rate. Many chemicals, including herbicides, can pose a health hazard to the applicator as well, as the chemicals may be absorbed through the skin or taken up through inhalation. They will certainly cause illness or even death if ingested, so many labels indicate that immediate medical attention should be sought if the chemical is swallowed or even exposed to bare skin. Eye irritation is another very real possibility.

Interestingly, when it comes to herbicides and various other chemicals, more is not necessarily better than less. It is tempting to exceed the recommended dosage. If 10 mg/l dose of chemical mixed with water is recommended, then surely 20 mg/l would be even better? That is certainly not the case. Excessive doses of herbicide may be just as ineffective as applying too little. Always read the label and follow the manufacturer's instructions.

Various water quality parameters can also influence the toxicity of some herbicides to animals in the pond. Those parameters include such things as temperature, alkalinity and pH, among others. The label should provide the user with the proper dosage for the conditions that exist in the ponds that need to be treated, and those conditions can vary from one pond to the next. So, if dosage is related to pond pH, measure the pH in each pond to be treated and mix the chemical that you plan to use in each pond according to the directions. The same would go for temperature and perhaps other variables.

Herbicides come in various forms: liquid, powder and granular being the most common. Liquid herbicides are generally distributed by mixing them throughout the pond water. That can be accomplished by turning on a paddlewheel aerator and putting the liquid virtually anywhere in the pond if the entire water column will become mixed by the paddlewheel. Another option is to use an outboard motor to mix the herbicide into the water. The motor can be mounted on a stand secured in the pond, mounted on a dock (if one is available) or operated as one would normally use such a motor; that is, from a boat. The boat can be secured so it does not move, or it can be driven around the pond to mix the water. In any of the approaches mentioned, the liquid herbicide should be poured into the wake generated by the paddlewheel or outboard motor propeller.

When heavy plant infestations are present in a stocked culture pond, attempting to eliminate all the plant material at once (herbiciding the entire pond) has the opposite of the desired effect. As the plant material dies and decays, it places a heavy demand on the available DO and can lead to oxygen depletions with resulting fish kills. Treatment of only a portion of a pond is difficult using liquid herbicides, so spot treatment with granular or powdered herbicides in limited areas of the pond is recommended. Depending on the extent of the plant infestation, from 5 to 25% of the surface area of an infested area of a pond can be treated at one time. Obviously, the heavier the infestation, the lesser the percentage of the pond that should be treated. Once the plants in the treated area have died and decayed to the extent that the oxygen level has returned to normal and is at an acceptable level before dawn each morning, an additional affected area of the pond can be treated. The process is repeated until the entire infested pond has been treated. It may be necessary to go back to previously treated areas and make a second application if the plants recolonize before the entire population has been controlled, as can happen if you are treating only one small portion of a pond at a time.

Some commonly used herbicidal compounds are copper sulfate, 2,4-D, Diquat, endothall, fluridone, glyphosate, potassium ricinoleate, Simazine and xylene. Brand-name herbicides can be found on the Internet by searching for pond herbicides. Some formulations for each of them have been developed and labelled for use in ponds. There may be restrictions on the use of the herbicides listed in some jurisdictions, while at the same time additional chemicals to those appearing on the list may be allowed. Regulations may preclude harvest and marketing of the fish or invertebrates under culture for a certain period of time after exposure to herbicide. Package labels will instruct the user on how much of the chemical to apply on the various types of plants that the herbicide will control and may also indicate the withdrawal time required before the animals in the pond can be safely harvested and consumed.

Some herbicides are quite specific with respect to the types of plants they will control, while others will control a broad spectrum of plants. Copper sulfate is only effective in controlling algae, for example, while chemicals such as Simazine and glyphosate will control a wide variety of higher aquatics. Glyphosate comes as a liquid and is effective in controlling a number of plants, including duckweed. A tank sprayer can be used to apply the product directly on the plants. Endothall can be purchased as a powder that will dissolve in the water, but it also comes as a product in which the chemical is adsorbed to sand grains. The latter form is excellent for spot treatment as it can be sprinkled on the leaves of target plants and will remain in place as the chemical is released to be taken up by the plants rather than being dispersed throughout the pond.

Other Factors

There are various other factors associated with culture systems that can significantly affect water quality. Some of the more important ones are considered in the following subsections. The importance of each may differ depending on the type of culture system that is being operated.

Light

Light quantity and quality, along with photoperiod, influence plant growth in aquatic systems. Because there may be an interest in, or need for, establishing and maintaining a phytoplankton bloom, or in growing seaweed or higher plants as primary or secondary products, the culturist will need to ensure that sufficient light of the proper wavelength is available for good plant growth. Animals may also grow better under the proper light conditions. During egg development and larval rearing, light may play a significant role in producing hardy animals. Light also plays a role in the smoltification process in anadromous salmonids. Photoperiod is important in promoting gonadal development and spawning of many species of aquatic animals and is discussed further below.

Light quantity will vary depending upon water depth and turbidity, as well as its source in the case of artificial lights. Light penetration diminishes with depth, even in clear water. The rate at which light penetration diminishes is increased as turbidity increases. Turbid water due to suspended sediments and other particulate solids, along with plankton blooms, are common in pond systems. Light penetration is reduced on cloudy days, as indicated above, and changes with the angle of the sun relative to the water in outdoor systems primarily. Indoor systems usually have lights that operate on timers or may be turned on when employees arrive in the morning and off at the end of the workday. The water in a recirculating system can become brown due to tannins that leach from feed pellets. The brown water will reduce light penetration. Recall that biofloc systems are very turbid, and typically the aquaculturist can only determine the status of the culture species by sampling with dip nets in the growout raceways as the turbidity does not provide the opportunity to visualize the culture animals.

Most raceway systems (particularly those that are of the flow-through type) and surface cages in the ocean will typically have relatively clear water, so light penetration is usually not limited. That may not be the case in closed systems due to the tannins and suspended fine particles that often accumulate in the water. Ponds and indoor systems wherein phytoplankton blooms are encouraged (such as using the green water technique for rearing larval shrimp) are described under 'Suspended solids' below and were mentioned previously as systems where light penetration is limited.

The depth at which the light level is decreased to 1% of that at the water surface is called the compensation depth, which means it is the depth at which phytoplankton photosynthetic productivity and respiration cancel one another out and there is no net increase in, or loss of, oxygen in the water as a result of those two metabolic processes. A properly maintained aquaculture facility will be one in which the water is sufficiently mixed to bring phytoplankton cells into the light (the photic zone) frequently enough that they can photosynthesize effectively. Mixing with aerators is an effective means of accomplishing that task in ponds. In tanks it is common to use compressed air or air blowers for aeration, which also lead to mixing of the water.

Light quality refers to the wavelengths of light that are present. Having evolved under natural light from the sun, plants are often best adapted to the full light spectrum that is available during the daylight hours. Light bulbs that provide the proper wavelengths are available and should be used in indoor facilities. Today, halogen lights are commonly used for plant production because not only do they provide the necessary wavelengths, but they are also very bright, and their light penetrates the water much better than light from fluorescent or incandescent bulbs.

The various wavelengths of light are absorbed in water at different rates. The first colour in the spectrum to disappear in water with depth is red. Many marine organisms that live below the depth of red-light penetration are red in colour, which makes them virtually invisible to predators since their colour is not reflected. Blue and green are the last colours to be absorbed in water, thus those wavelengths penetrate more deeply than the others. Actual light penetration of each of the colours in the spectrum varies with water clarity. Wavelength can have an influence on performance for some species. There are also reports that some animals may perform best in the dark.

Photoperiod refers to the number of hours of light that the plants and animals are exposed to each day. Natural photoperiod changes seasonally in association with the tilt of the earth relative to the sun. The greatest annual fluctuations in photoperiod occur in the polar regions and the least in the tropics. As many aquaculture species are produced in tropical or subtropical regions, the photoperiods commonly used in indoor culture facilities are 12:12 (light/dark) or 14:10.

As mentioned, photoperiod is commonly a controller, usually along with temperature, of gonadal development in fishes and other aquatic animals. Photoperiod manipulation can be used to delay gametogenesis. That approach has been shown to work well with the green sea urchin, *Strongylocentrotus droebachiensis* (the gonads are the only part of a sea urchin that is consumed). The idea is to produce gonads high in nutrients, but lacking the development of eggs or sperm, because it is the nutrient-rich gonads that are preferred by consumers. By maintaining the photoperiod associated with summer, gametogenesis is deterred while nutrients are deposited in the gonads.

The gonads of many species develop in the spring or autumn. In the spring, day lengths get longer and temperatures become warmer, while the opposite occurs in the autumn. Those conditions of changing photoperiod and temperature often trigger the hormones responsible for gonadal development and, ultimately, spawning. Aquaculturists have been able to compress the year into as little as a few weeks by manipulating photoperiod and/or temperature (most commonly both). Exposure to pre-spawning-season conditions for as little as a few days or weeks, followed by gradually changing the temperature and photoperiod to simulate conditions during the spawning season, may bring on gonadal development and spawning within another few days or weeks. Some species, such as red drum (*S. ocellatus*), are multiple spawners and can spawn every few days for months once the proper conditions are established and maintained. Other species, such as channel catfish (*I. punctatus*), spawn naturally only once a year, though it is possible to recycle them and produce at least two spawns a year. However, because channel catfish are predominantly pond-reared under natural conditions of photoperiod and temperature and are most often reared in temperate regions where the growing season is of limited duration, there is not much advantage in having multiple spawns. This is particularly true if one of the spawning events is several months out of phase with the normal spawning time. The exception might be in cases where off-season spawning and early rearing are conducted in a temperature-controlled indoor facility and where the second spawn is obtained during the autumn. The eggs could be hatched, and the fry grown to fingerling size indoors over the winter and then stocked for growout in the spring. That approach is theoretical as far as we know, though some catfish culturist somewhere may have tried that technique. The commonly used procedures for spawning channel catfish are detailed in Chapter 6.

Light will also stimulate gonadal development in shrimp. The eyestalk of marine shrimp is the site of chemicals that block gonadal development in females. Researchers have found that by removing one or both eyestalks in females (a technique known as ablation), the animals will produce the hormones that are required to induce gonadal development and spawning. That process can only be done once per female, and then new broodstock shrimp must be obtained. Unilateral eyestalk ablation of juvenile Indian river freshwater shrimp (*Macrobrachium malcolmsonii*) has been shown to induce rapid weight gain, which is also apparently associated with light perception.

Because shrimp spawn in nature without eyestalk ablation, it is only a lack of establishing the proper conditions that has held up progress in controlled spawning without cutting off eyestalks or removing the contents of the eye itself (enucleation). In the early 1980s, one of R.R.S.'s graduate students hypothesized that maintaining brood shrimp under extremely low light conditions at the proper temperature would induce them to spawn. That theory was based on the fact that spawning in the ocean occurs, with respect to at least some species, at depths where there is little or no light. Laboratory confirmation of the theory was obtained by another graduate student at Texas A&M University who had access to a shallow tank in which both temperature and light could be fully controlled. After discussing the idea with the first student, the other student set up the proper temperature for spawning and kept the room totally dark. The result was that spawning occurred as predicted.

Ablation continues to be widely used in marine shrimp hatcheries because it is difficult for personnel to monitor shrimp activity in the dark. Very low light and flashlights with red filters over the lenses are sometimes used to visualize shrimp in hatcheries, though even under those circumstances it may be necessary to ablate the female brood shrimp.

Some stages in the life cycle of animals, particularly the early life history stages, may require either a lot of light or no light at all. Eggs may not hatch properly if exposed to improper light conditions. By studying the conditions under which eggs and larvae are found in nature – much like looking at the conditions under which the adults mature and spawn in the wild – it may be possible to determine what conditions should be established in an aquaculture facility. Salmon eggs, for example, are laid in gravel, which would seem to indicate that they should not be hatched under bright light. Salmon egg heath tray incubators (Fig. 4.13) are typically kept in rooms where the light level is comfortable for workers, but the light does not shine directly on the eggs except when they are being handled (dead eggs are removed from the hatching trays periodically during the development to avoid the spread to healthy eggs of a fungus that attacks dead eggs). The technique is rather innovative. The eggs from each heath tray are passed in an apparatus where they pass under a light ray. Viable eggs allow the light to pass, while dead eggs are opaque. The opaque eggs are blown out of the line of moving eggs with a puff of air and collected for elimina-

Fig. 4.13. Heath trays.

tion. The viable eggs are returned to the heath tray for hatching. The process is now automated but in the past was one that required picking by hand.

The influence of light on egg development in fish may be related to either its intensity or wavelength. For example, a higher percentage of Atlantic halibut (*Hippoglossus hippoglossus*) eggs will survive to hatching if incubated in the dark or at low light levels than when exposed to relatively high light levels. Exposure of sac fry of the same species to white, blue, green or red light has indicated that there is little or no influence of wavelength on growth. That does not mean that performance of the fry of other species is not influenced by light colour.

A major issue associated with the rearing of striped bass (*Morone saxatilis*) has been instances of significant problems with larval swim bladder inflation. Swim bladders are present in most species of bony fishes. Air in the swim bladder helps keep the fish from sinking. The swim bladder develops during the larval period and, if it does not, the fish will fall to the bottom of the culture chamber and die. The problem has been reported from several cultured fish species, both freshwater and marine. The issue has been widely studied in striped bass. Research has indicated that more than one factor is involved with proper swim bladder inflation and that one of those factors may relate to photoperiod. Nutrition and light intensity have also been shown to be involved. High light intensity has been associated with increased larval mortality. It has been theorized that either increased cannibalism or swim bladder overinflation may be factors.

There has not been a great deal of research conducted on the effects of photoperiod on the growth of fingerling fishes or post-larval invertebrates, but what information does exist shows a good deal of variation from species to species. Again, knowing something about the conditions in which the animals live and prosper in the wild may provide an indication as to the type of aquaculture conditions that should be provided. That is not always the case, however. Some species have been shown to grow best when reared under conditions where there is constant light, a situation that does not occur in nature, except during the summer at the poles, where there is little interest and few opportunities for aquaculture. Even there, light intensity is reduced to some extent during the hours preceding sunrise.

Aquaculture animals, particularly motile species, should not be exposed to rapid changes in light intensity. For example, if the aquaculturist enters a dark windowless room of an indoor tank culture facility after arriving for work in the morning and immediately turns on all the overhead lights, it will cause a startle response in the animals. Some may jump out of their tanks, while others may bump into one another or the tank walls. This can cause physical damage or death, and at a minimum, will place stress on the animals. The best practice is to gradually increase the light level by using lights that are on a rheostat so they can be brought up to full strength gradually. Alternatively, one to a few low-wattage lights can be turned on first, followed by an appropriate time interval when higher-wattage lights are turned on sequentially. If the facility does not have windows that allow natural light to increase slowly in the morning and diminish slowly as the sun sets in the evening, the culturist should consider dimming the lights if they are on a rheostat or turning them off in the reverse order that they were turned on in the morning if they cannot be dimmed slowly.

Substrate

In nature, many animal species of aquaculture interest are often found in association with some type of substrate. That might be sand, mud, coral or even such things as fibreglass, plastic, metal, concrete or wood that has managed to find its way into the environment. Examples include a wide variety of fishes and such invertebrates as spiny lobsters that are associated with coral reefs; oyster and mussel larvae that can attach to virtually any hard substrate; and clams that burrow into the sand. Artificial reefs have been placed in both marine and freshwater bodies to attract fish. Marine cages and net pens attract fish, and of course are colonized by various fouling organisms. Fish are attracted to such facilities in part because of structure, but the opportunity to obtain feed that leaves the cage or net pen also plays a role. Lost feed may also attract species that might not normally go to structure. Small fish that are attracted to structure bring in larger predators. Floating debris such as logs, pieces of Styrofoam® and a wide array of other objects can also serve as FADs.

Some species are most commonly found in mangrove swamps in and around the mangrove plant roots. Others may prefer to associate with kelp beds, marshgrass areas or seagrass beds. Various species are most commonly found over mud or sandy bottoms. The question is: does the aquaculturist have to provide a certain, and perhaps different, type of substrate for each species under culture? Again, it makes sense to grow the culture species in an environment, including the type of substrate that is a part of that environment, in which it is normally found.

As indicated, hard substrates are required for the larvae of such species as oysters and mussels that attach themselves, though they can be removed from the cultch material and reared without attachment in the case of cultchless oysters. Mussels attach to substrates with byssal threads and if removed from a substrate they can, unlike oysters, reattach to another substrate. Some invertebrate species burrow into the substrate, though only a few aquaculture species fit in that category. Examples are clams (such as *Mercenaria* spp.), geoducks (*Panopea* spp.) and, apparently, sea cucumbers.

Flounders are often found on or partially buried in soft sediments or sand and change the colour and mottling pattern on the exposed (upper) side of their bodies to match that of the substrate, making them nearly invisible, and enhancing their ability to locate and attack food organisms. When some species of flounders are reared in tanks, a high percentage of them may become ambicolorate; that is, they will develop dark pigment on the lower side, which is normally white (Box 4.15). While having dark pigment on the lower side does not affect the quality of the flesh, the black areas on what consumers expect to be white (Fig. 4.14) leave the impression that something is wrong with the fish. Thus, ambicolorate fish are more difficult to market if sold in the round. If they are processed into fillets prior to sale, those fillets look like any others, so marketing is not a problem. Processors could reject ambicolorate fish, but it should be relatively easy to convince them that the unusual coloration is not a sign that the fillets from such fish would be any different than from normal coloured flatfish.

Box 4.15.

There are several species and families of flatfishes commonly referred to as flounders. Some are said to be left-handed (eyes on the left side of the head) and some are right-handed (eyes on the right side of the head) after metamorphosis.

In early studies with summer flounder, the R.R.S. research team at the Skidaway Institute of Oceanography in the early 1970s found that by providing a sand bottom in tanks or raceways (much less messy than mud in an indoor facility) we were able to reduce the extent of ambicoloration in summer and southern flounders (*Paralichthys dentatus* and *Paralichthys lethostigma*, respectively). However, other researchers have found no difference in pigmentation in fish of the same genera when reared on bare tank bottoms compared with those reared on sand substrate. Thus, the jury may be out on the issue of ambicoloration development in relation to the presence or absence of natural substrate. Whether natural substrate has a mitigating effect on the development of ambicoloration may relate to the age of the flounders when placed on the substrate, the colour of the substrate and colour of bare tanks used in the comparison, the amount of light the animals are exposed to, or perhaps other factors. We thought light might be a factor and that the bottom (ventral) side of the fish might have been reacting to reflected light from the tank bottom, as the black areas (which are melanin deposits) tend to occur first around the dorsal and anal fin margins (those fins run most of the length of the fish, from the head to the caudal fin, in the case of flounders).

Halibut (*Hippoglossus* spp.) are among the finfishes that can be reared in marine net pens. In the open ocean, halibut (and other flatfish) often swim up the water column, particularly to feed and during spawning. In tanks, halibut and other flatfish tend to lie at the bottom much of the time, though

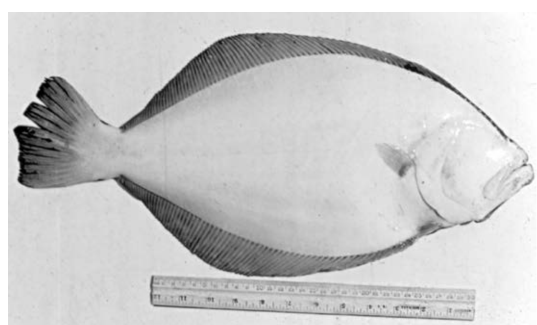

Fig. 4.14. The bottom side of a flounder, *Paralichthys* sp., with normal coloration. Ambicolorate flounders – those that have black pigment covering a portion of the bottom side, which should be white – are commonly seen in aquaculture facilities.

they will swim around in the water column, particularly when searching for food. When resting, halibut will lie atop one another at the bottom of tanks as well as in net pens.

From some of the early experiences that the graduate students of R.R.S. had at the University of Washington, we theorized that it would be necessary to provide a hard substrate in the bottom of a net pen for the fish to lie upon. We approached a friend who operated a salmon net pen operation and was willing to work with us by providing a net pen that we could modify. We installed a ridged bottom in the pen, which turned out not to be a simple task. Regardless, we stocked it and soon learned it was not necessary to modify the net pen when the fish adapted quickly and seemed to be quite at home. We abandoned any notion of putting hard bottoms in net pens and stocked our broodstock in a net pen at a US Fish and Wildlife Service laboratory without any problems. We also maintained some broodfish in a large indoor circular tank that was provided for us at that laboratory.

Flounders in the genus *Paralichthys* that R.R.S. has worked with will also stack up on one another when resting at the bottom of a culture tank, which is where they stay most of the time. The flounders assume an unusual posture prior to grabbing a feed pellet. They will prop themselves up on the bottom-side pelvic fin and assume a position somewhat like a snake that is about to strike. They follow the pellets with their eyes and then will select one and swim up to consume it. They will then return to the bottom of the culture tank. Once satiated, they will lie flat at the bottom again. Presumably, their behaviour in culture tanks is inherited and mimics lying in wait and attacking food in the wild.

Structure is often provided by the culturist who is involved with rearing cannibalistic species. Cannibalism is common following ecdysis (moulting) in crustaceans when the newly moulted animal is unable to protect itself. Cannibalism after moulting has been a significant problem associated with the culture of freshwater shrimp (*Macrobrachium rosenbergii*), as well as with crabs (e.g. blue crabs (*Callinectes sapidus*)) and American lobsters (*Homarus americanus*).

The rate of mortality from cannibalism of freshwater shrimp reared in tanks or raceways can be reduced by providing some type of shelter where the animals can find refuge while their exoskeletons harden after moulting occurs. Pieces of PVC pipe scattered around a tank bottom or sheets of fibreglass window screen suspended vertically in tanks have been used successfully to provide a place for newly moulted shrimp to find cover and protection from cannibalism. Marine shrimps are much less cannibalistic than their freshwater counterparts, so provision of shelter for those less aggressive species is not required. The extent to which cannibalism occurs in pond-cultured shrimp does not seem to have been thoroughly investigated, but it may be less than in tank-cultured shrimp, as those in ponds have lower densities and are often in turbid water, which may provide some protection.

High rates of mortality associated with cannibalism of newly moulted individuals are the main reason why blue crab culture has been slow to develop, though interest and activity in blue crab culture has increased in recent years in the USA. Research has shown that blue crabs can be cultured in ponds at very low salinities (a few ppt) with reasonable levels of survival. Blue crab hatcheries have been developed for producing small crabs for enhancement stocking, and also to supply crabs to small-scale producers of softshell crabs.

It is often said that if you start out with a tank full of young lobsters or crabs, you may end up with one big one! One solution is to provide lobsters with condominiums. That involves providing each animal with its own container so that there is no access by other lobsters in the tank to newly moulted individuals, which are vulnerable to cannibalism for at least a few hours while their new exoskeletons harden. Several plastic boxes fabricated so that they provide basically cages that allow water to flow freely though them can be placed in a tank or linear raceway and stocked with individual lobsters. Crab condos have not been developed to our knowledge, probably because the value of crabs is much less than that of lobsters, so the expense might not be warranted.

Suspended solids

Various types of materials can become suspended in the water within an aquaculture system. Among the most common are silt, mud and – in flowing water – sand (usually very fine sand). Organic particles such as plant and animal detritus of various sizes will also be seen suspended in the water, as will bacterial and algal mats. Food particles, faecal pellets and various types of microplankton and phytoplankton are among the other types of suspended solids. By definition, suspended solids are items of particulate matter larger than 0.45 μm that occur in the water column. Any particle smaller than 0.45 μm is considered to be colloidal or dissolved.

As we have seen, materials suspended in the water column will limit light penetration. Algal blooms can become self-limiting through shading unless sufficient circulation is maintained to bring each cell into the photic zone sufficiently often to allow photosynthesis to proceed. Inorganic and detrital particles will often cause sufficient turbidity to reduce the rate of photosynthesis in ponds. While phytoplankton is not a primary source of food for many aquaculture species, its presence is depended upon by filter-feeding molluscs and other aquaculture species, particularly those in their early life stages.

Establishing and maintaining a good phytoplankton bloom can be important even if phytoplankton is not a primary food source. That is the thinking behind the so-called green water technique that is widely used by shrimp culturists and many others. The technique, which merely involves maintaining a good phytoplankton bloom in the culture tanks, has been widely employed in Taiwan, where successful larviculture has been demonstrated on dozens of finfish species as well as shrimp. In Europe and North America, green water has also been used in the culture of the early life stages of a variety of species.

Establishing a phytoplankton bloom in ponds with turbid water can be very difficult because of greatly reduced light penetration. A couple of methods have been developed to reduce the turbidity if that is needed. One is to spread hay over the pond surface, though we must admit that our success using that technique has been unimpressive. In addition, when the hay decomposes, it will increase the BOD, potentially leading to anoxic conditions and resulting in fish kills if the pond has been stocked. A better approach, at least to our way of thinking, is to apply gypsum (calcium sulfate ($CaSO_4$)) at the recommended rate of 250–500 mg/l. Depending on the results, it may be necessary to repeat the treatment at weekly intervals. Alum has also been used with some success. That chemical, the formula for which is $KAl(SO_4)_2.12H_2O$, has been effective when used at 15–25 mg/l.

Suspended solids and in particular suspended inorganic particles, such as silts and clays, can be detrimental to aquaculture species when present at high levels. Gills may become clogged, eggs being hatched in ponds can be buried and smothered if the suspended material settles, and feeding may be impaired due to low visibility for visual-feeding species. Turbid water tends to warm more quickly than clear water, but it cools more slowly so it will retain heat longer, which may be good or bad depending upon the ultimate temperature that is reached and how that temperature might impact the species under culture.

Extremely turbid water should be allowed to settle or be filtered before being put in culture chambers. Filtration of large volumes of water can be expensive, so we are once again back to selecting a water source that has the proper quality with respect to suspended solids levels.

Some Additional Water Quality Effects on Cultured Organisms

Carrying capacity

The density of animals that can be reared within a particular area of water surface or volume of water is called the carrying capacity. There is a natural tendency among aquaculturists to push the limit with respect to putting as many animals in each culture chamber as possible, while maintaining good water quality and good performance of the species under culture. The tendency for the aquaculturist is to keep pushing the system with respect to stocking density. A fish farmer might stock 3000 kg/ha during a year, for example, and obtain good growth while maintaining acceptable water quality. The next year that same farmer may decide that an increase in density might work and would stock the fish at 3500 kg/ha with similar results. The third year, the stocking rate might be increased to 4000 kg/ha, with resulting reduction in morning oxygen levels that require aeration. While aeration may ward off oxygen depletions and allow the fish to survive to harvest size, the cost for electricity to run paddlewheels may offset the added income generated from increasing the stocking rate. At some point in terms of stocking rate, even constant paddlewheel aeration might not be effective, resulting in retarded growth at best and high levels or complete mortality as the outcome.

Whether grown on the bottom; grown on poles, strings or longlines; hung from rafts; reared in ponds; produced in raceways, cages or net pens; the concentration of animals that an area or volume of a culture system can support will be limited by food resources (which is related to nutrient level in systems that depend on natural food), water quality, competition and undoubtedly a number of other factors. There are no set rules with respect to maximum stocking rates that will ensure that carrying capacity is not exceeded. Each water body and culture system differs. Further complicating the situation is that various conditions in each water system are constantly changing. Nutrient levels (and consequently natural food availability) will change over time, particularly as the seasons of the year change, and water quality can be very fickle. That is, water quality may change rapidly with little or no warning in response to any one or combination of factors that influence the various water quality parameters that need to be kept within certain limits if the aquaculture animals are to perform optimally. In addition, biomass is constantly changing (increasing in most instances unless there is mortality or animals are removed for harvesting or graded and redistributed into new ponds, tanks, raceways, etc.). Avoiding a situation where carrying capacity is exceeded requires frequent water quality monitoring, paying attention to potential changes in the environment that may lead to problems, gaining experience over time and obtaining insight from other culturists in the region who are working with the same species under similar conditions.

Culturists should not be afraid to share information. In our travels, most of the aquaculture facilities we have visited have been very forthcoming with any details of their operation that we might have queried them about. Sometimes, as mentioned previously, you may run across an aquaculturist who thinks he or she has developed a technique, water system, feed, disease control, etc., that needs to be kept secret so that no one steals it. On those occasions when we have been shown a secret or two after promising not to divulge them, we have never really seen anything that was all that unique and had not been used elsewhere. On the whole, if somebody does develop a new technique, piece of equipment or some other type of breakthrough, they spread the word about it so others can incorporate whatever it is in their activities. In some cases, they do not share their idea as it may lead to a patent, which is reasonable. An example is that one of R.R.S.'s graduate students invented a fish fry feeding system that involved a timer that would drop feed from culture tanks at timed intervals. When we searched the literature, we found a paper in a journal showing a diagram that was almost identical to the student's design.

Recommendations have been developed with respect to carrying capacity in trout raceways that have been widely adopted and have withstood the test of time. Tables and formulas have been developed to inform the culturist of the proper trout stocking density when flow rate or water turnover rate, temperature, initial fish size and perhaps other factors are known (the book by Wedemeyer on hatchery management referenced in the 'Additional Reading' section of this chapter contains such tables and formulas). Recommendations or at least targets for various other species also exist and, as in the case of trout, those recommendations may vary considerably depending on the water system and management approaches that are used. For example, channel catfish can be stocked in ponds at densities that will result in maximum biomass levels from 3000 kg/ha to as much as 8000–10,000 kg/ha at harvest. Even higher levels have been reported in some cases. The range is associated with whether aeration is provided or not and whether aeration, when applied, is used periodically or continuously. To achieve the high end of the carrying capacity range, the fish farmer would have to run aerating devices 24 h a day. Routine stocking rate information for various other species is also available. General recommendations tend to be conservative as they are often applied over a variety of water quality conditions and in various types of systems. In many cases, recommendations may provide a starting point for culturists, who often will settle on the final rate that they are comfortable with after a period of trial and error. In Texas, USA, for example, a typical stocking rate for Pacific white shrimp (*Litopenaeus vannamei*) is of the order of 25–50/m^2, or 25,000–50,000/ha. Because the shrimp are typically harvested at 18–22 g, not the 450 g typical for channel catfish at harvest, it is not a high stocking rate. Higher shrimp stocking rates (up to 75/m^2) were used by Texas pond culturists in the past, but disease problems were exacerbated so the culturists cut back.

The approach associated with trial-and-error stocking to determine the upper limit of production per unit area of pond is a form of adaptive management, wherein an aquaculturist tries something (in this case, a particular stocking density), evaluates the results and modifies the stocking rate up or down the next time to see if production can be improved. To enhance the rate at which this type of information can be obtained, a culturist could stock several ponds at different densities, and carefully monitor water quality, growth, feed consumption, aeration requirements and so forth, to help guide the process of deciding upon the best stocking density. Those who try that approach should remember that no two culture chambers, whether they are ponds, raceways, tanks, net pens, cages or anything else, can be expected to perform identically. For most experiments of the type described, a researcher will use a minimum of three culture units for each stocking density, so the experiment is replicated in triplicate. It has been said that because of their extreme variability, pond experiments should be conducted using nine replicates for each treatment. Few researchers have ever followed that advice insofar as we know, and commercial culturists do not like to take the risks of experimenting with a significant fraction of their facility.

Some aquaculturists employ stepwise stocking; that is, they initially stock fry, post-larvae or fingerlings at very high densities in terms of numbers per unit area or numbers per unit water volume because total biomass is initially quite low. Later, based on the increased biomass that occurs over time as the animals grow, the density within the system will be reduced through partial or total harvesting and the harvested animals from an individual culture unit will be distributed among two or more culture units so that the density is greatly reduced from its original level. Depending upon species, the process may be repeated periodically during the growout period.

Intermittent partial harvesting is an approach that has been widely adopted in the channel catfish industry. You may recall that the technique involves harvesting marketable fish at intervals followed by restocking with fingerlings. The number of fingerlings restocked is usually about the same as the number of fish harvested, plus some additional fingerlings to make up for known or calculated mortalities that may have occurred between partial harvests. The approach may be employed over a period of years – sometimes, in excess of a decade – during which the pond is never drained, nor are all the fish ever removed. Even with careful record keeping, the fish farmer will not be able to make an accurate determination of the number and biomass of fish in the pond and may, at the time of a partial harvest, be holding fish well below the carrying capacity of the system, or perhaps far in excess of what might be considered appropriate with respect to the carrying capacity of the pond.

R.R.S. was once present during the partial harvest of a catfish pond where the farmer thought he had a small number of marketable fish remaining, since a few weeks earlier he had removed a large number of fish and sent them off for processing. He had brought in a seine crew to complete the task of removing the 'small number' of marketable fish that he thought remained. That harvest event netted about 4000 kg/ha, far in excess of what the farmer estimated would be caught. His pond had not been drained in about 15 years at that point, so it was clearly time to drain it and start again.

As technology advances, the instinct is to take advantage of that technology and try to produce more biomass without expanding the culture system. Once the carrying capacity using the new technology is exceeded and problems develop, there will be pressure placed on the research and engineering communities to develop newer technologies to overcome those problems. At some point this will be self-defeating as ultimately there are going to be upper limits on the carrying capacity of any water body or water system that technology will not be able to overcome, or at least not overcome and still allow the culture species to be produced profitably.

One of the students who worked with R.R.S. at the Texas A&M Aquaculture Center conducted a study in which we saw one incidence of the development of what we were told, by a colleague, appeared to be an autoimmune response in tilapia (*Oreochromis* spp.). What happened was that when the biomass of the tilapia in small tanks reached a certain level, an unidentified chemical was released into the water that caused an allergic reaction in the fish, some of which died, thereby reducing the biomass levels below the carrying capacities of the affected tanks. Additional research aimed at characterizing the chemical compound responsible for the phenomenon was curtailed when we were unable to reproduce the results, though we had seen the problem in at least two experiments. Support for the theory that the fish were producing a chemical responsible for the autoimmune response includes the fact that our collaborator on the project, who was a researcher in the College of Veterinary Medicine at Texas A&M University, was able to extract a high-molecular-weight compound from the water that, when injected under the skin of healthy fish, created an inflammation at the injection site that was indicative of an allergic reaction. Also, anecdotal information from people involved in the ornamental fish trade was that they had seen fish dying for reasons they could not determine, and that the mortality occurred when the fish were maintained at high densities. Those ornamental fish producers, too, concluded that there was a self-limiting factor involved in the deaths, as mortality ceased once biomass was reduced.

Harmful substances and off-flavours

The issue with gossypol in cottonseed meal and other anti-nutritional chemicals is various feedstuffs is discussed in Chapter 8, as is the problem of mould development on improperly stored feed or feed stored for extended periods of time; therefore, we will not go into most of those topics here. One mould issue that does deserve our attention now is *Aspergillus flavus*, a mutant blue-green mould that produces aflatoxin B_1, a toxic metabolite that sometimes occurs as a contaminant of cereal grains (such as maize (corn)) and oilseed meals (such as cottonseed meal and soybean meal). First identified as the causative agent for hepatomas (liver tumours) in rainbow trout (*O. mykiss*) in the early 1960s, aflatoxin has also been known to cause liver lesions in tilapia (*Oreochromis* spp.), is toxic to channel catfish (*I. punctatus*), leads to histopathology of the hepatopancreas in shrimp and has undoubtedly been a problem with respect to a variety of other species. The toxicity of aflatoxin to fish varies from species to species. Mould growth with concomitant production of aflatoxin may be induced through improper feed storage (discussed later in this chapter and in Chapter 8). Moist feed is particularly susceptible to development of aflatoxin-producing mould.

Toxic algae blooms can occur in both freshwater and marine environments and have been known to cause mass mortalities in wild as well as cultured fishes. Toxins may also accumulate in the flesh of aquatic organisms and lead to sickness or death when the affected organisms are ingested by members of higher trophic levels, and that includes being eaten by humans. For example, zooplankton, shellfish and finfish have been found to harbour paralytic shellfish toxins during blooms of the alga *Alexandrium fundyense*. That species and the better-known *Karenia* (formerly *Gymnodinium*) *brevis* are among the dinoflagellates responsible for the source of what are commonly called red tides. The term has little or nothing to do with the diurnal tides in the marine environment. They relate to the development of off-colour water that occurs when there is an algae bloom. Various species and groups of algae produce toxins that are concentrated in shellfish and can lead to human incidences of not only paralytic shellfish poisoning (PSP), but also diarrhoetic shellfish poisoning (DSP), neurotoxic shellfish poisoning (NSP) and amnesic shellfish poisoning (ASP). Careful monitoring of shellfish beds and the various other types of mollusc culture systems is necessary to ensure that contaminated products do not get into the human food supply.

Contamination of aquaculture species with trace metals and persistent organic compounds that are in the water has received a great deal of attention in recent years, as well as generated a lot of controversy. Research studies have often been contradictory with respect to whether the levels of various contaminants are higher in wild aquatic species used as human food or in the same species that are produced in aquaculture. Claims of bias and junk science have been associated with many of the studies but, on the positive side, the levels reported from a majority of the studies did not exceed concentrations considered safe for human consumption. There are places that have excessive levels of contaminants present and public health advisories – at least in many nations, but certainly not all – have been issued. In some cases, consumers are told to restrict their consumption of fish from certain locations or, in the case of women, if they are pregnant or nursing. Advisories also often include restricting consumption of certain aquatic species by young children. Limitations on fish consumption may be extended to immune-compromised individuals as well. Among the most commonly mentioned metals and organic compounds associated with health warnings are mercury, PCBs, dioxins and flame-retardant chemicals called polybrominated diphenyl ethers (PBDEs).

More common than direct toxicity is off-flavour in cultured animals. The problem has been associated with various chemicals, including geosmin and 2-methylisoborneol, produced by blue-green algae (cyanobacteria) and actinomycetes (also bacteria). The cyanobacterium *Planktothrix perornata* has also been found to produce off-flavour. The problem is typically reported as an earthy, musty flavour or a muddy taste. Off-flavour has been a significant problem with channel catfish (*I. punctatus*) in the USA and carp of various species globally, along with tilapia (*Oreochromis* spp.) and sharptooth catfish (*Clarias gariepinus*) in Europe. It is undoubtedly also a problem with respect to other species elsewhere. Off-flavour has not only been reported from ponds, but also from closed recirculating systems, where the responsible chemicals are produced by actinomycetes that are stimulated by the organic-compound-rich, aerobic environment provided in that type of water system.

Off-flavour commonly occurs during autumn when stocking densities are high, organic loading is also high and the water is warm. Feeding rate can also be a factor. The chemicals associated with the problem are stored in lipid tissues of the fish but can be metabolized. Placing affected fish in uncontaminated water can resolve the problem. Research has shown that depuration (Box 4.16) of 2-methylisoborneol and geosmin will occur in channel catfish from 96 to 150 h after removal of the fish from exposure to the chemicals. Attempts have been made to control the growth of one of the blue-green algae species responsible for production of 2-methylisoborneol with various chemicals. Of the chemicals evaluated, one that is both effective and environmentally and toxicologically safe is sodium carbonate. Copper sulfate also has been used to control algal growth, and levels that can do so do not produce toxic levels for other organisms or cause negative impacts on waters receiving aquaculture effluents. Adding such hydrophobic substances as paraffin and maize (corn) oil to the water has been shown to significantly reduce the levels of 2-methylisoborneol and geosmin in laboratory studies. How practical and economical that approach might be on commercial fish farms is another matter. Natural quinones (members of a class of aromatic hydrocarbons) have, at least in one case, shown promise as algicides that could possibly inhibit blooms of off-flavour-producing algae.

Box 4.16.

Depuration is the term used to define the clearing of the flesh of an organism of one or more chemicals or pathogens. In this case, it relates to off-flavour-producing chemicals in fish, but depuration is also commonly used in conjunction with shellfish, such as oysters, that have accumulated bacteria that can produce sickness and even death in humans when consumed. The problem is most common when people consume contaminated raw or undercooked oysters.

Some of the BMPs that have been recommended as means of reducing the chances of off-flavour development include liming ponds, aeration, and limiting nutrient levels by ceasing or restricting fertilization and avoiding overfeeding.

Most of the channel catfish marketed in the USA are processed in large plants that receive numerous truckloads of fish daily from various farms. A method for detecting off-flavour before the fish are processed needed to be developed if processing plants were to maintain quality control on their products. Even a small percentage of off-flavour fish that might reach the consumer is deemed unacceptable because any customer who purchases an off-flavour catfish will be unlikely to purchase the product again.

The method used to test for off-flavour in processing plants involves first cutting off the tail of a randomly collected fish that is brought to the plant by the fish farmer and smelling it (sometimes the odour can be detected in raw flesh). The tail is then placed in a microwave oven for a set time, after which the meat is sampled by a processing plant worker who has been trained to detect off-flavour at very low levels. The taste test is often conducted on at least three occasions before the fish from a pond are processed. The three times are: (i) several days before scheduled harvesting; (ii) three or so days before harvesting; and (iii) when the shipment of fish arrives at the plant or before the fish are captured on the day of harvest. If the fish fail any of the tests, the pond containing those fish will not be accepted for processing until the problem has been corrected. Obviously, the farmer does not want the fish rejected when they arrive at the plant because the animals will already have been stressed by capture and handling and a considerable amount of money may have been expended in hiring a seining and hauling crew. It is far better to have a fish tested by the processor prior to implementing the seining process in the event off-flavour is detected on the day the fish are scheduled for harvest, than having to truck them back to the farm. That could pose a real problem if the pond was drained for harvesting and another pond full of water was not available.

Off-flavour can be eliminated, as previously mentioned, through depuration within a few days if the fish are placed in water, such as newly drawn well water, that is free from the algae that caused the problem. Most farmers (and processors) do not have suitable facilities to depurate their fish, so unless they treat the pond using one of the previously mentioned approaches to kill the algae, they will have to wait for the algal bloom in the affected pond or ponds to die off. Thereafter, the farmers need to periodically keep testing the fish until the animals can be processed. In one visit I (R.R.S.) made to a catfish processing plant I was told that they were having a good day. Only about 50% of the fish they tested had off-flavour. On some days the rate was said to be considerably higher.

Summary

While virtually everything discussed in this text is important (or we would not have told you about it), perhaps nothing is as important as the establishment and maintenance of good water quality. Once the culturist has found a dependable supply of good-quality water, as discussed in Chapter 2, careful monitoring is required to ensure that the water quality stays within established parameters, which will vary from species to species in many instances as we saw in Table 4.1. It is possible to measure the levels of thousands of chemicals in water, but that is usually not necessary unless there is some suspicion of contamination with such things as biocides or trace metals, and even in that case screening would only involve determining the concentration of certain chemicals thought to be locally present.

The most important variables to measure on a routine basis are:

- Temperature: This controls metabolic rate and feed consumption.
- DO: This is necessary for survival and proper cell metabolism.
- pH: Maintaining a pH above 7.5 is particularly important for marine species with $CaCO_3$ exoskeletons.
- Nitrite: This can build up to toxic levels, particularly in recirculating water systems.
- Salinity: Each species has a range of tolerance and a range in which it performs best under culture conditions.

Ammonia should be monitored routinely in recirculating systems but tends not to be much of a problem in other types of culture systems. Hardness and alkalinity should be determined in freshwater systems and maintained at 20 mg/l or higher for maintenance of the buffering capacity in those systems.

In pond systems it is desirable in many instances to establish and maintain a plankton bloom. That is particularly important as a means of providing food for post-larval and fry stages of aquatic animals. Establishing a plankton bloom can be accomplished through fertilization with either organic or inorganic fertilizers, or the two in combination. Sometimes fertilization does not work properly and instead of encouraging plankton growth it may lead to the development of filamentous algae or higher plant growth. In that event, it may be necessary to eliminate the plants through biological, mechanical or chemical control.

Other factors that can affect water quality and aquaculture animal performance include light (intensity, wavelength and photoperiod), the type of substrate available in the water system and suspended solids. As culture animals grow, they impact water quality, which will then influence the carrying capacity of the water system, so it may be necessary to take appropriate action as conditions change to maintain optimum conditions. Finally, harmful substances in the water that are sometimes introduced through improper water management (though many times this is beyond the control of the aquaculturist) can impact performance and even survival of the culture species, and may affect flesh quality, including flavour.

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5 Diseases and Parasites of Aquaculture Species

Disease Array and Role of Stress

Sources of mortality in aquaculture systems may include cannibalism, predation, degraded water quality, nutritional imbalance and toxicants in the water, as well as toxins from improperly stored feed, poaching, pollutants and disease (Box 5.1). In this chapter, the focus is on diseases that occur in aquaculture species – and remember, we include shellfish when we use the word 'fish'. If we use the word 'finfish', shellfish would be excluded, and vice versa. Included among the major groups of organisms that cause disease in aquatic species are viruses, fungi, bacteria and parasites. The latter includes various species of protozoans, copepods, cestodes, nematodes, trematodes and isopods. There are also environmental and nutrient deficiency diseases that sometimes arise in aquacultured animals. A few examples are included in this chapter, but in an introductory text of this nature it is not possible to discuss every disease that has been identified from aquaculture species in any detail. A few disease agents are discussed in various sections of this chapter, and there is one section devoted to providing additional information on some of the diseases that were previously discussed briefly, as well as some that were not discussed at all.

One scenario of disease occurrence that has been observed repeatedly is as follows. During the initial stages of culture with a new species, disease problems tend to be rare but, as culture activity expands, diseases begin to occur with more frequency and the types of diseases that are encountered proliferate. Part of that phenomenon, perhaps most of it, has to do with attempts by culturists to increase production levels within their system, which increases stress, thereby leading to increased susceptibility to epizootics.

The relationship between genetics and disease resistance in aquacultured species has been the subject of research for more than 25 years. The usual approach is to challenge fish with a disease organism and determine if some of them (perhaps from various locations, families, or other variables) are more resistant than others. Selective breeding could then help in the development of disease-resistant strains, though that outcome seems to have been less than stellar. A better approach is to identify a specific gene that provides disease resistance and insert that into the genome of the species of interest. That leads to development of a GMO, which leads to controversy and even banning of the GMO animals in some countries. At least one gene specific to resistance to a virus (WSSV) has been identified in the marine shrimp *Penaeus monodon*. As genome maps of aquaculture species are developed, more and more genes associated with disease resistance will undoubtedly be identified for finfish and shellfish. Producing aquaculture species with resistance to diseases could go a long way towards the goal of reducing or even eliminating the need for antibiotics and other chemical therapeutics.

Disease organisms are cosmopolitan in aquatic environments and the animals that live in those environments are constantly exposed to pathogenic or potentially pathogenic organisms, just as are humans (Box 5.2). Yet diseases often fail to manifest themselves, either in the wild or under culture conditions. In the case of finfish, there are fairly well-developed innate and adaptive immune systems, but only the innate immune system is present in many (if not most) invertebrates of culture interest. Despite that, disease incidence is arguably not more common in invertebrates than in vertebrates, at least in culture situations.

DOI: 10.1079/9781800621145.0005

Box 5.1.

The term disease includes various conditions and organisms which can cause ill health such as parasites, of which there are crustacean (e.g. copepod, isopod, etc.), helminth (e.g. cestodes, nematodes, trematodes) and protozoan (single-celled eukaryotic) examples in various aquatic species.

Box 5.2.

During the flu epidemic of 1918, and recently during the COVID-19 pandemic, people have been advised not to congregate as a means of avoiding coming into contact with someone who is infected. Your chances of contracting the flu in a crowded room or on a bus, train or plane where one or more of the people are contagious are much higher than they would be if you are walking alone in the countryside and rarely come into contact with another person. Similarly, a bunch of salmon crowded in a net pen, or shrimp in a pond, are more susceptible to an epizootic than the same species would be if it were living free in the ocean where the density per unit area is but a fraction of that in a culture system.

There are literally thousands of diseases that can affect species produced in aquaculture, and those diseases are not limited to animals. Plant diseases also occur, though those are not addressed here, and have not received much attention by researchers. Some pathogens are species-specific or group-specific. For example, shrimp viruses, in general, do not attack other decapods – at least not the viruses that have caused epizootics to date, so we cannot rule out the possibility that some shrimp diseases will not affect lobsters or crabs. Channel catfish (*Ictalurus punctatus*) virus disease does not attack salmon or trout, and viruses that affect salmon or trout do not attack catfish. Diseases that are pathogenic to aquaculture species are not pathogenic to humans in most cases. Many bacterial pathogens are not very particular with respect to the species that they will infect, at least within a class or even phylum, while others are very specific. As you will see, however, molluscs can harbour bacteria that can cause illness and even death in humans, but not affect the molluscs that obtain them as part of their filter-feeding activities.

Despite the large number of diseases that have been identified – with more being identified routinely – the incidence of diseased fish in aquaculture systems is usually relatively low if the culture animals are not under stress. Examples where epizootics have occurred include situations wherein large numbers of heavily stocked net pens were placed in close proximity in marine areas, particularly if they were not well flushed. The result can be that carrying capacity is exceeded, with resulting impairment of water quality. In recent years, the Chilean Atlantic salmon (*Salmo salar*) industry, which is practised in protected coastal bays, has suffered from persistent epizootics of infectious salmon anaemia (ISA), which is caused by a virus. The disease had a major negative impact on the salmon culture industry that permeated through the economy of southern Chile, which is based largely on aquaculture, with Atlantic salmon being the major commodity produced. The problem has been ameliorated through new regulations and improved management practices, as mentioned in in Chapter 3. A good deal of mussel (e.g. *Mytilius* spp.) culture also occurs in Chile, often in close proximity to salmon net pens, though ISA has no impact on mussels.

When an animal is stressed, its susceptibility to disease increases exponentially. In both nature and aquaculture, stress may be brought on by changes in the environment; for example, rapid cooling or warming of the water, exposure to low DO, a significant diurnal fluctuation in pH, exposure to elevated levels of ammonia or nitrite, or other stressors. Animals may also be stressed during periods of physiological change. Examples are smoltification or alteration of normal activity such as that associated with the establishment of territories or breeding behaviour (which may involve fighting). Additional stressors associated with aquaculture include crowding and handling (handling stress also occurs in nature through catch-and-release recreational fishing and the release of by-catch from commercial fisheries).

A major priority of the aquaculturist who wishes to become and remain successful should be to maintain the least possible level of stress as possible on the animals in the culture system. That does not mean diseases can always be avoided, but their incidence can be dramatically reduced if procedures that keep stress to a minimum are adopted. The following example is illustrative of what we mean.

When R.R.S. first started conducting aquaculture research as a graduate student, he was working as a research assistant to James W. Andrews at the Skidaway Institute of Oceanography. Jim had designed a recirculating system in which he had stocked channel catfish at extremely high density (see also Box 3.8). The fish had virtually no way to swim about as they were literally stacked one on top of the other. For several months there was no sign of disease. Periodic examination of the fish showed no presence of lesions that might have been caused by bacterial infections, and no parasites were found on the gills or on the body surface. One night there was a brief power failure that shut down the pump associated with the system for a sufficiently long period of time that the DO level fell and the fish were exposed to low-oxygen stress, though there was no immediate mortality. A few days later, a very heavy infestation of a parasitic protozoan (in that case, one known as *Trichodina* spp.) erupted. The gills of the fish were covered with the microscopic parasites. A chemical treatment was applied, which once again stressed the fish. The *Trichodina* infestation was cleared up and the fish seemed to be normal for a few days, after which they began dying in large numbers. Examination of the fish showed that they had problems associated with both bacterial and parasitic infections. It should also be mentioned that the source of the water in the system was a deep well, so the incoming water was not considered to be the source of the disease organisms. Those organisms apparently had been harboured at low enough numbers to escape detection on the fish when the animals were healthy, and the diseases were not manifested until the fish became stressed (Box 5.3).

Box 5.3.

An epizootic may occur within 24 h after a stress event, but more commonly outbreaks do not become evident for 72 h or even up to 1–2 weeks after the animals are stressed. The longer between the stress event and the onset of an epizootic, the less likely it will be for the culturist to connect the two. Keeping good records will help you make that connection. The reason for the delay relates to the time it takes for the disease organism or organisms to develop large enough populations to become apparent to the culturist when signs of disease develop.

We have indicated that the incidence of diseases is relatively low in the typical aquaculture facility, and some authorities have said that no more than about 5% of aquaculture facilities experience a disease epizootic in any given year. However, that statement was made a few decades ago with relation to the channel catfish industry when it was in its development phase and now may be an underestimate. It is estimated that many millions of dollars in direct fish losses are incurred each year in the production of channel catfish in Mississippi, Alabama and Alabama, three of the largest catfish-producing states. Much of that mortality has been attributed to the bacterial pathogen *Edwardsiella ictaluri* which causes enteric septicaemia of catfish. Much of the industry has shifted to the production of hybrids between the channel catfish (*I. punctatus*) female and blue catfish (*Ictalurus furcatus*) male due to the resistance of blue catfish and hybrids to this pathogen.

The global cost of disease incidents to the global aquaculture industry is not insignificant. As we have seen with the Chilean Atlantic salmon (*S. salar*) example, a large percentage of an industry can be impacted, and that impact may last for more than one growing season. Millions of dollars in revenue were lost by the salmon industry. According to recent information put forth by the FAO, diseases cost the global aquaculture industry over US$3 billion annually. While the salmon industry in Chile is a good example, it is not by any means the only one where a major portion of an industry has been devastated by disease. In at least one instance, the impact was nearly global in nature.

Shrimp virus diseases have caused enormous losses to the commercial marine shrimp industry in various Latin American and Asian countries, though they do not necessarily occur every year or in the same locations from one outbreak to the next. The US marine shrimp industry is not large compared with those of Asia and Latin America, but disease has had a serious impact. While the first report of a viral disease in shrimp appeared in the early 1970s during the early stage of cultured shrimp production, widespread epizootics did not occur until the 1990s. WSSV was first observed in parts of Asia in 1992, and by 1999 the disease had found its way to Latin America, leading to shrimp losses in Guatemala, Honduras, Nicaragua and Panama.

That same year YHV, which had earlier caused significant shrimp losses in Asia, was also detected on shrimp farms in Latin America. Those two, along with other viruses including infectious haematopoietic necrosis virus (IHNV) and TSV, plagued the industry worldwide as they spread from one producing nation to another.

Further discussion of shrimp viruses can be found below, but for now the focus is on why an industry that developed in the 1970s experienced such devastating losses beginning nearly two decades later. As you may have guessed, at least part of the reason relates to stress. As is commonly the case in aquaculture more generally, as the shrimp industry developed, producers increased their stocking densities to the point of stressing the shrimp. Aeration needed to be provided 24 h a day to maintain oxygen levels. Other stressors were often present in addition to high stocking rates. Ponds were often constructed in mangrove areas that had soils with high sulfide levels in them. Over time acidity levels in the ponds increased significantly, leading to severe levels of stress and poor shrimp production. After a few years the ponds had to be abandoned.

In 2004, the heart of the commercial marine shrimp industry in Texas, USA, experienced serious losses due to a virus outbreak in shrimp that were produced in a hatchery that had been considered virus-free. The source of the infection is not known, but it is suspected that it may have been from the shrimp-processing industry. The processing waste from infected imported shrimp, along with processing waste from wild and uninfected cultured shrimp, was placed in landfills where it was accessible to birds that may have ingested contaminated waste and later defecated into shrimp aquaculture ponds containing previously virus-free shrimp, thereby infecting them with the virus. There has also been concern about the spread of shrimp viruses in frozen imported shrimp.

There have been documented incidents of transmission of bacterial kidney disease (BKD), furunculosis and the infectious pancreatic necrosis (IPN) virus from wild to farmed salmon. Opponents of salmon aquaculture have expressed the opinion that infectious incidences of ISA virus disease and increased incidences of high body burdens of sea lice on wild fish are the result of concentration of those disease organisms in fish reared in net pens. The concern is that wild fish swimming near net pens will be more susceptible to acquiring one of the diseases than if the organisms had not become so highly concentrated. Fish farmers often argue that the disease epizootics they experience on their farms are due to transmission from wild to cultured fish. There have been a number of studies and reports that have come to different conclusions relative to the issue. How much of that relates to the preconceived conclusions of those who conducted the studies and/or the organizations that funded the research is an open question.

Some universities, government agencies and other organizations around the world provide disease diagnostic services with respect to aquaculture species. For example, the Southeast Asian Fisheries Development Centre (SEAFDEC), based in the Philippines, offers free diagnostic services to shrimp farmers who experience disease problems. Some universities in the USA provide, or in the past have provided, diagnostic services to aquaculturists. They include Auburn University in Alabama, the University of Florida, the University of Arizona and the University of Arkansas Pine Bluff campus. The University of Stirling in Scotland is another, and we are sure the list is much longer than these few examples. However, in many places such services are not available, or the laboratories are not conveniently located in regions where aquaculturists can get their specimens to them in a timely manner. Because diagnosis and treatment cannot usually be delayed for a period of even a day or two after a problem is detected, it becomes incumbent upon the aquaculturist to learn how to diagnose and treat any disease epizootic that may occur – assuming it is a widely known disease that the culturist is able to identify and, further, that some form of treatment is available. The fact is that for some diseases no effective treatment is currently available. In addition, when some form of treatment is available there may be limits on how long it can be used and how often it can be repeated. Finally, approved treatment chemicals and protocols should be used. BMPs should be applied at all aquaculture operations but are particularly important in places where regulations on treatment have not been promulgated, as the BMPs may reduce the risk of an epizootic. Disease treatments that place the health of consumers at risk should not be used. Such practices are unethical and importing nations often screen for illegal chemical and drug use because they recognize that, while their numbers may be small, there have been a few unscrupulous producers in the aquaculture industry who knowingly (or perhaps unknowingly) used unapproved chemicals and apparently placed financial gain ahead of human health and safety.

Frequent examination of the culture animals is important so that early recognition of the signs of a developing epizootic is facilitated. Relying for long periods of time on automatic feeders (see Chapter 8) without visually ensuring on a daily basis that the animals are actively feeding has the potential for disaster. Such daily examinations are certainly BMP and should be a routine at every aquaculture facility. The importance of observing the animals while feeding when possible – since making that observation is difficult with respect to some species and in some culture systems – cannot be overemphasized. Indirect methods of checking on feeding activity have been developed and are discussed in Chapter 8. The need for early detection of a disease problem cannot be overstressed. The last thing you want to do is find out you have a problem when an epizootic has resulted in mass mortality.

There are several books devoted to aquatic animal diseases in general, or to diseases of certain culture species or species groups. There are also a few books that are devoted to discussing specific types of diseases. A good representation of such books can be found in the 'Additional Reading' section at the end of this chapter.

Avoiding the Occurrence and Spread of Disease

Disease avoidance in aquaculture is never totally assured, but there are some steps that can be taken by the culturist to reduce the likelihood of an epizootic. We have already mentioned adopting BMPs as a first step and implementing a biosecuring programme. Another is to produce or purchase healthy animals for stocking. Some producers of post-larval invertebrates or fish larvae, fry and fingerlings rear them in a manner that allows the producer to market the animals as being specific-pathogen-free (SPF) with respect to one or more particular diseases. Assurance of SPF status is based upon frequent testing of samples for specific diseases, for example one or more of a group of viruses specific to marine shrimp; though, as we saw in the case of a Texas hatchery, even SPF animals can acquire the disease that they are supposed to be free of even if they were apparently SPF in the hatchery. There is certainly no guarantee that the environment into which SPF animals are placed does not or cannot eventually harbour the pathogen. At one time there were those who claimed they were producing entirely pathogen- or disease-free animals for sale, but such claims are difficult or impossible to substantiate, so the terminology today involves only the assurance that the animals are free of only one or more identified pathogens.

Certification of SPF status may require examination by a certified aquatic animal pathologist or a veterinarian who is appropriately qualified to work with aquatic animal diseases. It is worth noting that most schools of veterinary medicine still do not focus much of their teaching on aquatic animal diseases. Regardless, there are some veterinarians who specialize in aquatic animal medicine, and we can anticipate that more will adopt that speciality as the need for such services expands. When culturists spawn and rear juveniles for stocking within their own facilities, the question of ensuring that the animals are healthy prior to stocking is still critical, and the culturists may have an expert in aquatic animal diseases check their animals prior to stocking to ensure their health status.

As we have seen, a primary means by which the culturist can reduce the risk of disease outbreaks is to maintain a culture environment that exerts a minimum amount of stress on the animals in the system. Stress avoidance cannot, if you will pardon the pun, be overstressed. It is something that needs to be continuously kept in mind. Stress avoidance should be at the top of the culturist's list of BMPs.

Vigilance is another factor that is important in relation to maintaining healthy culture animals. The culturist needs to frequently monitor the behaviour of the aquaculture animals. Changes in behaviour such as a reduction in food consumption, rubbing against the sides of tanks or raceways, swimming erratically (resulting in 'flashing' in some species) and gulping for air at the surface are obvious signs of problems with respect to finfish. Changes in behaviour are often much more difficult or virtually impossible to directly observe in invertebrates, particularly filter-feeding species.

Biosecurity of an aquaculture facility can provide some protection from disease transmission. By that, we mean that every effort should be made to ensure that the culture facility is not exposed to pathogens from another facility. Biosecurity also implies that the culturist has a responsibility to keep his/her animals from exposing someone else's facility to pathogens. So, the biosecuring concept goes both ways. When animals are introduced from an outside source, they should be quarantined for a sufficiently long period that the culturist is confident no diseases are going to be manifested in the form of an epizootic. Three weeks is probably a sufficient quarantine period. Use of SPF animals, when available, provides an additional level of protection, but we do not think it obviates the need for quarantine. Providing biosecurity is easier for some types of water systems than others. Indoor closed systems lend themselves to a high level of biosecurity, while cages, net pens and the various types of mollusc culture systems do not. Ponds and raceways fall between the extremes.

While every effort should be made to avoid epizootics, no facility is ever 100% assured of avoiding disease problems. As we have seen, even animals from which no pathogens can be isolated may still be carriers. Since diseases will occur at some point on most culture facilities, early detection is important.

An incidence of high-level mortality is an obvious sign that something is wrong, though a low level and relatively constant rate of mortality is not uncommon with many species under even the best environmental conditions and management practices. Regardless, moribund or dead animals should be removed from the culture system immediately upon discovery and should be examined both with the naked eye and under the microscope for signs of pathology. Swabs taken of the body gills and internal organs for incubation to assess the presence of pathogenic bacteria also is a good idea, but not practical in many situations (e.g. lack of the ability to culture the samples on site and/or absence of a nearby laboratory that can test the samples). Verification of viruses is more difficult and requires specialized techniques (cell culture, polymerase chain reaction (PCR) and electron microscopy, for example). The earlier a potential disease problem is detected, the sooner a treatment protocol can be initiated. As with behaviour changes, detection of mortalities is easier with respect to finfish with swim bladders since they will usually float to the surface soon after death. That is not the case with invertebrates. Reduced feed consumption or cessation of feeding is a frequent sign of disease onset that can be monitored with finfish and crustaceans, but it is difficult to determine if a mollusc is feeding actively. In the case of molluscs, the first sign of a problem may be large-scale mortality. Fish that receive floating feed can easily be observed and feed consumption can readily be monitored (see Chapter 8). Shrimp culturists often use trays on which feed is placed, after which the tray is lowered into the water. After allowing sufficient time for the shrimp to feed, the tray can be raised and examined to see if shrimp are present. Because shrimp feed slowly and the pellets are highly water-stable (see Chapter 8), the culturist can leave the tray submerged for a long period without fear that the pellets will be entirely consumed or will dissolve. The tray should be left in the water for at least 15–30 min before checking it.

Biosecurity procedures that will reduce the potential for spread of a disease around the facility need to be implemented and maintained throughout the culture period in instances where an epizootic occurs despite all the precautions that have been taken. The transfer of items from one pond, raceway or tank to another without properly disinfecting those items can lead to the spread of an otherwise localized disease. Dedicated supplies that are used on a day-to-day basis should be assigned to each culture chamber except in the case of culture chamber units that share the same recirculating water system. Items such as dip nets (Fig. 5.1) and cleaning brushes should not be used in more than one culture chamber unless they are disinfected between uses. It is even wise to have individual feed buckets dedicated to each tank in a hatchery or growout facility. In pond systems, items such as waders and seines should be disinfected before being moved from one pond to another (Box 5.4). It is not practical to have a seine or sets of waders dedicated to each pond.

People can carry and transfer aquatic animal disease organisms on their bodies, clothing and shoes. Hands should be cleaned with a disinfectant soap between the time the person works in one raceway and moves to another. Some facilities, or parts of them, are treated like clean rooms. People who enter may be required to wear special coveralls, or at least wear booties over their shoes or walk through an iodine bath (e.g. using Betadine® or a similar product to make the solution) to sanitize the bottoms of their shoes before entering the culture chamber room. In some facilities, such as biosecure hatcheries, there are restrictions on who can enter. There may also be a requirement for all people who enter the facility to wear clean coveralls over, or in lieu of, their street clothing; to put on a hat; and to exchange street shoes for rubber boots. The clothing worn in the clean area stays there between uses so as to not become contaminated.

Fig. 5.1. A group of circular tanks in a building, each of which has its own dedicated dip net to avoid cross-contamination.

Box 5.4.

Items such as dip nets, seines and waders that are used in multiple raceways, ponds and so forth should be disinfected after use. A typical disinfectant is a 10% bleach solution. Leave the item in the solution for no more than a few minutes and then rinse it with clean water. The item can then be used in another culture chamber. Large seines (which may be 100 m or longer when designed for use in large ponds) can be dried in the sun between uses. Smaller seines can be dipped in a large vat of disinfectant and rinsed before reuse in another pond.

We suppose you might want to launder the coveralls occasionally. When carried to its most extreme form, different colours of coveralls are worn in different locations, and no one is allowed in a room unless they are wearing the appropriate colour so as to avoid cross-contamination.

All the above biosecurity measures look good on paper, but it is not a simple matter to put them into practice. We have been to commercial facilities where you cannot enter the hatchery unless you wear rubber boots that remain just outside the door. And stepping in a disinfectant bath whether in the rubber boots provided or in your street shoes is also common. We are sure some people avoid stepping in the disinfectant solution as they might not want to 'damage' their street shoes. Avoiding the foot bath could easily cause contamination, and if someone wants to avoid the bath, they should not be allowed into the facility. Many of the other precautions mentioned are not frequently adhered to in the typical aquaculture facility.

Diagnosing Disease Problems

A disease problem may first be suspected when there is a change in behaviour of the species under culture (as previously noted), when lesions are observed or when unusually large numbers of mortalities begin to appear. The earlier the disease is detected, the higher the likelihood that it can be controlled, assuming a treatment protocol is available. In some instances, such as is the case with many viral diseases, no good treatments are available and the culturist may just have to be prepared to accept significant levels of mortality, destroy the remaining stock and disinfect the culture system. In many cases, a disease can be confined to one or a few culture chambers if precautions to avoid cross-contamination (as discussed in the preceding section) are followed.

When a disease strikes in a larval or post-larval tank, raceway or pond, it may be possible to avoid the spread of the disease around the facility (as well as be economically prudent) by destroying the entire group of animals in the culture chamber, sterilizing the unit or units that experienced the problem (Box 5.5) and properly disposing of the dead animals. One good method of disposal is by burial. By being mindful of the need for good sanitation and not using potentially contaminated items in uncontaminated culture units, it may be possible to contain a disease and avoid having it spread throughout a facility.

It is important to precisely identify the cause of any disease that is detected if proper treatment is to be employed. It makes little sense to treat a bacterial infection with a chemical that kills only parasites, and an antibiotic treatment will not have any impact on a nutritional deficiency problem or virus, for example.

The first step is to examine some of the animals that are exhibiting signs of disease but are still alive. Decomposing dead animals will typically be covered with fungus, which is often a secondary infection that has nothing to do with the actual cause of the mortality. Thus, it is better to examine living but perhaps moribund animals that appear to be infected, than to focus your attention on dead animals.

External examination usually comes first. If there are open lesions on the body or gills, they are likely to have been caused by a bacterial infection. Swabs should be taken so that the bacteria can be plated out and identified. Some culturists have been trained in bacterial identification and maintain laboratories that are capable of incubating culture plates. However, most culturists have neither sophisticated bacteriology laboratories nor the training required to type bacteria. In that case, one or more infected fish should be placed in plastic bags that are put in a cooler on ice and taken to a diagnostic laboratory. As we shall see, the number of antibiotics approved for use in treating aquatic animal diseases is small, particularly in developed nations (Box 5.6), so one of those compounds is frequently used immediately when a bacterial infection is suspected. Waiting for a specific diagnosis may be impractical because by the time the results come back, the level of the epizootic may have accelerated to the point that little benefit will result from treatment. At the same time, it is useful to find out just what bacterium was involved as you may be able to identify future outbreaks from the form of the lesions that you observed in the first instance.

A variety of external parasites may also be found on the body or gills of an infected aquatic animal. Gill diseases, caused by either bacteria or parasites, are particularly common in finfish. Many protozoan parasites are visible to the naked eye, while others are microscopic and should be looked for under a microscope. Low power is usually sufficient for detecting them.

As previously indicated, fungus infections are often secondary to a disease of some other type, though primary infections of fungus can occur. The

Box 5.5.

Sterilizing tanks and linear raceways is relatively simple. It can be done by scrubbing the affected culture units with a 10% bleach solution and flushing them with water to remove all traces of bleach. Ponds are more difficult to treat. While bleach could be an option, the volume needed makes its use impractical. One common method to sterilize ponds is to drain them and allow them to dry completely. Lime (CaO) is sometimes applied and disced into the pond bottom to oxidize the sediments and provide some assurance that any latent disease organisms that exist in the sediments have been destroyed.

Box 5.6.

While there are many nations in which little or no control on antibiotic use is imposed, some countries have regulations that prohibit imports of aquaculture species that have been exposed to certain antibiotics, or to any antibiotic that is not approved for use in the importing nation. Residue testing is now common in some countries, so that the importing nation can ensure that the regulations are being followed, though it should be recognized that it is virtually impossible to test every shipment of aquaculture products that is imported to a nation that does such testing. Random testing is probably the norm.

Fig. 5.2. Fingerling tilapia with furry growths of fungus on their bodies.

Box 5.7.

Humans exhibit symptoms when we contract a disease, and in most cases can communicate those symptoms to medical professionals and other people. Animals other than humans are not able to tell us how they feel when they contract a disease, so they exhibit signs and do not have symptoms.

most common fungal infections are caused by *Saprolegnia* (Fig. 5.2). The problem appears as cottony patches on the body surface in fingerling or larger fish. Egg masses are particularly susceptible to fungal attack. Verification that what you are seeing is fungus can be easily accomplished through microscopic examination.

Many parasites attack the various organs within the bodies of aquatic animals. Helminthic parasites such as cestodes and nematodes will occur within the digestive tract. If you cut open up a fish, you may find nematodes in its stomach. These roundworms are not typically pathogenic, though they may reduce the growth rate of infected fish because they use nutrients from the feed the fish consumes. So, it is wise to look for other problems in a moribund fish that has intestinal nematodes. Trematodes (flukes), on the other hand, are nasty little beasts that can lead to mortality. They may infect the liver or other internal organs, along with possibly being present in the musculature. Eye flukes (*Diplostomum* spp. and *Tylodelphys* spp.) have been found in cultured salmonids. Digenetic trematodes may occur as intermediate stage cysts as well, in which case your culture animals are serving as intermediate hosts. White patches in the liver may be due to parasites, though fatty livers can be caused by nutritional deficiencies. Close examination using a microscope will reveal the differences between those causes of discoloured livers.

Viruses are often identified through behavioural signs (Box 5.7) associated with outbreaks. Histopathology, light microscopy and electron microscopy have been widely used to diagnose specific viral diseases. In recent years, deoxyribonucleic acid-based (DNA-based) detection methods for viruses have been developed. Because of the devastation that has been caused to the cultured shrimp industry from a number of viruses, a great deal of effort has gone into sequencing shrimp viral DNA and in developing rapid detection methods using such molecular biology techniques as PCR and reverse transcription polymerase chain reaction (RT-PCR). Basically, these are methods by which portions of a DNA strand are copied millions of times. The gene sequence in the strand can then be identified and related to the known sequence in a particular virus.

Viruses are often species-specific, though some can infect a range of species or families. More viruses are detected each year, largely because scientists are spending more time looking for them, not because they haven't been around for long periods of time. They are only new to science, not new to the environment. Finding new viruses is facilitated by sophisticated detection methods that have been developed in recent years. Many of the viruses found each year do not appear to cause pathology in the aquatic species of current aquaculture interest. Sometimes a virus is found that looks for all the world like a known pathogen, but when present causes no problems. There have been cases where a virus that looked like a highly pathogenic type was isolated in a hatchery, but no mortality that could be associated with the virus occurred. Hatcheries have been known to destroy millions of fish thinking they were avoiding an epizootic.

A complete listing of the disease-causing organisms that have impacted aquaculture around the world would require volumes, though we have provided a brief discussion of some of the more common ones at the end of this chapter. To provide you with at least an indication of the array of diseases that can affect cultured aquatic species, some are shown in Table 5.1. The examples in Table 5.1 include all the major groups of disease-causing

Table 5.1. A list of some of the disease organisms that have caused problems in aquaculture, along with notes on species or species groups affected and other pertinent information.

Disease agent	Examples	Notes
Fungi	*Branchiomysis* spp.	Causes a condition called gill rot in a variety of species
	Saprolegnia spp.	Cosmopolitan in freshwater. Often a secondary infection
Viruses	CCV	Channel catfish virus
	Infectious dropsy	Affects carp and other finfish
	Infectious haemolytic anaemia	Probable waterborne virus affects coho salmon in Chile
	IHHNV	Infectious hypodermal and haematopoietic necrosis virus in shrimp
	IHN	Infectious haematopoietic necrosis in salmonids
	IMNV	Infectious myonecrosis virus reported from shrimp
	IPN	Infectious pancreatic necrosis primarily, but not only, in salmonids
	ISA	Infectious salmon anaemia affects Atlantic and Pacific salmon
	Laem-Singh virus	Reported from *Penaeus monodon* in India
	Lymphocystis	Occurs in freshwater, brackish water and marine finfish
	Nodavirus	Has caused viral encephalopathy and retinopathy in cod
	PmergDNV	*Penaeus merguiensis* densovirus
	Rhabdovirus	Affects salmonids and other finfish
	RSIV	Red sea bream iridovirus
	SDV	Sleeping disease virus affecting rainbow trout in northern Europe
	TSV	Taura syndrome virus in shrimp
	WSSV	White spot syndrome virus in shrimp
	YHV	Yellow head virus in shrimp
	VHS	Viral haemorrhagic septicaemia in salmonids
	VNN	Viral nervous necrosis in many freshwater and marine fishes
Bacteria	*Aerococcus viridians*	Gaffkaemia in lobsters
	Aeromonas hydrophila	Tail rot, fin rot, haemorrhagic septicaemia in finfish
	Aeromonas liquefaciens	Bacterial haemorrhagic septicaemia in salmonids
	Aeromonas salmonicida	Cause of furunculosis primarily in salmonids
	Bacillus spp.	Pathogen of various finfish and invertebrate species
	Edwardsiella ictalurid	Enteric septicaemia of channel catfish
	Edwardsiella tarda	Edwardsiellosis affects various finfish species
	Flavobacterium branchiophilum	Bacterial gill disease in salmonids
	Flavobacterium columnare	Cause of columnaris disease in various finfish species
	Flavobacterium psychrophilum	Coldwater disease in salmonids, ayu, carp and other finfishes
	Francisella piscicida	Problem in Norway cod production
	Haemophilus piscium	Ulcer disease of salmonids
	Lactococcus garvieae	Lactococcosis in rainbow trout
	Lactococcus lactis	*Lactococcus lactis lactis*
	Nocardia seriolae	Nocardiosis in yellowtail
	Nocardia spp.	Nocardiosis in the snakehead, *Ophiocephalus argus*
	Piscirickettsia salmonis	Atlantic salmon rickettsial septicaemia
	Pseudoalteromonas spp.	Ulcerative disease in sea cucumber, *Apostichopus japonicas*
	Pseudomonas spp.	Pseudomonas disease in finfish
	Renibacterium salmoninarum	Bacterial kidney disease (BKD) in salmonids
	Spiroplasma sp.	Cause of tremor disease in the Chinese mitten crab
	Streptococcus ictaluri	New species reported from channel catfish
	Streptococcus iniae	Has caused high losses in warmwater finfish globally
	Vibrio alginolyticus	Infects penaeid shrimp
	Vibrio anguillarum	Vibriosis occurs in both cultured finfish and invertebrates

Continued

Table 5.1. Continued.

Disease agent	Examples	Notes
	Vibrio harveyi	Widespread species that has posed problems in shrimp culture
	Vibrio nigripulchritudo	Cause of summer syndrome in *Litopenaeus stylirostris*
	Vibrio ponticus	Reported from Japanese sea bass
	Vibrio vulnificus	Vibriosis in marine finfish
	Yersinia ruckeri	Enteric red mouth disease of salmonids
Protozoa	AGD	Amoebic gill disease of Atlantic salmon
	Amyloodinium ocellatum	Dinoflagellate that affects marine finfish
	Chilodonella cyprini	Affects carp, trout and other finfish species
	Cryptocaryon irritans	Marine dinoflagellate similar to Ich
	Dermo disease	American oyster disease caused by *Perkinsus marinus*
	Henneguya spp.	Myzosporidians that attack a variety of finfishes
	Heterosporis anguillarum	A haplosporidium in eels in Japan
	Loma salmonae	Haplosporidian gill parasite in salmon
	Ichthyophthirius multifiliis	White spot disease prevalent in freshwater and brackish-water finfish
	Ichthyobodo necator	Causes a disease known as costiasis in many finfishes
	Lernaea spp.	Known as the anchor worm, it affects various finfishes
	Marteilia sp.	Observed in the mussel *Mytilus galloprovincialis*
	MSX	American oyster disease caused by *Haplosporidium nelsoni*
	Myxosoma cerebralis	Causes whirling disease in salmonids
	Neoparamoeba spp.	Causes amoebic gill disease in salmon
	Paralembus digitiformis	External ulcerative disease in Japanese flounder and turbot
	QPX	Quahog parasite unknown that attacks *Mercenaria*
	Trichodina spp.	Affects various finfish species
Copepods	*Argulus* spp.	Sea louse that affects various finfish species
	Caligus elongates	Sea louse of salmonids
	Caligus rogercresseyi	Sea louse of salmonids
	Caligus teres	Sea louse of salmonids
	Ergasilus spp.	Finfish gill parasite in fresh- and marine waters
	Lepeophtheirus salmonis	Sea louse of salmonids
	Lernaea cyprinacae	Anchor parasite on the body of finfish
Isopods	*Ceratothoa oestroides*	Reported from *Dicentrarchus labrax*
Helminths	*Anguillicola crassus*	Nematode pathogenic in eels
	Bolbophorus damnificus	White grub which is a threat to channel catfish
	Cleidodiscus spp.	External trematode on the gills and fins of finfish
	Dactylogyrus spp.	Called the gill fluke, it can attack various finfish species
	Gyrodactylus spp.	External trematode on the body and fins of finfish
	Pseudodactylogyrus anguillae	Monogenetic trematode in eels
	Pseudodactylogyrus bini	Monogenetic trematode in eels
Others		
Bonamia spp.	Novel intracellular parasite	Found in *Crassostrea ariakensis*, *Ostrea puelchana*
Enteromhyxum leei	Myxozoan parasite	Found in conjunction with sharpsnout sea bream
QPX	Quahog parasite unknown	Affects the clam *Mercenaria*
RLP	Rickettsia-like prokaryote	Found in the abalone *Haliotis diversicolor*
Unknown	Loose shell syndrome	Filterable unknown agent affects *Penaeus monodon*

organisms that are widespread as well as some that have only been reported from small geographic areas, or in one or only a few species. Some that have rarely been seen to date could certainly become more widespread in the future. You will see a number of them mentioned more than once as you read through the chapter, while in some cases the only place you will see them is in Table 5.1.

Once the causative agent behind a disease has been identified, and assuming the problem has not become so severe that it is necessary to destroy the affected population, it is time to begin taking steps to treat the animals. The first step is to isolate the infected animals to the extent possible. Extra care should be taken to make certain that items that come into contact with infected groups of animals are not used in conjunction with healthy ones. Because you already know that you should avoid potential cross-contamination at all times, you should not have to change what you are doing, just be particularly judicious about it. In instances where the water supply to each culture chamber is separate (i.e. if the water flowing out of one unit does not enter one or more others) achieving isolation is simplified. Common drain lines from a number of culture systems are the rule on many facilities. If that water is entering public waters, it should be treated before release to avoid passing a disease on to susceptible wild aquatic species. If the effluent volume is small enough, it can be flowed into an evaporation pond. Some culture systems, such as cages and net pens in public waters, are difficult or virtually impossible to isolate either from one another or from wild organisms in the vicinity.

Treatment Options

The modern world has become dependent upon a wide variety of pharmaceuticals to treat human and livestock diseases, and the aquaculture industry has also adopted some of those chemicals. While the range of treatment chemicals and drugs that have shown efficacy in relation to their use in aquaculture is broad, the application of many of them to aquaculture is strictly regulated in many countries both with respect to animals grown for domestic consumption and those produced for export. Pharmaceutical products developed for use in treating human and terrestrial animal diseases are common, but the development of such products specifically for aquaculture use is not seen as being warranted by the drug companies, probably because the demand does not justify the cost. That could change as world aquaculture continues to grow, but for now aquaculturists are largely dependent upon existing pharmaceutical products which have usually not been developed for use on aquatic species. Many such products are not effective when used to treat aquatic animal diseases, and as indicated, there are only a few that are approved for use in most developed countries. By extension, if a product is for example banned in European aquaculture, a country that exports aquaculture products to Europe would not be allowed to use that drug, or the aquaculture species would be prohibited from import. In addition to pharmaceuticals, there are some non-pharmaceutical chemicals that have found widespread use in aquaculture. The list of pharmaceuticals, immunostimulants and chemicals developed for use in aquaculture to control specific types of disease organisms is long. Many of them are presented in Table 5.2.

Regulations are not only placed on approved chemicals by producing nations; there are also regulations in place in many countries that set acceptable maximum levels of chemical residues that are allowed in imported seafood, including those of aquaculture origin. Because the regulatory environment is so diverse and changes are routinely made in terms of which chemicals and drugs can be used and on what species, it is probably inappropriate to provide even an indication of what the current situation is across the world (assuming the data can actually be found). The reason is that the situation is dynamic, so what is true today may not be tomorrow.

A search for approved drugs for use with aquaculture species in the USA revealed the following website: https://www.fws.gov/fisheries/aadap/home.htm (accessed 14 December 2021). It provides a considerable amount of information encompassing different classes of drugs and chemicals, including those approved by the FDA and those of low regulatory priority; the species for which each is drug or chemical is approved; and gives the usage profile: e.g. florfenicol for catfish to control enteric septicaemia at 10 mg/kg of fish for 10 days. The website also is a tremendous resource, with links to *The Guide to Using Drugs, Biologics, and Other Chemicals in Aquaculture*, as well as information on extra-label drug use and the Veterinary Feed Directive (VFD). Information on aquaculture drug use and regulations in Canada and the EU are also available on the Internet. Such information is updated periodically, so it would be wise to check with the responsible regulatory agency routinely to obtain the latest information, if such an agency exists in your region; and, if so, whether the information on the species of interest is available.

For new species, detailed information on diseases and their control may not be available, or an identified disease may occur in a species for which the

Table 5.2. Pharmaceuticals, immunostimulants, various chemicals and derivatives from plants that have been found to provide resistance or control of diseases in one or more aquaculture species. Effective doses of the various compounds may vary considerably depending on means of administration and targeted species. In addition, registration and approved use of various chemotherapuetic agents may vary by country.

Use	Name	Other information
Antibacterials	Bakers' yeast	*Saccharomyces cerevisiae*
	Basil extract	*Ocimum basilicum*
	Black nightshade extract	*Solanum nigrum*
	Chaga mushroom extract	*Inonotus obliquus*
	Common sage extract	*Salva officinalis*
	Enrofloxacin	
	Gallic acid	From *Rosa chinensis* flowers
	Garlic	*Allum sativum*
	Honeybee venom	*Apis mellifera*
	Kudzu extract	*Pueraria thunbergiana*
	Lavender extract	*Lavandula* spp.
	Lemon balm extract	*Melissa officianalis*
	Orange peel extract	*Citrus sinensis*
	Oregano extract	*Origanum vulgare*
	Oxolinic acid	
	Peracetic acid	
	Red bilberry extract	*Vaccinium vitis-idaea*
	Rosemary essential oil	*Rosmarinus officinalis*
	Satar essential oil	*Zataria multiflora*
	Shitake mushroom extract	*Lentinula edodes*
Antibiotics	Aquaflor	
	Doxycycline	
	Florfenicol	
	Oxytetracycline	
	Sulfa drugs	
Antivirals	Cat's claw	*Uncaria tomentosa*
	Eastern purple cornflower	*Echinacea purpurea*
	Tubulin	
Disinfectants	Chloramine-T	
	Hydrogen peroxide	One form is sodium percarbonate
	Iodine	Egg disinfectant
	Tannic acid	Egg disinfectant
Fungicides	Azoxystrobin	
	Hops (plant flower)	Egg fungus
	Zataria multiflora	A spice – no common name
Immunostimulants	Azomite®	
	β-1,3-Glucan	
	Barodon	Anionic alkali
	Black cumin seed oil	From *Nigella sativa*
	Brewers' yeast	*S. cerevisiae*
	Cecropin	
	Chinese foxglove extract	From *Rehmannia glutinosa*
	Debaryomyces hansenii	Live yeast
	Ginger	*Zingiber officinale*
	Glycyrrhizic acid	Extract from liquorice
	Gracilaria tenuistipitata	Alga
	GroBiotic®-A	Partially autolysed brewers' yeast, whey solubles, and citric acid fermentation solubles
	Heal-all plant extract	*Prunella vulgaris*
	Lactoferrin	

continued

Table 5.2. Contiuned.

Use	Name	Other information
	Levamisole	
	Lycogen™	Also enhances growth
	Neem leaf extract	*Azadirachta indica*
	Night-flowering jasmine	*Nyctanthes arbor-tristis*
	Pediococcus parvulus	Lactic acid bacterium (also probiotic)
	Peppermint	
	Spirulina	*Arthorspira platensis*
Parasiticides	Caprylic acid	Antihelminthic
	Emamectin benzoate	For treatment of sea lice
	Formalin	
	Isometamidium chloride	
	Ivermectin	For treatment of sea lice
	Matine	From *Sophora flavescens*
	Nicarbazin	
	Praziquantel	Antihelminthic
	ProVale™	Yeast against microsporidians
	Quinine	
	Romet30®	
	Sodium chloride	Increased salinity kills Ich
	Tobacco leaf dust	Nicotine is the active ingredient
	Trichlorfon	Sea lice

treatment is not approved for that species. In the USA, exemptions may be approved by the FDA through granting of an Investigational New Animal Drug (INAD). INADs can take a considerable amount of time to be granted as they require research to be conducted, so the producer who wants to follow the regulations before the INAD becomes available may be out of luck, and possibly out of business.

While Table 5.2 provides a long list of treatment options, we have not provided details as to which of them has efficacy with respect to a particular species or disease. Some are products one might not think of as being useful in conjunction with disease treatment or protection from disease (see Box 5.8). For detailed information on a number of diseases, please consult the references listed in the 'Additional Reading' section at the end of this chapter.

Chemicals are not always the best approach to disease control. Indiscriminate use of antibiotics has not only become heavily criticized, but also strict controls on the amounts that can be used, the period of time they can be used and withdrawal time before the animals can be marketed have been imposed in at least one nation. In addition, regulations and required inspections have been introduced in some countries to ensure that unapproved antibiotics do not get into the human food supply, including seafood that comes from aquaculture. In the USA, there are very few antibiotics approved for controlling bacterial infections. Because of concerns about developing drug resistance in target bacteria, antibiotics must only be used when necessary, and not prophylactically. Aquaculturists tend to accept that approach because the cost of medicated feed increases operating costs substantially and could make the difference between profit and loss if used prophylactically.

An example of how uncontrolled antibiotic use can lead to unintended consequences was associated

Box 5.8.

Among the treatments for diseases of aquacultured species are some that are unusual. A couple of examples are the use of Chinese herbal medicines to effectively control the protozoan *Paralembus digitiformis* in Japanese flounder and, one of our favourites, adding Korean mistletoe to the feed of Japanese eels to enhance their immune response against *Aeromonas hydrophila*. Various others are listed in Table 5.2. Other approaches that are not discussed are the use of ultrasound to control parasites, and slow-release drug implants.

with penaeid shrimp farms a few years ago. At that time, many producers in Asia and Latin America were using a broad array of antibiotics to prevent and treat various diseases, particularly during the hatchery phase of production. Among those antibiotics were some, like chloramphenicol, to which some people are highly allergic. In fact, some sensitive people will die if exposed to even minute amounts of that antibiotic. While the use of chloramphenicol was outlawed in imported shrimp by countries such as the USA at the time the antibiotic was being used, exporting nations often ignored the restriction and turned a blind eye to shrimp leaving their countries. Methods were developed in importing countries to detect the presence of chloramphenicol and other banned antibiotics quickly and accurately, prompting the shrimp culture industry in the offending nations to search for other ways of preventing or treating diseases, because countries receiving shrimp with traces of banned antibiotics placed a ban on those imports until the offending countries complied with the regulations.

One way to avoid antibiotic treatments is the use of prebiotics and/or probiotics. Prebiotics are non-digestible ingredients provided in feed that serve as substrates to stimulate the growth of beneficial intestinal bacteria, thus providing resistance against pathogenic bacteria and stimulation of the immune system. Prebiotics may also improve growth rate, feed conservation and provide other benefits. Probiotics are live microbial dietary supplements provided to control bacterial infections by improving intestinal microbial balance and increasing stress tolerance as well as other physiological responses. Since prebiotics and probiotics have benefits in addition to their impacts on disease, they are shown in Table 5.3. More information on the use of prebiotics and probiotics in aquaculture is provided in Chapter 8.

A significant amount of research has been aimed at developing vaccines against various diseases in aquacultured species. Since vaccines are preventative rather than being treatments, they are not included in Table 5.2, but some of the species and diseases for which vaccines have been developed are shown in Table 5.4.

Various chemicals that have been, and in many cases are still being, used in aquaculture can be harmful to the animals being treated or may place the health of the culturist in jeopardy. One example of a chemical that can be directly toxic to the animals being treated, and which poses a hazard to human health as well, is formalin (Box 5.9). Caution should be used by the applicator to avoid skin contact and breathing the fumes of formalin whenever the chemical is used. Also, formalin will cause stress in the animals being treated and can be toxic if not applied at the proper rate, so only the recommended amount should be used. That is true of any treatment chemical. More is not necessarily better. More, in fact, may exacerbate the problem or create a new one such as direct mortality or, if not, certainly an increase in stress.

A once-popular treatment chemical that is now banned in some nations is malachite green. That aniline dye was widely used in the past to treat fish eggs against fungus and was the prevalent chemical used in treating channel catfish eggs by those farmers in the USA who pioneered in the industry. It was once said that you could tell a catfish farmer because of his green hands (their hands became dyed when they dipped catfish egg masses in malachite green solutions without using rubber gloves). It has been determined that malachite green is carcinogenic (cancer-causing), and that finding led to a ban on the use of the chemical in US aquaculture.

Treatments do not always involve the use of chemicals applied directly to the species being cultured. Sometimes, chemical control of another species may be effective at preventing a disease of the culture species. For example, some parasites use snails as intermediate hosts. Elimination of the snails in culture ponds can disrupt the life cycle of the parasites and protect the final host, which in this case would be the cultured fish species. Such a strategy is used by catfish farmers in the USA to control white grub (*Bolbophorus damnificus*) that can adversely affect fingerling catfish production.

Modifying the environment can also result in the control of some diseases. Certain diseases of oysters function best within a particular salinity range, for example. While it is not possible to alter the salinity regime in an estuary where oysters are being reared, it is possible to establish the culture facility in a region where the salinity is sufficiently low to avoid certain diseases while still providing conditions that allow the oysters to grow at a good rate. In the case of oysters, diseases such as MSX occur at fairly high salinities, so rearing the oysters in a relatively low-salinity environment can be effective. While we are not concerning ourselves specifically with predators here, it should be pointed out that growing oysters in relatively

Table 5.3. Prebiotics and probiotics that have been evaluated in conjunction with one or more aquaculture species.

Action	Name	Other information
Prebiotic	Bakers' yeast	*Saccharomyces cerevisiae*
	Bio-MOS®	Derived from yeast
	β-Glucan	Polysaccharide
	Galacto-oligosaccharide	
	GroBiotic®-A	From brewer's yeast and dairy fermentation products
	Inulin	Polysaccharide
	Lactococcus lactis	Gram-positive bacteria
	Mannan oligosaccharide	
	Previda™	
Probiotic	*Actococcus lactis lactis*	Bacterium
	Alteromonas macleodii	Bacterium
	Bacillus cereus	Bacterium
	Bacillus clausii	Bacterium
	Bacillus foraminis	Bacterium
	Bacillus licheniformis	Bacterium
	Bacillus pumilus	Bacterium
	Bacillus subtilis	Bacterium
	Ocimum basilicum	Basil leaves
	Biomin Start-grow®	
	Brown propolis extract	Beehive resin
	Efinol®	
	Lactobacillus acidophilus	Bacterium
	Lactobacillus plantarum	Bacterium
	Lactobacillus rhamnosus	Bacterium
	Mycolactor Day Probiotic®	
	Neptunomonas spp.	Now *Pseudoalteromonas*; bacteria
	Oregano essential oil	*Origanum vulgare*
	Paracoccus marcusii	Bacterium
	Pediococcus acidilactic	Bacterium
	Peppermint	*Mentha piperita*
	Phaeobacter sp.	Bacterium
	Pseudoaltermonas sp.	Bacterium
	Pseudomonas acidophilus	Bacterium
	Pseudomonas synxantha	Fluorescent bacterium
	Sanolife Pro-W®	
	Shewanella baltica	Bacterium
	Shewanela haliotis	Bacterium
	Shewanella putrefaciens	Bacterium
	Streptococcus faecium	Now *Enterococcus*; bacterium

low-salinity waters also prevents attacks by oyster drills and starfish that are intolerant of low salinity. The downside is that oysters grown in high-salinity water are preferred by consumers who eat them on the half shell as they taste better (according to oyster lovers) than those produced at low salinities.

A major parasite problem in relation to freshwater fish is the protozoan *Ichthyophthirius multifiliis* or Ich, which is characterized by large numbers of white spots on the body surface. By rearing fish – at least channel catfish – at a minimum salinity of 2 ppt, the parasite can be avoided as it cannot tolerate even that level of salt in the water. That level of salinity is well tolerated by fish. Channel catfish, for example, will tolerate at least 10 ppt salinity.

Temperature also has an effect on disease development in many instances (Box 5.10). Tilapia, for example, tend to be more resistant to disease when the water temperature is well above 20°C, but as the temperature approaches that level, the fish may develop any number of diseases, apparently because of stress-related loss of immunity. High water

Table 5.4. A partial list of aquaculture species and diseases for which vaccines have been developed.

Aquaculture species	Disease
Invertebrates	
Lobster, American	*Aeromonas viridians* (gaffkaemia)
Shrimp	
Black tiger	*Vibrio alginolyticus*
	White spot shrimp virus (WSSV)
Indian white	*Vibrio harveyi*
Kuruma	*Vibrio* spp.
Finfish	
Ayu	*Vibrio* spp.
Carp	
Catla	*Aeromonas hydrophila* (infectious abdominal dropsy)
Common	*A. hydrophila*
Rohu	*A. hydrophila*
Catfish, Channel	Channel catfish virus (CCV)
	Edwardsiella ictaluri (enteric septicaemia of catfish)
	Ichthyophthirius multifiliis (Ich)
Eel, European	*Vibrio vulnificus*
Flounder, Olive	*V. vulnificus*
Halibut, Pacific	*Vibrio anguillarum*
Salmon, Atlantic	*Vibrio salmonicida*
	Renibacterium salmoninarum (bacterial kidney disease)
	Piscirickettsia salmonis (salmon rickettsial septicaemia)
	Infectious haematopoietic necrosis virus (IHNV)
Sea bass	
Asian	*V. anguillarum*
European	*V. anguillarum*
Sea bream, Red	Red sea bream iridovirus (RSBI)
	V. alginolyticus
	V. anguillarum
Tilapia, Nile	*Streptococcus iniae*
Trout, Rainbow	*Vibrio* spp.
	Aeromonas salmonicida
	S. iniae
	Lactococcus garvieae
	Yersinia ruckeri (enteric red mouth disease)
	A. salmonicida (furunculosis)
	Viral haemorrhagic septicaemia (VHS)
	Infectious haematopoietic necrosis (IHN)
	Rhabdovirus
	Rhabdovirus salmoninarum (bacterial kidney disease)
Turbot	Rhabdovirus
	Streptococcosis
Yellowtail	*Nocardia seriolae* (nocardiosis)
	Streptococcus

temperature (around 32–33°C), on the other hand, has been found to prevent the onset of WSSV in the Pacific white shrimp, *Litopenaeus vannamei*.

Another, complementary approach involves stocking animals at the proper densities, sizes and time of year. Studies on the occurrence of WSSV outbreaks in shrimp ponds led researchers to conclude that survival can be increased by stocking ponds with older post-larvae, using small ponds and reducing stocking density. Seasonal temperature regime is another factor that influences survival during WSSV outbreaks, as was previously

Box 5.9.

Formalin is what many refer to as formaldehyde. Actually, formaldehyde is a gas, which when dissolved in water produces formalin solution. It is formalin that was widely used to initially preserve specimens in museums, after which the specimens can be transferred to alcohol. Because of its toxicity to humans, exposure to the chemical is not advised, though it is still used as a treatment chemical in aquaculture.

Box 5.10.

As the tilapia culture industry has matured, the pattern that has been observed in many other species, as previously mentioned, also occurred with tilapia. Several diseases have occurred under what are considered good culture conditions, including optimum or near-optimum temperatures. Still, cold water is often the trigger for an epizootic.

mentioned. Elevated temperatures can also lead to significantly reduced mortality when Pacific white shrimp are exposed to TSV.

There are a variety of ways to actively treat aquaculture animals. The following subsections provide information and some examples of what we are talking about regarding disease treatment.

Chemicals

Chemicals such as table salt (NaCl) are relatively inexpensive and can be used in large amounts, such as in ponds, without breaking the proverbial bank. For example, if you wanted to increase the salinity in a freshwater pond to the recommended 2 ppt to eliminate an Ich infection, it would be economically feasible to add the appropriate amount of salt to a typical aquaculture pond. That said, in most instances, chemicals used to treat diseases of aquatic animals are used in baths, which can include short-term dips in which the chemical is typically administered at higher concentration as compared with more prolonged exposures at lower concentrations.

Obviously, adding salt to a pond provides a long-term bath treatment option. More common is either adding the treatment chemical to the water in a flow-through raceway or tank system; or capturing the fish to be treated and placing them in a concentrated solution of the treatment chemical for a fairly brief period of time (usually not more than a few minutes).

Dip treatments that involve collecting the fish to treat them in a concentrated solution place an additional stress on animals that have already been stressed due to the presence of the disease. Thus, while the treatment may effectively treat the problem, mortalities can continue to occur and, in many cases, a secondary disease will subsequently appear.

Treating aquatic animals in cages or net pens using chemicals is particularly problematic, and the difficulties increase as the size of the culture chamber increases. It is theoretically possible to put an impervious bag around a cage or net pen in which a treatment chemical will be contained after it is introduced. Once the animals have been exposed to the chemical for a sufficiently long period, the bag can be removed, allowing the chemical to dissipate. One major problem involves placing a bag around a cage or net pen. A second is that when the chemical is released it enters the environment, which may violate regulations on its use. In addition, when the bag is in place and water flow through the culture system is prevented, water quality conditions such as DO and ammonia can become limiting rather quickly unless corrective measures are taken.

Small cages can be floated to shore where, if they are properly constructed, they can be lifted from the water and immersed in a tank containing the appropriate treatment chemical. That approach is labour-intensive and stressful to the animals; and, if there is any weakness in the cage, it may rupture when raised from the water. This will release the ailing fish into the environment or, if the culturist is fortunate, into the chemical bath where the culturist would have to be prepared to capture them. The culturist would also have to have an extra cage ready to put the animals in or make a quick repair on the ruptured cage. The reality is that few cages can survive being lifted from the water when they are stocked with fish, particularly when those fish are approaching market size. We should tell you that it is an unwritten rule in aquaculture that the most likely time for you to experience a problem, such as a disease epizootic, will be shortly before you intend to harvest and market your crop. It is known as Murphy's Law – what can go wrong will go wrong. The corollary to that law is that it will go wrong at the most inopportune time.

Bath treatments can easily be used in conjunction with tank and raceway culture. The water can be turned off, the chemical added and sufficient time allowed to pass for the treatment to be effective before the water flow is reinitiated. After the water begins to flow through the tank, the chemical will be quickly diluted and fairly rapidly will be entirely flushed out of the system. Any tank in which a dip or bath treatment is conducted in static water should be provided with aeration during the period of exposure so that a suitable DO level is maintained.

Flush treatments involve allowing the water to run continuously through a tank or raceway after the treatment chemical is introduced. The chemical is added at a concentration calculated to remain sufficiently high to effect control of the disease before it is diluted to a level where it is no longer effective. After the water in the tank or raceway is exchanged a few times, the chemical will be completely removed from the system, as in static bath treatments after water flow is restarted. While the initial concentration of the chemical to which the animals are exposed may be higher than in a dip treatment, overall stress may be less than in instances where the animals are handled as a part of the treatment process and are exposed to the treatment chemical for a longer period of time than would be the case with a flush treatment. When R.R.S. and a graduate student were working with Pacific halibut *Hippoglossus stenolepis* during the 1990s, we had success using flush treatments with formalin to remove an unidentified species of parasitic isopod from the body surface of the fish (Fig. 5.3). The parasites did not seem to cause any damage, but when their numbers built up, we thought it was in the best interest of the animals to treat them.

Antibiotics

While antibiotics are certainly types of chemicals, they deserve separate consideration because they are basically in a different category from the chemicals that have previously been mentioned. Antibiotics are commonly used to treat bacterial infections (Fig. 5.4). There are three approaches that can be used when administering antibiotics. One is to dissolve the substance in water and use it as a dip, bath or flush treatment using the same protocols discussed under the ‘Chemicals’ subsection. While that approach is often employed, it is not highly effective in many instances.

The second method, which can be very effective, is to inject each fish with the antibiotic using a needle and syringe. However, handling and inoculating individual fish is not practical on a mass scale because of the time and labour involved, not to mention the stress induced when thousands of individual fish need to be injected. For broodfish or other such valuable fish as ornamental koi carp (which can be worth hundreds or even thousands of dollars), individual injections may be appropriate, and may be the most efficacious treatment method. The numbers of animals involved are also much less prodigious than would be the case with a pond full of fingerlings.

The third and most common manner of introducing antibiotics is through the feed. Oxytetracycline (Terramycin®), Romet® or florfenicol is commonly

Fig. 5.3. An adult Pacific halibut, *Hippoglossus stenolepis*; female broodfish with parasitic isopods on the body surface.

Fig. 5.4. A channel catfish with a bacterial infection.

employed in that way. Feed companies can often supply diets formulated for the locally produced aquaculture species that have had the antibiotic incorporated at the appropriate level. To do so, an Animal Feed Directive must be issued by a licensed veterinarian to allow the medicated feed to be obtained by the culturist and administered to the targeted fish.

The protocol for oxytetracycline involves feeding the animals for 10 days, and 10 days only. In some instances, regulations are in place that mandate how many days must pass after application of an antibiotic before the fish can be marketed (this provides an opportunity for the antibiotic residue to be purged from the animals so there is no trace of the compound when the product is consumed). You should keep in mind that one of the first signs of a disease problem, and that includes bacterial diseases, is that the fish cease feeding. It is incumbent upon the culturist to identify the problem early. It stands to reason that if the fish will not eat, it is not going to do you much good to treat them with an antibiotic that is incorporated in the feed. However, feeding the medicated feed will hopefully protect those fish still actively feeding and prevent the disease from spreading.

At one time, many culturists routinely fed antibiotics to finfish and used them routinely in shrimp hatcheries as well. The situation with respect to finfish has changed as previously described and the same is true of shrimp hatcheries. Finfish producers and shrimp hatchery managers recognize that feeding antibiotics routinely is expensive and, as importantly, that antibiotic-resistant bacteria may be developed. In cases where antibiotics are used in cages and net pens, there has also been concern expressed about releasing those types of drugs into the environment where beneficial bacteria may be killed. While having impacts on non-target bacteria is theoretically possible, dilution should reduce that likelihood. In addition, significantly higher levels of a much larger array of antibiotics enter many natural waters through sewage treatment plant effluents (the source being antibiotics excreted by humans) and from land runoff (antibiotic residues excreted by livestock). To us, those latter sources of antibiotic input into the natural environment pose a greater threat than aquacultural sources.

Vaccines

A great deal of research and development activity has been focused on producing vaccines to protect aquatic animals against viral and bacterial diseases (Table 5.4). The effects have been highly positive with respect to treating some finfish viruses and bacterial diseases in finfish and some shellfish. Finding vaccines for treating shrimp viruses has not been highly successful to date, though a DNA vaccine has been developed for black tiger shrimp. In addition, a purified monoclonal antibody (obtained by cloning an immune cell) has been developed that can inactivate WSSV in at least one marine shrimp species.

Vaccines can be provided to fish through individual inoculations, by means of dip treatments or orally. Injecting individual fish with vaccines faces the same problems mentioned previously with respect to injecting antibiotics and, while it is often a very effective means of immunization, it is only used when a small number of fish are to be vaccinated or mechanical vaccination equipment is used that has been developed and implemented in some areas where Atlantic salmon are cultured.

Dip treatments are used for mass-scale vaccination. The vaccine is put in a tank of water into which groups of fish are introduced for an appropriate period of time to allow the vaccine to be absorbed.

Administering vaccines orally can be effective so long as they are not destroyed by digestive enzymes. A technique called ultrasonic immunization was developed a few years ago as a means of delivering vaccines. The technique appears to have been applied to a few finfish species, but it is not clear how widely it is currently being used.

Phage Therapy

Phage therapy has been employed with respect to several bacterial diseases in finfish. Bacteriophages (viruses that infect bacteria) have been developed to control bacterial diseases in shrimp hatcheries. Phage therapy appears to be a good approach in cases where bacterial resistance means that antibiotics are no longer effective. Lysogenic phages are those that exist in a bacterial cell as dormant DNA. The phage reproduces and is released when the bacterium dies, allowing the phage DNA to infect other bacteria. One potential problem is that lysogenic phages could turn non-virulent bacteria into virulent ones. Thus, unintended consequences have become an issue.

Nutritional Diseases

A few diseases are attributable to nutritional deficiencies. Signs of nutritional deficiencies associated with vitamins in particular are mentioned in Chapter 7, where you will see that a variety of problems can occur. Intestinal problems associated with the consumption of diets with excessive levels of soybean meal have been reported in Atlantic salmon (*S. salar*) in which case severity appears to be related to dietary inclusion level and water temperature. Other feedstuffs that contain anti-nutritional factors are discussed in Chapter 7. In some cases, nutritional deficiencies may first be diagnosed as attributable to a disease caused by a virus or other pathogen. The culturist should rule out a nutritional deficiency as the cause of a problem by making sure that some other cause exists.

If a nutritional deficiency is suspected, the solution is to supplement the missing nutrient in the feed. It should also be added here that sometimes excess supplementation of the feed with a particular nutrient may, in fact, provide some protection against pathogenic diseases. Over-supplementation with vitamin C (ascorbic acid), for example, is thought to provide some such protection. A cautionary note is also appropriate here. Excessive levels of some nutrients such as fat-soluble vitamins may lead to direct toxicity, so the culturist needs to know which nutrients can be safely supplied in excess and which should not be used in that manner.

If the aquaculturist suspects that the feed being used is deficient in one or more nutrients, he or she can have a sample analysed to verify or rule out that suspicion. If the feed was not manufactured to the proper specifications, it may be the responsibility of the feed company to replace the deficient feed at no cost. There have also been instances where feed companies have had to reimburse farmers for crop losses due to improperly manufactured feed (Box 5.11). We take another look at nutritional deficiencies in Chapter 7.

Toxins

Natural toxins, such as from red tides and brown tides, occur as the result of blooms of various types of algae and have been mentioned in Chapter 4. A related phenomenon, in that it is also attributable to algal blooms, has been incidences of salmon mortalities in net pens associated with gill clogging and resulting asphyxiation. In that case, the problem was a high concentration of a large-celled species of algae in the water and not release of a toxin, though the two problems could conceivably occur simultaneously.

If a toxin is detected that might be pumped into a closed system or a system that is partially recirculated, it may be possible to avoid introducing

Box 5.11.

Several years ago I (R.R.S.) was asked by a feed company representative to look at some fish that one of their customers claimed were showing signs of a nutritional deficiency. The fish were being grown in cages in a lake. What I discovered when I got to the facility was some very skinny channel catfish that, in many cases, had severe scoliosis or lordosis (deformations of the spinal column). There was also some indication of bacterial infections. When I looked at the feed formulation being used, I found that it was an old one designed as a supplemental food (in other words, it was not a complete diet in that, in particular, it was not supplemented with a vitamin and mineral package) for pond-reared catfish raised at low densities. The misshapen and often broken spinal columns of the fish were a sure sign of vitamin C deficiency, so I recommended feeding organ meats, such as calves' liver, in an attempt to provide a rapid infusion of vitamin C into the fish. It turned out that one of the company's feed salesmen had convinced the fish farmer that the company's feed was as good as what the farmer had been using, which would have been true if the farmer was feeding a few hundred fish per hectare in a farm pond. The salesman said he thought the feed had been specifically designed to meet the complete needs of catfish being reared at high density and not dependent upon any natural food. The fact that the feed was considerably less expensive than other brands (which were designed to meet all the known nutrient requirements of catfish) was undoubtedly a strong selling point, even though it was untrue. The company's feed was certainly less expensive, but it was also totally unsuitable for caged fish. I reformulated the feed so it would provide the proper nutrients for rearing catfish at high density. The feed company ended up paying fair market value of the fish to the farmer, and I was later told that the farmer was allowed to keep the fish, many of which recovered once their vitamin C requirement was accommodated and those fish were ultimately marketed – so the farmer was able to profit from at least some of them twice.

new water until the problem is no longer a threat to the fish. In open raceway systems and in cage and net pen facilities, it would be very difficult to prevent exposure of the aquaculture animals to the toxins.

Another problem that is probably more widespread than algal toxins in natural environments, in terms of causing mortality problems, is consumption of mouldy feed. *Aspergillus* spp. is a common mould that can infect feed. That and other moulds can produce various toxins that may negatively affect fish performance and can lead to mortality. Manufacture of feeds with ingredients that are not contaminated with moulds and proper storage of feed pellets are necessary to prevent establishment of mould. Dry pellets should be stored in a cool dry place and should be used within 90 days of purchase. Many outdoor feed bins, such as those shown in Fig. 5.5, are exposed to what are, in some cases, dramatic temperature fluctuations temporally, particularly during summer and winter in temperate climates. Feed stored in outdoor bins is certainly going to be consistently exposed to high temperature and often high humidity in tropical regions and in temperate regions during several months of the year. Low temperatures are not a problem, but heat certainly can be, in that some nutrients are heat-labile. In addition, residual moisture can be driven out of dry feeds while in storage bins and possibly cause condensation on the walls. Storage of feed in bins or silos is typically not a significant problem if those types of feed storage containers are used only on facilities where turnover of the feed supply is rapid – meaning the bins are refilled with fresh feed from a feed mill every 1–2 weeks. Replenishing the supply at that interval provides little opportunity for mould formation. Of course, the culturist should use up the old feed on hand before using feed from a newly delivered batch in order to reduce the amount of time the feed is stored on the farm. That applies to bagged as well as bulk feed. It's called stock rotation and is a routine procedure in food stores – sell the older products first, then the newer ones. That's particularly important when products have 'sell by' or 'best if sold by' dates on them. Adding new feed through the top of the feed bin and dispensing it from the bottom ensures that the stock will be properly rotated.

Common Aquaculture Diseases

The following subsections provide brief descriptions of some of the more common aquaculture

Fig. 5.5. Dry pelleted feed storage bins beside a lake where fish were being commercially produced in cages.

diseases. More detailed information can be found in the books listed in the 'Additional Reading' section. Yes, you have seen some of the information before, but there is nothing wrong with a little memory refreshment.

Viral diseases

Viral diseases have posed significant problems in aquaculture for many years. Some diseases that began to devastate cultured trout and salmon beginning many decades ago defied treatment, and fish culturists who searched for ways to prevent or halt the epizootics were understandably frustrated. The best approach was often associated with good management practices that included reduction or avoidance of stress (which continues to be an important strategy to this day as has been repeatedly stated – in fact, you are probably tired of hearing about it by now). If an epizootic is attributable to viral pathogens, destroying exposed stocks and disinfecting the culture facility are typically the only course of action.

Once the science of fish pathology had become established and professional animal disease specialists began applying their science to aquaculture species, it became clear that many untreatable diseases were caused by viruses. That led to the development of new treatments such as vaccines, many of which are currently available as discussed above and listed in Table 5.4. More vaccines are being developed all the time, so the toolbox of the aquatic animal pathologist is filling up. Yet, we can expect that as vaccines are developed to address existing problems, new viral diseases will appear. There is still plenty of work ahead in this arena.

Viruses that went by the initials of the first letters of their common names, such as CCV for channel catfish virus, were discovered several years ago and have been studied in some detail. A number of such viral diseases have been found in association with coldwater fishes, warmwater species – with channel catfish (*I. punctatus*) virus being one example – and marine fish of several species. At least 40 species of freshwater and marine fishes have been found infected with viral nervous necrosis (VNN). Included are parrot fish, turbot, European sea bass and barramundi. The coldwater viruses include IHNV in salmonids and viral haemorrhagic septicaemia (VHS) in trout. A virus called ISA appeared in Atlantic salmon (*S. salar*) being cultured in the north-eastern Atlantic region in the 1990s (see Table 5.1). Outbreaks of significant proportions were first reported from Europe. Subsequently, the disease found its way – probably via shipments of smolts from Europe to Canada – into net pens off the Maritime Provinces of Canada and then to net pen farms in the state of Maine, USA. With no treatment available, the toll on cultured salmon was extremely high in many instances. Fish farmers blamed wild fish for transmitting the disease from Canada to Maine, while critics of salmon farming expressed concerns about farmed fish transmitting the disease to wild fish. In 2002, all the salmon farmers in Maine were ordered to destroy the fish in their pens, sterilize everything to the extent possible and keep the farms fallow for 90 days, after which restocking was allowed. An additional hardship imposed on the industry was that the salmon farmers were not allowed to restock with non-native strains of salmon. All the fish had to come from Maine stocks. The economic impact of the new regulations was reduced, but not eliminated, through provision of some buyout funds provided by the federal government. Today, the salmon farms of Maine are apparently prospering once again, though the culturists and those in affiliated industries, such as processing and equipment suppliers, did suffer a period of intense hardship.

In marine and estuarine environments, lymphocystis, caused by an iridovirus, is commonly seen in both wild and cultured finfishes. There have also been some incidents of lymphocystis in a few freshwater fishes. The disease is characterized by hypertrophy of cells in the connective tissue of the body surface as well as on the fins. Basically, unsightly lumps will appear which, in severe cases, may cover the majority of the fish's body and fins (Box 5.12).

The shrimp culture industry worldwide has suffered a devastating series of epizootics associated with various viral diseases that began in the 1990s. Having increased from very little production in the 1960s to modest production in the early 1970s, commercial penaeid shrimp culture exploded thereafter with high levels of production ultimately entering the world shrimp market from Thailand, China, the Philippines, Malaysia, Ecuador and several other countries. Taiwan was one of the countries that pioneered penaeid shrimp culture, but farmers in that nation got out of commercial shrimp culture entirely due to disease-related losses. Outbreaks of viruses such as taura, white spot and yellow head devastated the industry after it had become well established as a primary source of the

Box 5.12.

During the 1970s, when colleagues and I (R.R.S.) were conducting research to develop culture systems and diets for southern and summer flounders, we observed lymphocystis lesions on numerous occasions. Usually, the lesions were limited to no more than 1% or 2% of the body surface and fins – typically, there would be only one lesion on a particular infected fish. While lymphocystis will not kill the fish, it is unsightly and could certainly make marketing infected fish difficult if the fish were sold in the round. By exposing the incoming estuarine water to UV light, we were able to eliminate the problem.

commodity in international trade. Many farms were forced out of business in countries other than Taiwan, and production in those that survived was often greatly reduced. In China, where the industry was developed in the north using the coldwater Chinese shrimp, *Penaeus chinensis*, production levels during the 1990s fell from 200,000 tonnes or more for a couple years due to disease, followed by a rollercoaster ride where the industry fell to less than 100,000 tonnes later in the decade, back to nearly 200,000 tonnes in the 2000s and down again to the vicinity of 50,000 tonnes in the 2010s. After the first drop in Chinese shrimp production, farming was re-established in southern China using warmwater species and China became (for the second time), and continues to be, one of the top – if not the top – shrimp-farming nations in the world. Thailand vies with China for the top spot. Implementation of BMPs, which includes reducing stocking densities and intensive research efforts in the 1990s to develop SPF broodstock and commercially available SPF seedstocks, has helped stem the tide of viral diseases in Asia and the Americas, allowing the industry to recover to a greater or lesser extent, though virus disease outbreaks continue to occur.

Bacterial diseases

Bacterial diseases in finfish and shellfish are rather common and can be attributed to a wide variety of microorganisms, many of which target a particular species or species group of cultured organisms. For example, the Gram-negative bacterium *Aeromonas salmonicida* targets salmonids, while *Edwardsiella ictaluri* attacks ictalurid catfishes. Other bacteria are not so specific. There are a number of species within the bacterial genus *Vibrio*, for example, that attack a wide range of aquatic organisms. Some of them, such as *Vibrio vulnificans* and *Vibrio parahaemoliticus*, can cause pathology in humans as well, so they pose a public health threat. That threat is particularly great for immune-deficient people who eat raw oysters as these animals can harbour all sorts of human pathogens as a result of their normal filter-feeding activities. When oysters are harvested from contaminated waters and not properly depurated, consumption of them by humans, whether or not they have immune deficiencies, can lead to severe health problems including death in some cases.

In addition to vibrios, molluscs exposed to polluted water can concentrate the organisms associated with such things as Norwalk hepatitis A virus, along with bacteria that cause cholera, salmonella and other human diseases. *Escherichia coli*, including pathogenic strains, may also be concentrated by molluscs. While not widely recognized by fish culturists, the processing of fish contaminated with some bacteria such as *Mycobacterium* spp. may also be a human health concern for those processing the fish. Movement of pathogenic bacteria from one area to another in frozen processed fish also has been recognized by some people as a possible means of transmission. That concern has resulted in a ban on the importation of even frozen rainbow trout (*Oncorhynchus mykiss*) to New Zealand. That nation has its own cultured rainbow trout as a result of deliveries of live fish that date back to the 19th century and the government does not want to take the chance of importing trout (even if frozen) that might be able to transmit a disease organism.

While we are on the subject of disease transmission from raw seafood consumption, we should not forget that the consumption of sushi has led to illnesses in some cases. If the finfish and shellfish used for incorporation in sushi are contaminated, which may come from improper sanitation in the manufacturing plant, problems can occur. However, for the most part, sushi is safe, particularly in developed countries where great care is taken to ensure the quality of the ingredients and the way those ingredients are handled. Sushi is a favourite food in Japan where it is consumed in large quantities. Meticulous handling of the products that go into sushi in that country ensure that the consumer has little to worry about in terms of food safety.

Pufferfish are the source of a neurotoxin that can lead to paralysis and death in people who eat their flesh (fugu). The toxin is located in certain internal organs and can contaminate the flesh when the fish are cleaned. Fugu is a delicacy in Japan and can only be prepared by trained chefs who know how to clean the fish without contaminating the meat, though the customer at a restaurant that serves fugu is still playing Russian roulette. Surprisingly, species of puffers are now being cultured (Table 1.1), which does not obviate the potential for consumers to be exposed to the toxin.

As described in Box 5.10, where once cold stress seemed to be the primary cause of disease epizootics, today culturists are seeing increasing numbers of occurrences during warm weather. A number of bacterial diseases have been found in association with diseases in tilapia facilities. Epizootics have often been associated with *Streptococcus* spp. in North America, South America, Asia and the Middle East.

Bacteria of various species, many of them pathogenic, are a common problem in hatcheries, particularly when static or nearly static water is used during egg and/or larval development. Serious losses of developing marine shrimp and marine finfish in hatcheries due to bacterial problems are common. Antibiotics have been used routinely in the past to reduce the levels of bacteria in hatcheries; but, as mentioned, that approach is being discontinued in shrimp hatcheries as other means of dealing with the problem have been developed, including implementation of BMPs. The same is probably largely true in finfish hatcheries as well. We know that is the case with respect to such species as channel catfish and salmon. Routine siphoning of waste materials from culture tanks is also helpful in keeping down bacterial levels and is certainly a BMP. If heavy mortalities occur in a hatchery tank, it is often best to drain the tank, sacrificing the remaining animals and sanitizing it before using it again, as was discussed earlier.

Fungal diseases

The most common fungus found in association with freshwater aquaculture is *Saprolegnia* spp. as previously mentioned. While generally considered to be a beneficial fungus, as its primary job is to break down dead tissue, it can grow on necrotic tissues surrounding bacterial lesions on fish. The fungus will also attack fish eggs. Dead eggs will first be attacked by the fungus, which appears as a white cottony growth. Infected eggs should be removed from the egg mass and discarded, as the pathogen will quickly spread to healthy eggs. In salmon hatcheries, the egg trays are routinely checked for dead eggs, which are removed. This is facilitated with special equipment that can best be described as an automatic egg picker. The eggs are passed in single file past a light source that shines on each of them in turn. Opaque (dead) eggs do not allow the light to pass through them. These eggs are removed from the stream with a puff of air that blows them into a bucket for disposal. Translucent eggs pass along to a collection area and are returned to the hatching trays. For channel catfish (*I. punctatus*) eggs, which are laid in adhesive masses, the automated system is not appropriate, though there are ways to disrupt the adhesiveness of the masses and separate the eggs. The salmon system might still not work since catfish eggs are considerably smaller than salmon eggs. Thus, for catfish, dip treatments to control fungus are used. Malachite green used to be the chemical of choice for egg fungal control but, as you have learned, it is a known carcinogen and has been banned in the USA and undoubtedly in other nations. Hydrogen peroxide and formalin have been used effectively and are approved for use with fish eggs as fungicide (see Table 5.2).

A number of ulcerative diseases associated with fungi in the marine environment have been reported from various parts of the world. Among the fishes of aquaculture interest that have been found with so-called water moulds are barramundi (*Lates calcarifer*), mullet (*Mugil* spp.), walking catfish (*Clarias* spp.), snakehead (*Channa striatus*, *Ophiocephalus argus*) and ayu (*Plecoglossus altivelis*). Estuarine species of aquaculture interest in North America that have been attacked by ulcer-causing fungi include southern flounder (*Paralichthys lethostigma*), striped bass (*Morone saxatilis*) and red drum (*Sciaenops ocellatus*).

Protozoan parasites

A wide variety of protozoans have been found in association with aquacultured fish in freshwater systems. Examples of a couple that have already been mentioned are the ciliated protozoans *I. multifiliis*, commonly known as 'Ich' or 'white spot disease', and *Trichodina* spp. Another is *Ichthyobodo* *necator*. Then there are the ever-popular myxosporidian protozoans such as *Henneguya* spp. All of them pose problems with respect to warmwater fishes, and some species of *Henneguya* are associated with salmonids. Many, like Ich, are found on the body surface (in the case of Ich, there are white spots (encysted protozoans) that may literally cover the body surface). Others, like *Trichodina* spp., attack the gills, while *I. necator* can make itself at home on the body surface, gills or both.

Dinoflagellate protozoans, such as *Amyloodinium ocellatum*, have been responsible for fish deaths of both aquaculture and aquarium trade species grown at estuarine and marine salinities. *Cryptocaryon irritans* is a marine dinoflagellate that has a life cycle similar to that of Ich. Trichodinids have been found to infest red drum (*S. ocellatus*) in estuarine waters.

A killer of the American oyster, *Crassostrea virginica*, is *Perkinsus marinus* (formerly known as *Dermocystidium marinum* and still commonly known as Dermo), which was first identified in the 1950s. Once thought to be a fungal disease, the problem was ultimately found to be caused by a parasitic protozoan. The disease has been observed in American oysters from New Jersey to Texas. *P. marinus*, or perhaps a few closely related species within the genus, are known to parasitize a large number of molluscs throughout the world in temperate, subtropical and tropical waters. Another disease of oysters is caused by the sporozoan parasite, *Haplosporidium nelsoni*. The common name for the disease, MSX, stands for multinucleated sphere unknown. Also first reported in the 1950s, MSX has been responsible for high levels of mortality in American oysters. Lack of good treatments for Dermo and MSX has led researchers to attempt developing disease-resistant oysters, though that effort has not been entirely successful to date.

Because of greatly reduced production in the *C. virginica* oyster industry, particularly in Chesapeake Bay on the east coast of the USA, there has been interest in introducing an exotic oyster, the sumino or Asian oyster (*Crassostrea ariakensis*), which is apparently resistant to both Dermo and MSX. Several states border Chesapeake Bay, and there has been a controversy with respect to whether the exotic oyster should be introduced and what consequences there might be for native species other than American oysters. In addition to other concerns that have been raised about stocking *C. ariakensis*, it has been shown highly susceptible to a novel intracellular parasite, *Bonamia* spp., which can lead to 100% mortality.

Helminth parasites

Parasitic worms are parasites that may be found in the internal organs or flesh of fish and other organisms. In freshwater, helminths are represented by nematodes, trematodes and cestodes. Most nematodes (roundworms) are non-parasitic, but parasitic ones can be found in the intestinal tracts of fish. Because many nematodes look alike to the untrained eye, a nematode expert may have to look at samples to determine if the worms are parasitic or not. The flatworms in the trematode and cestode groups are all parasitic. In the marine environment, not only do the same three groups mentioned occur, but there are also parasitic acanthocephalans, turbellarians, nemerteans and leeches. Finfishes are not the only group that can become infected. Shrimp, crabs and lobsters are also susceptible.

Helminth epizootics are usually not lethal in and of themselves, but they can lead to secondary infections, thereby increasing the chances for mortality. A successful parasite does not kill its host, it merely takes advantage of the opportunity to infest and feed on the tissues of the host species.

Digenetic trematodes have life cycles that involve secondary hosts. As previously mentioned, it is sometimes possible to avoid problems with such parasites by breaking that life cycle, which often involves a mollusc as an intermediate host. By eliminating snails in a pond, it may be possible to wipe out the parasite. Another intermediate host for some digenetic trematodes is mayfly larvae which, when eaten, pass along the parasite to the final host – in this case, the fish. Eliminating aquatic insects in ponds can also break the life cycle of certain parasites. One way to do that is to spray diesel fuel on the pond surface. The insect larvae must come to the surface to respire, and the diesel fuel will prevent that process from occurring, thereby asphyxiating the insect. That will also get rid of predacious insects, such as dragonfly nymphs, that often prey on young fish.

Monogenetic trematodes have a simpler life cycle that involves only one host. Many monogenetic trematode species are only found in the intestinal tract and do not cause severe problems, though they may reduce growth rates by taking up nutrients that would otherwise be used by the fish. Other trematodes, however, can be found on the body and fins (e.g. *Gyrodactylus* spp.) or on the gills of fish (e.g. *Cleidodiscus* spp.). Trematodes may also be found in the liver, other organs and the musculature, as previously mentioned.

Copepod parasites

Finally, there are a number of parasitic copepods that can be found in association with aquaculture species. Parasitic copepod problems appear to be most common in freshwater aquaculture, with finfish being the most susceptible. Among the parasitic copepods that are found in freshwater is *Argulus* spp., known as the fish louse. While predominant in freshwater, there is also an estuarine species, *Argulus nobilis*, which may also be parasitic, though we are not aware of any reports of problems with that species for mariculturists.

Lernaea cyprinacea, often called the anchor parasite or anchor worm, has been a problem with respect to various species of freshwater fishes. When the free-swimming parasite comes in contact with a fish, the parasite attaches and its head becomes modified so that it is permanently imbedded in the flesh of the host animal. A genus that occurs in both freshwater and marine environments is *Ergasilus*.

Because of an ongoing controversy concerning their transmission between wild and cultured salmon and treatment protocols, the sea lice issue deserves special attention. As shown in Table 5.1, there are two parasitic copepods that are referred to as sea lice and have caused significant problems for Atlantic salmon (*S. salar*) culturists in Canada, Norway, Scotland, Ireland, the US state of Maine and Chile. Other species of current or potential aquaculture importance attacked by sea lice are Atlantic halibut (*Hippoglossus hippoglossus*), rainbow trout (*O. mykiss*), Pacific salmon (*Oncorhynchus* spp.) and Arctic charr (*Salvelinus alpinus*). Sea lice species associated with North Atlantic salmon-growing nations are *Caligus elongates* and *Lepeophtheirus salmonis*. Additional species of *Caligus* reportedly occur in Canada, while *Caligus rogercresseyi* and *Caligus teres* have caused significant problems in Chile. These external parasites cause erosion of the epidermis with subsequent loss of body fluids. Heavy infestations lead to stress which makes the fish susceptible to a variety of other diseases.

The controversy with respect to sea lice transmission has been raging in the North Pacific, particularly in British Columbia, Canada, where one group of scientists believes that sea lice shed from salmon net pens are infecting migrating wild salmon and thereby negatively impacting native salmon runs. (The cultured salmon in western Canada are primarily Atlantic salmon, *S. salar*, while all the wild salmon are in the genus *Oncorhynchus*.) Other studies have indicated that currents actually carry any sea lice that are shed from net pens away from areas through which wild salmon are migrating. Scientists on each side of the argument have accused the other side of bias. The conclusions for each group are largely derived from computer simulation models, so each side claims the assumptions used in model development by the other are flawed. Thus, the battle continues to rage on.

The other major issue swirling around sea lice involves the use of emamectin benzoate (SLICE®) to treat the problem. The chemical is now approved under an INAD in the USA. Each facility must pay a US$700 fee to come under the INAD exemption (information is available at https://www.fws.gov/fisheries/aadap/inads.html, accessed 29 December 2021). The efficacy of treatment has been found to vary from one location to another, so there are concerns that the sea lice are developing resistance to the chemical, though other reasons may be responsible for the variation in efficacy seen in different geographical regions. SLICE® is approved for use in Canada but is strictly regulated. Salmon treated with emamectin benzoate and then imported to Canada are required to have had a 68-day withdrawal period prior to harvest. SLICE® is not the only brand of sea lice control available. Other pesticides that have been used in attempts to control sea lice include are AlphaMax®, Betamax®, Salmosan®, Interox®, Paramove™, Excis®, trichlorfon and azamethiphos. There has been concern expressed that non-target species could be impacted in the vicinity of salmon facilities where SLICE® (or some other product) is used. Thus, there have been major efforts over the last several years to ramp up the production of cleaner fish such as wrasse (*Labrus bergylta*) and lumpfish (*Cyclopterus lumpus*) to serve as biological control agents to help reduce sea lice numbers on caged or penned salmon. Molluscs also are known to consume sea lice larvae and could possibly be stocked in salmon cages and net pens to achieve at least partial control of sea lice. Mechanical control methods also have been developed in which fish are exposed to elevated water currents to wash off the sea lice and collect them for disposal.

Summary

Disease is a common occurrence in aquaculture systems, though the susceptibility of the species to outbreaks (epizootics) can generally be reduced if the animals are not stressed. New diseases seem to crop up more frequently as the production level of the industry associated with a particular species increases. That may relate to the increasing biomass in a culture system during growout, attempts by culturists to increase their production by increasing the density of animals in the culture system and the increased stress that can result from both of those situations.

The primary diseases of aquacultured species are associated with fungi, viruses, bacteria, protozoans, helminths and copepods. The latter three are parasites that may not, in many cases, cause direct mortality, but their presence can result in the development of secondary infections that are potentially lethal. In addition to diseases attributable to the sources indicated, there are some diseases associated with adverse environmental conditions and nutritional deficiencies. The aquaculturist also needs to be aware of toxins that may lead to mortality or that may be concentrated in the aquaculture species, and impact human health when the fish are marketed and consumed. Contamination of cultured animals with human pathogens (e.g. pathogenic bacteria taken up by filter-feeding molluscs) is another pathway by which human health can be jeopardized.

The first line of defence should be avoidance of disease through BMPs, which includes stress avoidance. However, diseases will sometimes occur even in the best-managed facility. When they do, there are a number of treatment options available, the selection of which depends upon the specific disease and the availability of a vaccine, pharmaceutical drug or other type of chemical that has been shown effective against that particular disease, and which is approved for use. All regulations and treatment protocols that apply in your area should be rigorously followed when a disease is treated. Approved treatments will vary from nation to nation, and it is the responsibility of the aquaculturist to be familiar with current regulations in his or her area.

There are various ways in which treatment can be provided. The chemical or vaccine may be dissolved in water into which the aquatic animals are dipped, or they may be added to culture tanks or raceways under either static or flowing conditions. Injections of antibiotics and vaccines are possible, but generally impractical if large numbers of animals are involved. Antibiotics are most commonly applied by incorporating them into the feed. The animals to be treated must not have ceased feeding, however, or that means of getting the drug into them will not work. Phage therapy has been employed with some success and there have been some successes in controlling pathogenic bacteria through the use of prebiotics, probiotics and other feed additives, which are discussed in Chapter 8.

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6 Reproduction and Early Rearing

Introduction

One of the most important activities associated with developing a successful aquaculture industry involves controlled reproduction of the species being cultured. The whole issue can be avoided by aquaculturists who purchase post-larvae or fingerlings for stocking and do not conduct spawning activities themselves. For those who do spawn their own stocks, it is not always enough to just have the ability to spawn and obtain sufficient fertilized egg and larval survival to supply the numbers of animals needed for projected growout. It is often desirable for the timing of spawning to be under the control of the culturist. In nature, all it takes to maintain a population from one generation to another is survival to adulthood by one individual of each sex from among the often millions or even hundreds of millions of fertilized eggs produced over the lifetime of each spawning female. (As described below, some aquatic species bear live young, but they represent a minor group compared with the majority of species produced in aquaculture.) The chances of an individual egg surviving through hatching, larval development and growth to adulthood are extremely small for most aquaculture species. It improves greatly for those few species where some degree of parental care is provided, though those species tend to produce far fewer eggs than species that provide no such parental care. The lower number of eggs makes sense because the chances for survival are relatively good. The eggs tend to be much larger, as well, in species that provide parental care as compared with broadcast spawners that just release their gametes and then go on about their normal activities. Some examples of both highly fecund species and those with low fecundity are presented in this chapter.

Whether fecundity is high or low, it is incumbent on the culturist to take the steps necessary to promote a high relative level of survival of the species under culture from egg to at least stocking size, after which survival rates tend to be acceptable for all species if the proper growout conditions are maintained. The critical stages in the life cycle – the periods when mortality rates are highest – are during hatching and larval development for most species. The time of first feeding is particularly critical, especially with respect to marine species. For low-fecundity species, survival rates of 90% or more from egg to stocking are not uncommon, while for highly fecund species survival as low as a few per cent may be sufficient to provide enough animals to stock one or more culture facilities. Obviously, it will take more adults of low-fecundity species to provide the numbers of post-larvae or fry needed for stocking than for species that are highly fecund, again assuming an adequate level of survival. For highly fecund species, a good survival rate from egg to fingerling size would be around 5–10%. That level has been very difficult to achieve for many marine fish species (though there are exceptions, one of which is discussed later in this chapter). As experience with any particular species and the results of research on them often lead to new technology, more information on water quality and nutritional requirements, we can expect to see survival percentages from egg to market increase.

How Aquaculture Animals Reproduce

Animals of aquaculture interest and importance generally reproduce sexually (exceptions are algal species that are produced as larval food and as food for humans). In nearly all the species currently being cultured the sexes are separate and, once sex has been established, it remains constant for life, though, once again, there are exceptions (Box 6.1). Reproductive strategies in aquaculture species vary considerably. Some, in fact most, species of finfish produce very small eggs and may produce up to millions of them each year. That is particularly true of marine fishes and invertebrates, the eggs of

DOI: 10.1079/9781800621145.0006

Box 6.1.

Initially, the sex of some aquatic species is not differentiated in the early life stages. That situation can be taken advantage of by the aquaculturist who can in some instances influence the ultimate sex of the animal. More about this is presented in this chapter under the topic of sex control. There are some families of fishes that contain species that are hermaphrodites; that is, at some stage during their lives they produce both eggs and sperm. A fish may be a synchronous hermaphrodite (having ripe testes and ovaries at the same time) or a sequential hermaphrodite (having ripe gonads of one sex first and the other sex later in life). If a sequential hermaphrodite is first a male and later a female, it is called a protandrous hermaphrodite. If it is first female and later male, it is a progynous hermaphrodite. Sequential hermaphrodites are not prominent among aquacultured species, though such species do occur in families of fish that are or have been looked at as candidates for aquaculture. Included are the families Sparidae (porgies) and Serranidae (sea bass). Many ornamental reef fishes that are currently being cultured or may be produced in the future for the aquarium trade are sequential hermaphrodites.

which may be only a few hundred micrometres to a millimetre or so in diameter.

A few species of both marine and freshwater species produce relatively large eggs, which may be a few millimetres in diameter (Box 6.2).

In the case of invertebrates, the vast majority produce very small eggs, often microscopic or barely visible to the naked eye. Lobsters are an exception, though not by much. Spiny lobsters (i.e. *Panulirus argus*; Fig. 6.1) carry their eggs on their pleopods. Depending upon the size of the female, the egg mass may be in the hundreds of thousands. The eggs are about 0.5 mm in diameter. Clawed lobster females (such as *Homarus americanus*) carry their eggs masses on their swimmerets. Their eggs may be present in numbers of a few thousand and are about 2 mm in diameter. So, lobster eggs are anything but large, but they are many times bigger than the eggs of such invertebrates as marine shrimp, oysters and mussels.

Species with relatively large eggs may spawn only a few hundred to several thousands of eggs annually. As a rule, species that produce such numbers of eggs broadcast their eggs and milt into the water column. They may spawn one time annually or in some cases they may be multiple spawners. For some species, culturists can manipulate the environment and keep the fish spawning every few days for several months. Examples include red drum (*Sciaenops ocellatus*) as well as Atlantic and Pacific halibut (*Hippoglossus hippoglossus* and *Hippoglossus stenolepis*, respectively). Regardless of spawning frequency, broadcast spawners do not provide parental care for their fertilized eggs or later life stages.

Box 6.2.

Interesting exceptions to the development of small eggs are marine catfish in the family Arridae, which includes the hardhead sea catfish (*Ariopsis felis*) and the gafftopsail catfish (*Bagre marinus*). Both hardheads and gafftopsail catfish enjoy a bit of popularity with recreational fishermen who enjoy eating them, so they would seem to be candidates for aquaculture (though there does not seem to be much, if any, interest in their culture at present). One advantage is that the eggs of those fishes are very large (up to 2.5 cm in diameter), and they are incubated in the mouth of the male before hatching into large fry that have a high probability of survival. The problem is that the females only produce a few tens of eggs per spawn, so the number of broodfish required to supply an aquaculture facility would be prohibitively high. An aquaculturist could probably not afford to feed and maintain the number of broodfish that would be required and have any chance to earn a profit.

Fish species that produce large eggs often prepare a spawning site and may or may not guard the eggs; some species even protect the larvae for a period of time, once the eggs hatch. Examples that fit among those types are species that spawn once a year like channel catfish (*Ictalurus punctatus*) and rainbow trout (*Oncorhynchus mykiss*), or multiple times per year, such as tilapia (*Oreochromis* spp.). Then there are species that spawn once in their lives and die, the best examples of which are Pacific salmon like coho (*Oncorhynchus kisutch*). Atlantic salmon (*Salmo salar*) are somewhat unique in that at least a small percentage of spawning adults (referred to as kelts) survive spawning and return to the sea from where, if they survive one or more years at sea, they can return to spawn again.

Fig. 6.1. A large spiny lobster foul-hooked at night in Charleston Harbor, South Carolina, by R.R.S. in 1973. The lobster was far from its normal northern range in the Atlantic Ocean in Florida. It is possible the Gulf Stream carried the lobster north from the Caribbean.

Turning back to invertebrates, we see something of the same pattern as with finfish. Many species broadcast their gametes into the water column and do not provide any parental care. Species that do provide parental care usually do not prepare a spawning site but will instead carry the fertilized eggs around with them as previously described for lobsters. In general, molluscs are broadcast spawners, particularly the species of aquaculture interest. Crustaceans such as penaeid shrimp also broadcast their eggs, though as we will see, a form of copulation followed by internal fertilization occurs before the eggs are released. Freshwater shrimp females carry their fertilized eggs on their abdomens until hatching occurs, so there is some protection for the developing embryos. The primary freshwater shrimp species in aquaculture is the giant Malaysian prawn, *Macrobrachium rosenbergii*, though several other species are currently being cultured or developed for culture (see Table 1.1). While freshwater shrimp produce about 30,000 eggs per spawn, penaeids may produce 2 million eggs but provide no protection, so the chances of survival are not high in nature for marine shrimp.

Closing the Life Cycle

One of the most critical goals of aquaculturists who are working with a new species is obtaining the knowledge and developing the technology required to maintain the entire life cycle of the species of interest in captivity. A major step in that process is to be able to initiate and have control over reproduction. Before the culturist develops the ability to reproduce the animals in captivity, he or she may be forced to collect post-larvae or juveniles from the wild for stocking. That is also still being done in some instances where the life cycle has been closed but where catching wild larvae, fry or juveniles is less costly and the desired life stage is readily available in the required numbers to meet the demand by aquaculturists. There is increasing awareness that there also needs to be sufficient numbers in nature of such aquaculture species, so that they can be expected to recruit in quantities that are large enough to support any existing commercial fishery with enough left over to replenish the population. Some of those species may also be critical to the survival of non-commercial species, so maintenance of food web integrity is also something that needs to be taken into consideration. Whether food web integrity will be employed around the world will vary from nation to nation, and even region to region, but that goal should become universal.

Some marine shrimp farms, at least in Latin America, have been known to stock their ponds by filling them on incoming tides when post-larval shrimp are abundant, even though captive spawning is widely practised. Certainly, the cost of stocking wild post-larvae is attractive because it is basically free, but the incoming water will also contain predators that may consume the shrimp post-larvae before they reach market size. Capture of post-larval shrimp for pond stocking has been widely practised in Latin America, though probably not so much currently since hatchery technology has matured and can be used to produce SPF animals.

Milkfish (*Chanos chanos*) fry or small fingerlings are still being collected in parts of South-East Asia and sold to aquaculturists but, increasingly, hatcheries have become the primary source of milkfish fry or fingerlings for stocking (Box 6.3).

Once the life cycle of a species is closed in captivity, it is possible to begin selective breeding programmes and perhaps some genetic manipulations that, over time, will produce animals that not only are better adapted to aquaculture conditions, but will have more desirable traits than their wild counterparts. The ultimate goal would be domestication of the species, which tends to be a long way off for most animals being cultured today, though considerable progress has been, and is being, made with several prominent aquacultured species in contrast to species produced for stock enhancement (Box 6.4).

Trial-and-error is a process by which the culturist can work out how to spawn and rear the young of a species for which the life cycle apparently has not been closed. Another way is to study the literature that may exist on the life history of similar species, which could give lead to techniques that can be adopted by the target species. The struggle to close the life cycle of the Malaysian giant freshwater shrimp, *M. rosenbergii*, is illustrative, so we are relating it here rather than saving it for another section of this chapter.

During the 1950s, a scientist by the name of S.-W. Ling was working in South-East Asia under the auspices of the FAO. Ling became interested in freshwater shrimp as a potential aquaculture species. He took a number of freshwater shrimp into his laboratory and soon found that they would readily spawn in captivity under the conditions he had established. After fertilization and extrusion from the gonad of the female, the eggs are, as already mentioned, carried on her abdomen during incubation. This helps protect the developing embryos from predators unless, of course, an egg-bearing female is eaten by a carnivore, which would pretty much be the end of the story for her developing eggs.

Once the eggs hatched in Ling's laboratory, the larvae lived for a few days and then died. Ling concluded that either some environmental variable was not conducive to survival, or the young shrimp were starving. Once he eliminated starvation as the cause, he deduced that some chemical was missing from the water. According to the story that has been repeated many times over the years, Ling put small numbers of larvae into each of several watch glasses filled with freshwater and added various chemicals that he had on hand to the individual watch glasses to see if any of those compounds would promote larval survival.

Box 6.3.

In the case of shrimp, reductions in shrimp harvest from the capture fishery due to the taking of post-larvae for aquaculture have been reported. That may or may not also be true in the case of milkfish. There has been considerable concern expressed by some groups who believe taking wild larvae or juveniles to stock aquaculture facilities will, in the long term, deplete their populations in nature and, in the short term, rob commercial fishermen of their livelihoods. The argument is particularly strong when it comes to the capture of juveniles but extends to relatively large sub-marketable tuna (several kilograms at capture) used for further growout in net pens, as described in Chapter 1. There is increasing interest in producing tuna in hatcheries, as supplies of wild juveniles appear to be dwindling; perhaps, at least in part, in response to capture of them for aquaculture.

Box 6.4.

One thing that aquaculturists should be very cautious about is attempting to alter the genotypes of the species with which they work, particularly those cultured in public waters, especially in the ocean. Not only is it wise to use native species in cage and net pen culture, but it is also important to use wild broodstock, replace the broodfish frequently and do everything possible to retain the same genetic diversity in the cultured fish that exists in the wild. This is being done, for example, in conjunction with the red drum enhancement programme in Texas, USA. This admonition does not apply to industries that have already been developed using exotic species, such as is the case with salmon farming in Chile and Atlantic salmon farming in Washington, USA, and British Columbia, Canada. Those industries were developed before concerns about how escapement of exotics might negatively impact native species. When exotic species are used, avoiding escapes must be a high priority, but concerns about maintenance of genetic stock integrity – done by not trying to selectively breed fish to domesticate them – become less of an issue.

Alas, as they say, there was no positive result. All the larvae died in each of the watch glasses. One day, after experiencing another in a long series of frustrations as he watched his latest groups of larvae dying, he turned to his lunch, which his wife had prepared for him each day while he worked to find a solution to the problem. Ling, being Chinese, had been provided soy sauce with his lunch. On a whim, he poured a bit of the soy sauce into one of the watch glasses. To his dismay, the larvae in that container survived. So, do freshwater shrimp hatcheries now purchase large quantities of soy sauce prior to spawning their animals? And, if so, where would freshwater shrimp find soy sauce in nature?

Of course, the answers to those questions have nothing to do with the fact that the missing factor was associated with soy sauce, but it had everything to do with one of the ingredients in soy sauce – common table salt, sodium chloride. Now we can speculate that it is surprising that Ling apparently did not have some sodium chloride in his laboratory and had not already tried it, but the soy sauce story is much more entertaining. In any event, Ling was able to close the life cycle of the freshwater shrimp by adding salt to his larval-rearing containers.

Whether anyone had looked at the life history of freshwater shrimp in nature prior to the time Ling was conducting his experiments, we do not know. However, we have seen no publications from freshwater shrimp researchers over the past several decades that report upon earlier research associated with the salt requirement of the eggs of freshwater shrimp for development. But we now know that adult *M. rosenbergii* spawn in freshwater and that the egg-bearing females migrate to estuaries, seeking a salinity of around 12 ppt where the eggs complete their development and hatch. As the larvae go through their various larval stages and ultimately moult into post-larvae, which is when they take on the body form of the adult, they can tolerate reduced salinities until they can ultimately thrive in freshwater. In fact, as they develop, they will begin to migrate upstream into water of lower and lower salinity.

Since the 1950s, culturalists seeking information on the reproductive process of new species under aquaculture development need not repeat Ling's trial-and-error approach. There are literally thousands of publications that can advise aquaculturists with details on how to provide the proper conditions conducive to supporting the reproduction of literally hundreds of species. It behoves the modern aquaculturist who is trying to close a life cycle to consult that extensive literature base, which may provide quick answers to difficult, sometimes seemingly insurmountable, problems. Information is increasingly available at no cost on the Internet, and many university libraries have good collections of books and journals on aquaculture that can be consulted.

Reproduction in captivity may be a very simple matter that merely involves allowing nature to take its course. That might involve putting broodstock in a pond where they will find their mates and spawn naturally when environmental conditions are such that gonad development and the release of gametes occur without any human intervention. On the other hand, various amounts of human intervention may be required (e.g. hormone injection to induce ovulation) that will provide the culturist with better control over the process (such as selective breeding). Included are such things as manipulation of environmental conditions, most commonly involving adjustments to temperature and photoperiod (e.g. red drum) or providing spawning containers (e.g. catfish).

Sex Identification

For some species, sex identification is relatively easy, particularly when the fish are approaching spawning condition. In other cases, there may be few if any clues to either the sex or the reproductive status of a particular animal. In recent years ultrasound has been used to allow the aquaculturist to determine the sex of each animal. The technique has been used to determine sex in such aquaculture species as channel catfish (*I. punctatus*), sharptooth catfish (*Clarias gariepinas*), Atlantic cod (*Gadus morhua*), Atlantic salmon (*S. salar*), hapuku (*Polyprion oxygeneios*), striped bass (*Morone saxatilis*) and hybrid striped bass (*M. saxatilis* × *Morone chrysops*). Reproductive status has been determined by the technique in Atlantic cod, Atlantic salmon, striped bass and hybrid striped bass. Males will often develop bright colours during the spawning season, which is probably a means of attracting females (as is the case in many bird species).

Male Pacific salmon (*Oncorhynchus* spp.) will grow an extended upper jaw, called a kipe, when they approach spawning condition. As the gonads develop, the abdomen of females of many species of fish become distended. Other anatomical features may be found that help the culturist differentiate the sexes. Examination of the vent will sometimes allow the culturist to distinguish between male and female fish, though that method is not 100% reliable in many species. Marine shrimp females have a small round opening on the ventral surface anterior to the last pair of walking legs called the thelycum into which a packet of sperm called a spermatophore is placed by the male during mating. The spermatophore is transferred with the help of an organ called the petasma, which is located on the first pair of the male's pleopods. Freshwater shrimp males have larger chelae than the females and develop more colour on their chelae. Behavioural differences may also occur, as with nest-building tilapia (*Oreochromis* spp.). For the tilapia species of aquaculture interest, the nests are constructed and defended by the males.

Following spawning, it is very easy to identify the females of at least some species. Examples are freshwater shrimp, spiny lobsters (*Panulirus* spp.; Box 6.5) and female blue crabs (*Callinectes sapidus*). The egg mass of crabs is called a sponge so, not surprisingly, the crabs are called sponge crabs. Many species of tilapia are mouthbrooders, and in the case of aquaculture species, mouthbrooding is the job of the female which is driven from the nest after spawning so that the male can go back to guarding the nest and trying to attract another female (Fig. 6.2).

Box 6.5.

While several species of spiny lobsters (genus *Panulirus*), among a number of other species, are included in Table 1.1, commercial culture has been difficult to achieve. The stumbling block has been the fact that getting larvae through the phyllosomal (larval) stages requires the better part of a year (typically of the order of 9 months). The phyllosomes are feather-like animals that do not look anything like the adults, have no exoskeleton, are weak swimmers and remain suspended in the water column. If that is not enough, they are also very fragile. If two of them contact one another other, they tend to become entangled and will usually end up as mortalities. While some *Panulirus* species have been successfully brought through the larval period to the post-larval stage, at which time they resemble the adult, the rearing of spiny lobsters remains a challenge, though some progress has been reported from Japan.

With species such as oysters, clams, scallops and related species of shellfish, it is not a simple matter to identify the sexes. In fact, many oyster species are hermaphroditic. They may have gametes of both sexes present, change sex from one year to the next and even go through phases where they have no gonadal tissue present. In the hatchery, oysters in the genus *Crassostrea* may be opened and examined under the microscope until ripe males are found. The testes are removed, and a slurry is made from them. Other oysters, presumably females among them, are then exposed to temperature shock of a few degrees elevation or a chemical shock to induce them to release their eggs. The sperm slurry is mixed with the eggs, which are then fertilized. Oysters in the genus *Ostrea* brood their eggs in the mantle cavity so the method described for *Crassostrea* would not be appropriate. Either large numbers of eggs may be found in the mantle cavity of the genus *Ostrea* simultaneously or small numbers may be present over long periods of time, depending on species.

Controlling Spawning

In looking at human intervention to control spawning, let us first look at environmental manipulation. We will then look at spawning induction through hormone injection and other techniques. We need to indicate that hormone injections will not work if the animals are not physiologically approaching full ripeness. Hormones can serve as a trigger, but gonadal development is generally initiated by environmental cues, and only final gonad development and release of gametes can be induced with hormone injections.

As mentioned above, temperature and photoperiod tend to be controlling factors, though in some cases the phase of the moon is also important, with spawning in some species occurring at night under a full moon. Most aquaculture species spawn during a particular time of year, especially species that inhabit temperate regions where spawning often occurs in the spring or autumn when water temperature is rising or falling and when day length is increasing or decreasing. Once again, knowing what the environmental conditions are in nature when a particular species spawns will help the culturist recreate those conditions in the hatchery and should help reduce the number of various approaches required to get things right.

Fig. 6.2. The circular depressions a drained pond are nests that were constructed by male tilapia.

It is not always necessary to control both photoperiod and temperature to induce gonadal development. For example, tropical species, such as tilapia, seem to develop when the proper temperature range exists, regardless of photoperiod. If maintained within the proper temperature range, tilapia females can spawn at a frequency of about once a month. Males can spawn much more frequently if they can find mates. In the tropics, tilapia females have been known to spawn at least eight times in a year. While channel catfish (*I. punctatus*) females spawn only once a year (unless as induced to spawn out of season as previously discussed), the period over which they spawn begins in March or April at the southern end of their native range (southern USA east of the Rocky Mountains extending north into portions of southern Canada) and may extend into August even in the southern end of their range, with different females spawning at different times over that period of several months. Male catfish can fertilize multiple batches of eggs. Spawning commences later in the year with increasing latitude in the native range of the species, because the water warms more slowly during the spring as one goes north. It is possible to put channel catfish through an artificial winter and induce gonadal development in a part of the year that is outside their normal spawning period. In fact, R.R.S. was able to accomplish that several years ago. However, the way in which the industry is configured does not provide any significant advantage with respect to off-season spawning, so focusing on the normal spawning season seems to be exclusively relied upon within the industry. We have thought of a reason one might want to spawn channel catfish in the autumn and mentioned that, if you will recall, in Chapter 4.

Some of the fish species that have been spawned using temperature and photoperiod manipulation include American lobster (*H. americanus*), ayu (*Plecoglossus altivelis*), southern flounder (*Paralichthys lethostigma*), gilthead sea bream (*Sparus aurata*), milkfish (*C. chanos*), some species of rabbitfish (*Siganus* spp.), red drum (*S. ocellatus*) and turbot (*Scophthalmus maximus*). At least some species of marine shrimp (family Penaeidae) can be induced to spawn by maintaining the proper temperature and light levels. The species mentioned are probably only a small percentage of those that can be susceptible to the approach.

In some instances, once the proper conditions have been established, a species can undergo repeat spawning for extended periods of time – well beyond the normal spawning season. That has been demonstrated convincingly with red drum (*S. ocellatus*), which were first spawned in captivity in 1977 and are currently being produced in commercial hatcheries in the USA and parts of Asia, most notably China. Tens of millions are also being produced annually for enhancement stocking by public hatcheries operated by US state and federal fisheries agencies such as the Texas Parks and Wildlife Department (TPWD), the Florida Fish and Wildlife Conservation Commission, and the US Fish and Wildlife Service facility in South Carolina. The Texas programme has been ongoing for over a few decades. After a period of research that demonstrated feasibility, the first hatchery was put into operation in 1982. A second hatchery was completed in about 1998. Adult broodstock are collected from nature in the case of enhancement programmes and are replaced periodically to maintain genetic diversity of the cultured population (Box 6.4). In the case of commercial pond aquaculture of red drum, the broodstock initially used to develop an aquaculture programme were obtained from the wild. Subsequent generations of broodfish are produced by selecting fish from the preceding generations and grown to adulthood. Fish from different stocks are commonly introduced into captive broodfish populations to help avoid inbreeding.

Because escapement of red drum from ponds can be prevented to a very large extent – at least there should be no mass escapes, which is what geneticists are most concerned about – selective breeding to improve their performance under aquaculture conditions, which may involve some loss of genetic diversity, is not considered to be a significant issue.

The first step in preparing red drum for spawning – and one that has been applied to various other species – is to take the fish through a brief annual cycle that ultimately will get them into temperature and photoperiod conditions that mimic those present during the spawning season. The red drum is an autumn spawner. To run it through the abbreviated seasons, it may first be exposed to temperatures and photoperiods that simulate winter, with that simulated season being truncated into no more than a few weeks. Similarly, spring and summer conditions are simulated sequentially, followed by autumn. The transition between seasons is made by changing the water temperature slightly each day and extending or reducing the photoperiod by several minutes a day as appropriate. When autumn conditions are in place, manipulation is maintained as are the temperature and photoperiod. If the process is done properly, the fish will begin spawning during the simulated autumn. In some cases, females may spawn every few days for up to several months, and some have even spawned repeatedly for a year or more. Because prolonged spawning has been shown as being stressful and can, if it continues long enough, lead to the death of broodfish, it is common practice to spawn fish several times over a period of weeks, and then recycle them once again. Enhancement programmes such as for red drum in Texas produce fish from spring through autumn when outdoor pond temperatures are conducive for rearing larvae, while commercial hatcheries typically produce only the number broodfish needed to meet their own stocking needs and to fill any orders obtained from other growers. Texas is now using the same basic technique to produce southern flounder (*P. lethostigma*) and spotted sea trout (*Cynoscion nebulosus*). The technique does not need to be used only for multiple-spawning species but should be applicable to those that only spawn once a year. Tropical species may spawn throughout the year without any environmental manipulations, as we have discussed with respect to tilapia.

The use of hormones for controlling spawning has been around for at least several decades.

The first hormone to be developed to induce spawning in finfish of numerous species was sourced from carp pituitary. To prepare the injections, pituitary glands from common carp (*Cyprinus carpio*) are removed, desiccated in acetone, ground into a powder and dissolved in sterile water. The solution is then injected into a gravid female fish to induce spawning. Carp pituitary and pituitary hormone from other species are still widely used today, though various other hormone sources that produce the same result are also available. Two common ones are pregnant mare serum (PMS), which is self-explanatory, and human chorionic gonadotropin (HGC) obtained from the urine of pregnant women. Others are luteinizing-hormone-releasing hormone (LHRH), gonadotropin-releasing hormone (GnRH) and follicle-stimulating hormone (FSH). Those and other hormones can be purchased from drug and chemical supply companies. Some commercial products may be restricted to ornamental fish, while others may be approved only for one or a few food-fish species. The status of approval should be determined for the species and nation in which hormonal induction of spawning is being considered. The Aquatic Animal Drug Approval Partnership (https://www.fws.gov/fisheries/aadap/home.htm, accessed 15 December 2021), which was mentioned in Chapter 5, has a list of the various types of spawning aides and other biologics available for use in aquaculture.

Among the many species in which ovulation has been successfully induced by one or more of the hormones mentioned are various carp species (family Cyprinidae), milkfish (*C. chanos*), channel catfish (*I. punctatus*), walking catfish (*Clarias* spp.), sea bass (family Serranidae), mullet (*Mugil* spp.), striped bass (*M. saxatilis*), hybrid striped bass (*M. saxatilis* × *Morone chrysops*), Atlantic salmon (*S. salar*), red drum (*S. ocellatus*), rabbitfish (*Siganus* spp.) and gilthead sea bream (*S. aurata*). With all the species being added to the list of those that are of interest or already being produced commercially by aquaculturists, it is highly likely that the above list represents only a fraction of the species that have been induced to ovulate through hormone injection.

While sexual maturity occurs in both sexes generally at the same time of year, individual male and female individuals that the aquaculturist may want to mate with each other may not mature simultaneously, particularly in species that spawn once during a particular spawning season. A culturist might find a male that has some traits that are desirable to pass along to the next generation and not have a ripe female to mate it to, for example.

In some cases, it is possible to rapidly freeze sperm – a process called cryopreservation – at extremely cold temperatures and to later thaw the sperm for use when the desired female is ripe. Cryopreservation involves the use of an extender or cryoprotectant chemical, such as glycerol, methanol, dimethylsulfoxide or dimethylacetamide, and freezing the milt in liquid nitrogen (–196°C). While cryopreserved sperm from several species of invertebrates and finfish has been successfully thawed and used to fertilize eggs, cryopreservation, thawing and fertilization of aquatic animal eggs have been major stumbling blocks, though there are reports that at least some progress has been made. There is no problem associated with freezing eggs but thawing them and retaining viability has been difficult to achieve.

Examples of aquaculture species in which sperm has been successfully cryopreserved are Japanese sea cucumber (*Apostichopus japonicus*), Atlantic and Pacific halibut (*H. hippoglossus* and *H. stenolepis*), yellow catfish (*Pelteobagrus fulvidraco*), common carp (*C. carpio*), Brazilian flounder (*Paralichthys orbignyanus*) and rohu (*Labeo rohita*). In the case of rohu, milt in one case was obtained and cryopreserved several hours after the fish had died. The sperm was later successfully used to fertilize eggs that developed normally. Chilling, but not freezing, of sperm to keep it in good condition until needed has also been a technique that has found success in conjunction with Atlantic halibut. Chilled halibut sperm can remain active for up to several weeks. Chilling spermatophores of Pacific white shrimp, *Litopenaeus vannamei*, is also a way of storing the sperm from that species for some period of time.

Spawning Methods

A few methods associated with spawning have been described previously, and more detail on individual species or species groups that have already been mentioned – as well as some that have not – are described in the subsections that follow. Before looking at those examples in more detail, we would like to build upon some of the information that has already been provided. This discussion, as is the majority of this book, is limited to commercial food-fish species and is not meant to be comprehensive since that would involve hundreds of species and a great deal of repetition, because the same approaches often apply quite broadly.

Many aquaculture species construct nests, find existing depressions or structures in which to find concealment during spawning, or burrow into the sediments during some part of their reproductive cycles (Fig. 6.2). The following examples are illustrative and include some information on rearing the early stages of the animals discussed. By early stages we mean the larval, post-larval or fry life stages.

For many species, when the egg hatches, the animal that emerges is still in a relatively early stage of development. Often, the mouth and digestive system have not formed; nor, in the case of many finfish species, will the fins be fully developed. Those primitive life forms, which typically initially become members of the zooplankton community in nature, are referred to as larvae. They show little resemblance to the adults as is clear from Fig. 6.3, a photograph of an Atlantic halibut (*H. hippoglossus*) larva.

Tiny larval finfish will have an oil droplet in the belly area. The oil is the source of their nutrition until they begin exogenous feeding. A typical marine fish larva is nearly invisible to the naked eye when it hatches, not only because it is very small, but also because it will typically be highly transparent. We have often compared them with eyelashes, except they are shorter than the typical eyelash and are often unpigmented. In many species, the larvae are no more than a very few millimetres in length upon hatching.

Some fish – tilapia, channel catfish, trout and salmon being examples – are basically similar in appearance to the adults when they hatch, the major difference being that they are very small and hatch with a yolk sac, which appears as an enlargement of the abdomen (Fig. 6.4). That is known as the sac fry stage of development. The yolk sac, which is a source of endogenous nutrition, becomes smaller and smaller as the yolk is metabolized, and it will ultimately disappear. Once the yolk is absorbed the fish are called fry. In the case of channel catfish, the yolk sac fry are yellow in colour and, as the yolk is absorbed, they turn black. Once the yolk has been absorbed, the fry swim to the water surface and are called swim-up fry (Fig. 6.5). The fingerling stage is reached when the animals become a few centimetres long. Typically, they are still called fingerlings in aquaculture parlance when they reach stocking size, which really is defined by the individual aquaculturist; that is, it has a broad range. For example, catfish farmers refer to fish up to at least 20 cm as fingerlings though the fish are often stocked for growout at lengths of 10 cm or less. Young salmon are an exception to the terminology

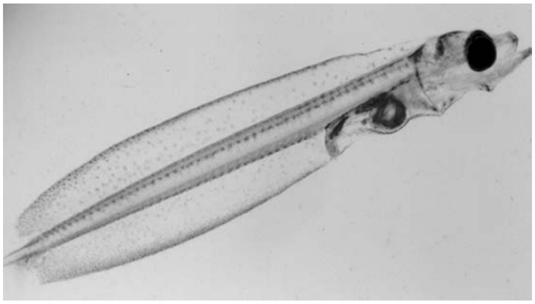

Fig. 6.3. A larval Atlantic halibut that is at least a few weeks old since its yolk sac is well absorbed. Note that its mouth has formed but its fins are not developed. (Photograph courtesy of Michael B. Rust.)

Fig. 6.4. A group of newly hatched channel catfish sac fry.

Fig. 6.5. Channel catfish swim-up fry in a culture tank looking for food.

that is used in conjunction with other species, because after the sac fry stage they are called alevins. Fingerling salmon in the freshwater phase of the life cycle are called parr, and they become smolts when they are ready to migrate or are introduced into saltwater.

Invertebrates often have a considerable number of larval stages to go through – often 20 or more. The difference in appearance from one stage to the next may be small, but the animals moult at each stage and often some differences can be perceived if one looks closely enough. Invertebrate larval stages are often numbered by alphanumeric designation. Once the animals take on the appearance of the adult in terms of basic shape and structure, they are called post-larvae.

Many species of finfish can be spawned by a process called stripping. That process involves first ensuring that the fish are ripe; that is, that they are spermiating in the case of males and ovulating in the case of females. Only females that release all their ripe eggs simultaneously can be stripped. For most species subject to stripping, modest pressure on the abdomen near the vent will cause milt or a small number of eggs to be expressed, depending on the sex of the fish being handled. When that happens, the culturist can apply greater pressure to the abdomen from the sides beginning at the anterior belly and moving towards the vent. The eggs can be expressed into a bucket or pan with or without water, after which milt is added using the same stripping method as was used on the female (Fig. 6.6). It is common practice to strip more than one male with each female because sperm viability may vary from fish to fish. Also, using milt from two or three males to fertilize the eggs of a single female helps ensure maintenance of genetic diversity in the offspring. If the bucket or pan contains water prior to receiving the eggs and milt, the wet method of fertilization is being used. In the dry method, there is no water added until the eggs and milt have been thoroughly mixed. Traditionally, feathers obtained from some species of large bird have been used to mix the gametes, though that approach is not widely employed today. Hand mixing works just as well. No matter which method is used, wet or dry, the mixture of eggs and milt is allowed to stand for a few minutes to allow time for fertilization.

Following fertilization, the eggs are washed to remove the milt, after which they are placed in an appropriate incubator such as hatching jars or heath trays (Fig. 4.13). An alternative to hatching jars and other types of incubators is to hatch the eggs in a tank. That works well for animals such as marine shrimp and various marine finfish species that have pelagic eggs in nature. Many times, hatching tanks have conical bottoms. Because tank hatching and early larval rearing in tanks are often carried out under static or very low water-exchange-rate conditions, conical bottom tanks with centre drains will allow waste products and mortalities to collect around the drain where they can easily be removed by siphoning or by pulling the standpipe briefly. It should be noted that some species are amenable to either stripping or tank spawning. Striped bass and hybrid striped bass are examples.

Fig. 6.6. A male salmon being stripped of milt into a bucket containing eggs.

Hormone injections may be used to help induce ovulation in females and, in some cases, may also be used to promote spermiation in males. For most species there is a fairly large window of opportunity for the culturist to strip the fish once they are spermiating and ovulating (the condition is known as running ripe, as milt or eggs may be released in small amounts if a fish is picked up so it can be stripped). That window of opportunity may be up to several hours, as in the case of salmon. However, there is a very small period during which running ripe striped bass and hybrid striped bass must be stripped or the eggs will die due to lack of oxygen. Females that are to be induced to spawn are injected with 275–330 international units (IU) of HCG per kilogram of body weight in the musculature. Males may also be injected, though with a lower dose (110–164 IU/kg) of the same hormone.

With respect to striped bass and its hybrids, it has been necessary to periodically determine the stage of egg development. Though that process can be accomplished using ultrasound technology, the standard technique involves sampling a few eggs with a 3 mm (outside diameter) glass or plastic catheter that is inserted through the vent and into the ovary. The collected eggs are then examined under a microscope and placed into one of a number of stages. Photographs of the various stages have been published to help the culturist determine egg stage (see the book on striped bass culture by Harrell *et al.* listed in the 'Additional Reading' section at the end of this chapter if you want to look at the pictures). Knowing the developmental stage, the culturist will have some idea as to how many hours the eggs are from being ovulated. The process of egg sampling is often repeated with increasing frequency as the apparent time of ovulation approaches. To make sure the eggs are obtained in good condition, the culturist obviously needs to be there at the time ovulation occurs to strip the females within in the ovulation window. That means ovulation can occur anytime of the day or night, so trained staff members need to be on duty around the clock. Pressure on the abdomen before ovulation occurs will cause premature release of the eggs which cannot be fertilized, so extrusion of eggs using pressure is not done until the eggs have been released from the ovary. Squeezing a fish that has not released its eggs will also damage the ovary. A few examples of other species that are routinely stripped to obtain eggs and milt are common carp, Atlantic and Pacific halibut, rainbow trout and Atlantic salmon.

When eggs are placed in jars or trays for incubation, they are allowed to remain until they hatch, after which they should be removed from the incubators and may either be stocked into fertilized ponds or, as is now common, stocked into nursery tanks or raceways for a period of time – often up to several weeks or months – before being stocked in ponds, growout raceways, tanks, cages or net pens, depending on the type of water system that is appropriate.

Atlantic and Pacific halibut are excellent examples of species that cannot tolerate flowing water during the early life history stages. An adult halibut will lay thousands of eggs at a time and spawn every few days under the proper environmental conditions. Halibut eggs are usually hatched in tanks of static water. Hatching requires about 1 month because the metabolic rate of the developing embryos is very low in the cold water required during hatching (typically 6°C). If eggs bump into one another or hit the tank walls during development, the embryos will die. Larval development is also allowed to occur under virtually static conditions, at least until the larvae can swim sufficiently well to overcome small currents. The early-stage larvae have very poor swimming ability and, as is the case with eggs, will die if they contact each other or the tank walls. This is reminiscent of the situation discussed with respect to spiny lobster larvae (Box 6.5), though the larval period of halibut is much shorter. Halibut larvae do not begin feeding for nearly 1 month after hatching but live off their oil droplet for that period. Metamorphosis does not occur until 3–4 months after hatching (Fig. 6.7). Following metamorphosis from a typical fish configuration with one eye on each side of the head to the typical flatfish body shape (both eyes on one side of the head), the fish are very hardy. Before metamorphosis they are extremely fragile. That may have something to do with the fact that they

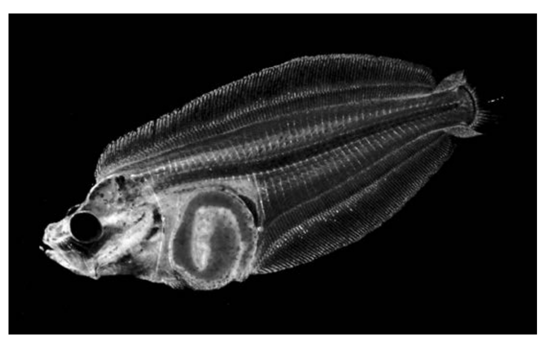

Fig. 6.7. A halibut larva in which metamorphosis to the post-larval stage is nearly complete. Note that the body shape is similar to the adult body configuration, but eye migration is not complete. (Photograph courtesy of Michael B. Rust.)

spawn in the deep ocean in nature and would not be exposed to harsh conditions, other than cold temperatures. They would also be unlikely to bump into anything during development.

The following subsections provide more detail to build upon details on spawning methods and also present more information on early rearing. There are also some additional examples that have not been given much attention previously in this chapter.

Tilapia

Male tilapia are nest builders (Fig. 6.2). In very soft sediments they will actually excavate deep nests, particularly in muddy sediments, though the typical nest is only 3–5 cm deep. The circumference of each nest is slightly wider than the length of the male that builds the nest. When tilapia adults are stocked heavily in ponds, many of the nests may have common sides. Because they defend their nests, male tilapia do not swim around the spawning ponds during the spawning season, which may actually be virtually year-round in the tropics. Females do swim around and are courted by the males until the female selects a mate. Once a pair has been formed, the eggs, which are a few millimetres in diameter (typically 3–4 mm), are expelled from the female and fertilized by the male as they fall into the nest. The female picks up the fertilized eggs in her mouth and leaves the nest, after which the male goes into courting mode once again.

It is not necessary to pond spawn tilapia. The fish can be spawned in tanks, raceways or aquaria with or without a substrate into which the males can construct a nest. While some species of tilapia can be reared in saltwater (the salinity tolerance varies among species – some species and hybrids can survive in hypersaline water), spawning is conducted in freshwater (Box 6.6).

Incubation of the eggs takes place in the mouth of the female. While the incubation time for them is somewhat variable depending on temperature, the eggs will hatch within about 5 days on average. There is an additional 5 days or so required for yolk absorption, during which the sac fry remain in the mouth of the female. Once the yolk is absorbed, the fry will venture out and begin foraging, but for at least a few days they will return to the mouth of the female if they sense danger. So, when tilapia follow their normal breeding and egg incubation processes, there is a period of 2 weeks or more during which the female does not feed; but she has the ability to spawn about every 30 days under the proper conditions (though only up to eight spawns per female have been reported, which is certainly less than once every 30 days). In any event, there is little time to make up for the lack of growth of the female that occurred during egg and sac fry incubation. The males, on the other hand, continue to eat normally throughout the year. Even when males are guarding their nests, because they are plankton feeders, feed is basically available to them without requiring them to leave their guard over eggs. Also note that tilapia, depending upon species, will mature and spawn at as little as 3 months of age, so even in temperate climates there can be two or more generations spawning within the same year in the same pond if the initial stocking is with adults. In the tropics, three or four generations may occur

Box 6.6.

Mozambique tilapia (*Oreochromis mossambicus*) and some red hybrids (various species combinations have been crossed to produce red hybrids) are tolerant of high-salinity water. There are reports of tolerance levels exceeding 100 ppt salinity and it has been theorized that tilapia evolved in the marine environment and invaded freshwater. While there are no extant native marine populations of tilapia, there are some escapees from freshwater tilapia systems that have established populations in coastal waters. One example is Mozambique tilapia, which has become established in Pearl Harbor, Hawaii, USA (Fig. 6.8). Also, research and commercial facilities have been established for rearing red tilapia in seawater (Fig. 6.9).

Fig. 6.8. An example of Mozambique tilapia, *Oreochromis mossambicus*.

Fig. 6.9. Red hybrid tilapia being fed in small ponds in the Bahamas.

in the same pond within a year after stocking. Because they mature so young, adult tilapia females may not reach marketable size within a typical growout period of about 8 months, though in some cultures marketing of small tilapia frequently occurs (Box 6.7). The result of the long periods when females do not eat can be stunting of the pond's adult female population. In addition, when two or more generations of fish are produced, overcrowding may occur. Those problems have led, as we will see in the sex control section of this chapter, to the desire on the part of tilapia food-fish producers to stock all-male populations, because that will preclude reproduction.

Tilapia eggs and fry can be incubated outside the mouth of the female in much the same way the eggs of many other species are incubated. After capturing a mouthbrooding female, the culturist can open her mouth and gently shake her so that she will drop her eggs or fry, which can then be put in an appropriate incubation unit; often some type of hatching jar or modification thereof, such as a clear plastic tube. Figure 6.10 shows an example of a hatching unit. Hatching jars should be provided with frequent replacements of water or slow, constant new water flow through the jars, and should also receive aeration to maintain an appropriate DO level. The eggs and fry are not particularly fragile so movement of the water due to aeration will not cause problems as long as the agitation is not too vigorous.

Tilapia fry school after yolk sac absorption and can typically be found swimming in the shallow water next to a pond levee where they can be netted and transferred to a fertilized pond or raceways

Box 6.7.

In some cultures, small tilapia (as little as 10 cm or so in length and possibly weighing less than 50 g, and certainly less than 100 g) can readily be marketed. We have seen tilapia and other species of fishes of that size, and often smaller, in fish markets in the Philippines, for example. In general, market size for tilapia is around 450 g.

Fig. 6.10. The tilapia fry in the hatching jar were introduced as fertilized eggs and allowed to develop and hatch. They remain in the jar through yolk sac absorption.

for growout. Not all fry will be captured in that manner but can be captured later. Whether or not some of the fry have been removed as indicated, they may also be left in the spawning pond for a few weeks before being seined and moved as small fingerlings. It is never possible to capture all the fry or fingerlings from a brood pond, which is why the uncaught fry from the early spawns will be reproducing within a few months, potentially leading to overcrowding. In the meantime, if fish of both sexes are stocked for growout, they too will be spawning within a few months. Once the brood pond has produced enough fry or fingerlings to fully stock the growout ponds, adults from the brood pond can be harvested and fish of marketable size can be sold. Alternatively, the culturist may separate the sexes and stock them in separate ponds until the next year. If the culturist has a need for young fish year-round, it is likely that the broodfish will need to be captured and moved periodically to separate them from offspring that avoided capture for restocking in growout ponds.

Tilapia fry will take finely ground feed as soon as they begin exogenous feeding, though establishing a plankton bloom is a good idea if you plan to stock the young fish in a pond, so they will have readily available food within easy reach. In tanks it is easy to spread the feed over the entire surface area and the fish will not have to go far in search of food. The same technique applies to other species that will accept prepared rations as first feeds.

Tilapia culture is popular with artisanal fish farmers in the tropics where mixed-sex populations are commonly produced. Due to lack of facilities, artisanal tilapia producers are the ones who tend to have the most problems with stunting and overpopulation of tilapia in their ponds. Often, they have one pond, so when the fingerlings they initially stock begin to spawn, they need to be removed to the extent possible. The farmer can capture fry and fingerlings with nets of appropriate mesh size and dispose of them, but that, as you have seen, does not necessarily solve the problem. Another method that has been used involves stocking predatory fish at about the time the initially stocked tilapia approach or reach reproductive size and age. Predators, such as snakeheads (*Channa striata* or *Ophiocephalus argus*, for example), can be stocked in fairly small numbers and should be of a size that can easily take unwanted fry and young fingerlings without being able to consume the adults that are being grown out for marketing. Snakeheads are popular predators, but a variety of other predatory fish species have been used in this manner.

Salmon and trout

In nature, salmon and trout build nests, called redds, by scouring depressions in stream gravel. The female of a pair will hover over the redd and extrude her eggs, which are immediately fertilized by one or sometimes more males as they fall into the redd, where they are provided refuge by dispersal in the gravel. Incubation and yolk sac absorption occur in the gravel after which the juveniles emerge to begin feeding and ultimately, in the case of anadromous species or strains, smolt and migrate to the ocean. While some culturists have constructed spawning channels that mimic the natural conditions in a streambed, most spawning and hatching occurs at a hatchery under controlled conditions where the adults are stripped and eggs are incubated.

Pacific salmon (*Oncorhynchus* spp.) can be stripped like their trout (*Salvelinus* spp. and *O. mykiss*) cousins and Atlantic salmon (*S. salar*). However, because all Pacific salmon die after spawning, the technique used in conjunction with females is to open the abdominal cavity with a knife and to pull out the ovaries (known as skeins). The skeins are then sliced open, and the eggs are poured into a bucket where milt is added from stripped males as previously discussed (Fig. 6.11). In government hatcheries in countries such as Japan, Canada and the USA where the objective is to produce smolts for release and eventual recruitment into capture and/or recreational fisheries, the milt from two or three males may be used to fertilize the eggs from each female as a means of helping maintain genetic diversity.

Hatching of Pacific salmon follows the same methods as are used for trout and Atlantic salmon; that is, it is usually done in heath trays (Fig. 4.13). Rearing of swim-up fry and fingerlings for release typically occurs in tanks or raceways. Once the fish reach a particular size, which will vary depending upon the purpose of culturing them, they may be released to augment recreational or commercial fisheries, or they may be grown to market size in cages or net pens (primarily salmon) or raceways (trout). Stocking of salmon and sea-run trout such as steelhead, a race of rainbow trout (*O. mykiss*) that spends much of its life at sea like salmon, occurs at the smolt stage. The amount of time a sea-run trout or salmon spends in freshwater after yolk absorption and prior to smolting varies with

Fig. 6.11. Culturists have opened the belly of a ripe female Pacific salmon, removed one skein and are expelling eggs into a bucket prior to adding milt.

species and can range from a few weeks to a year. Atlantic salmon (*S. salar*), the most widely aquacultured salmon species, spend several months in freshwater and smolt at a size of about 40 g, at which time they can be stocked directly into cages or net pens.

Providing the proper diet is always an important consideration for broodstock of salmonid species and strains that do not die following spawning. Species of *Oncorhynchus* that spawn and die will usually not feed once they leave the ocean, rather survive on energy reserves they obtained while at sea until they spawn. In the case of rainbow trout (*O. mykiss*), for example, a diet supplemented with vitamin C (ascorbic acid) at several times the required level enhances sperm quality. For many species, not just salmonids, but covering all species that are fed prepared feeds, the standard growout diet is used in conjunction with broodstock throughout much of the year, but vitamin supplementation and sometimes organ meats or live fish are provided for a period of time prior to gametogenesis. Such so-called conditioning diets, when used, vary considerably from species to species and from one culturist to another.

Catfish

The description of catfish spawning and early life history that is presented here can be used for blue catfish (*Ictalurus furcatus*) and white catfish (*Ictalurus catus*) as well as the channel × blue catfish hybrid, because they all have virtually identical life cycles. While there was considerable interest in the 1960s and early 1970s in commercially culturing blue and white catfish, and some research was even conducted on various hybrid crosses among them, interest declined when the industry concluded that the channel catfish was the most amenable species to culture. That all began to change in 2001 when a commercial hatchery made the first hybrid channel × blue catfish available to catfish farmers. The percentage of hybrid catfish produced in the USA reached 15% in 2011 and has continued to grow. Research has shown that the hybrid performs better than the channel catfish in terms of growth rate, feed conversion ratio, disease resistance (particularly to *Edwardsiella ictaluri*), tolerance to crowding and harvestability with seines.

Channel catfish mature in their second or third year of life, when they reach about 2 kg. Farmers tend to use adults that are only a few years old and replace them when they reach over about 5 kg. Fish in that range of weight have reasonable fecundity and are relatively easy to handle. The spawning season, you may recall, is in the spring and summer when the water temperature is in the range of 21–29°C and varies with latitude – starting later in the year at higher latitudes, as might be expected.

The native habitat of channel catfish is in rivers, though they are now found in reservoirs as well as natural lakes where they have been stocked, along with myriad farm ponds and aquaculture facilities around the USA. They are now being reared in a few other countries as well, so there is some competition in the USA from abroad. Despite that, most of the competition has been from imported basa (*Pangasius bocourti*), primarily from Vietnam. Competition by basa has had a significant impact on the US catfish industry. Many stores that sell catfish purchase only those that are identified by their source. Because basa are less expensive than channel catfish, places like nursing homes and retirement complexes apparently have a history of selecting basa over domestic catfish. How broadly the cost factor applies to the selection of basa over domestic channel catfish (or sources of that species in other nations where they are cultured) has not been identified in detail insofar as we have seen; but we can speculate that at least some fast-food restaurants, prisons, schools, etc. may be involved. Certainly, cost is a consideration. In addition, consumers often don't care about country of origin and, in fact, do not discriminate between domestic catfish and basa.

In its natural environment, the male catfish will find a depression in a stream bank or under a fallen tree or he might come upon a hollow log or some other hiding place that will serve as a nesting site. There have been anecdotal reports indicating that catfish had spawned in ponds without any apparent nesting structure, but that seems to be rare. Males do not construct nests but will clean up debris from natural nests and artificial nests provided by culturists.

Early attempts to spawn channel catfish in hatchery ponds failed until the time a hatchery worker in the early part of the 20th century discovered that the males need a nesting place. Nail kegs were among the first artificial nests used to create conditions appropriate for spawning. Milk cans, grease cans and various other containers, including some constructed specifically as catfish nests, have also found wide use (Box 6.8).

Box 6.8.

Nests do not need to be associated with the bottom, either. A study conducted by a graduate student when R.R.S. was his major professor at SIU looked at whether catfish in a rather deep, steep-sided strip-mine lake would come up near the surface to spawn in open water. The spawning nests were submerged several centimetres under the surface of the water. The fish did not seem to mind, because the nests were well utilized.

Channel catfish broodstock can be stocked in open ponds and allowed to select their own mates, or they can be stocked in pens (Fig. 6.12). Usually, two females are stocked for each male in open ponds. Spawning nests are distributed around the sides of the pond in about 1 m of water with their openings facing the middle of the pond (Fig. 6.13). Fouling is usually not an issue in spawning pens because they are in freshwater, but there is better water circulation through pens with large mesh than would be the case if fine mesh is used. The mesh can be of wire – bare or plastic-coated – or some type of plastic material. Nylon netting is another option. The commercial farms that R.R.S. has visited use the open pond spawning method.

Catfish have been spawned in aquaria with induction of spawning through hormone injection, but the method was used by researchers primarily to see if the technique would work. To our knowledge no commercial catfish culturists are currently using the aquarium spawning approach. However, hormone inducement of spawning is required to synchronize the strip spawning of eggs from female channel catfish and sperm from male blue catfish. Then the fertilized eggs are incubated artificially.

After the male catfish cleans out any debris that is in the nest, he will entice a female that is approaching spawning condition into the container. The gelatinous egg mass (Fig. 6.14) produced by the female will contain several thousand eggs, each 2–3 mm in diameter. The eggs are laid in batches that are immediately fertilized as they are released. Each batch adds to the mass, so only one egg mass is produced. Once the process is complete, the male chases the female from the nest as she would disrupt the egg mass or possibly eat the eggs if allowed to remain. To give the males an advantage, they need to be larger than the females that are stocked.

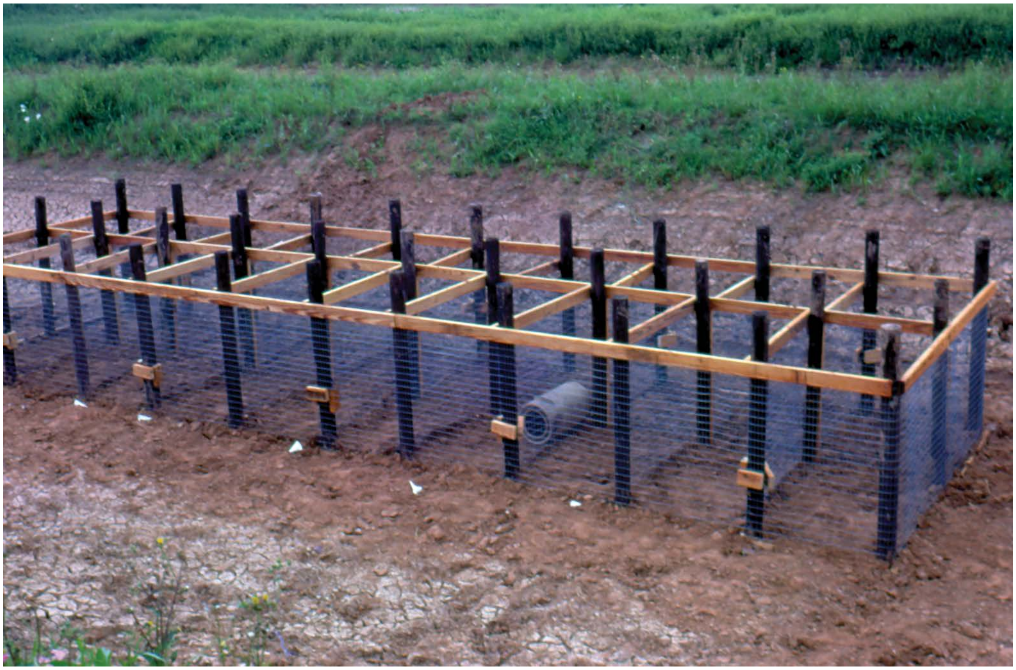

Fig. 6.12. A group of spawning pens, one of which contains a metal can used as a spawning nest.

Fig. 6.13. Spawning cans in a shallow pond (some of which are marked by arrows).

Fig. 6.14. A channel catfish egg mass that was removed from the spawning nest and is headed for the hatchery.

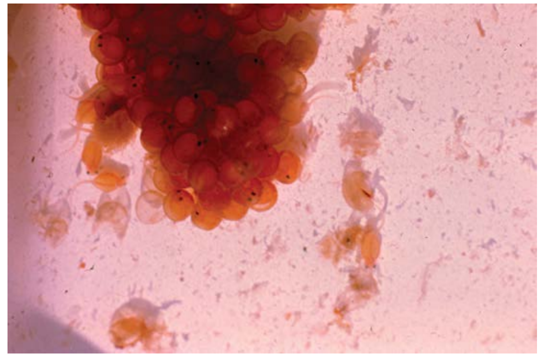

Fig. 6.15. A small portion of an egg mass showing mostly eyed eggs (the black spots in the eggs).

The male catfish will tend the eggs by fanning them with his fins to keep oxygen-rich water moving over and through the mass. He will also remove dead eggs by picking them up in his mouth and depositing them outside the nest. The egg mass is initially yellow in colour but turns increasingly pinkish as the larvae develop. Also their eyes develop prior to hatching (Fig. 6.15).

The eggs will hatch into sac fry about one week after fertilization, depending on water temperature. After hatching they will remain in the nest under male supervision and protection through yolk sac absorption. They will then leave the nest and begin foraging for food.

If open pond spawning and free choice mating is used, the fry may be left in the broodfish pond until they reach fingerling size, after which they can be caught and redistributed to other ponds at reduced densities for further rearing prior to being stocked in growout ponds. An alternative could be to leave the fry or early fingerling fish in the spawning pond after the spawning season, seine out the broodfish and move them to a holding pond. In that case, the seine mesh should be large enough to allow the young fish to pass through. It would still be necessary to capture the fingerlings before their biomass exceeds the carrying capacity of the pond. The fingerling pond – whether it is the same as the spawning pond or not – is fertilized prior to the onset of spawning so the fry will have abundant food in the form of plankton as described in Chapter 4.

The problem with leaving the newly produced fish in the spawning pond and moving the adults to another pond is that the culturist will have no idea how many fingerlings were produced until they are captured for redistribution. This is one reason why, whether the pen or open pond spawning technique is used, it is common practice to collect egg masses and take them into a hatchery.

If a hatchery is available, the spawning receptacles should be checked for eggs at intervals of 3–4 days. It is not necessary to check the cans daily because at least 5 days need to pass between the time the eggs are laid and when they hatch. If the broodfish are in the act of spawning when the culturist examines the spawning receptacles, that activity may be disrupted and a complete spawn may not be obtained, so it is not a good idea to check the nests too often, as that increases the chances of interrupting spawning activity. When an egg mass is found it is collected and moved into the hatchery.

To check a spawning receptacle, it is common practice to slowly lift it to the surface, pour out some of the water and visually inspect it for the presence of an egg mass. Some receptacles, however, have been designed with removable tops. If such receptacles are placed in shallow water that is not too turbid, visual inspection is simplified. The lid can be removed and the eggs collected without having to move the receptacle. If the male does not leave the nest when the culturist is making a visual inspection and the culturist sticks a hand in the nest, a bite may result. While catfish have very small teeth, the natural tendency when bitten is to pull your hand back, which can result in some nasty scrapes. If the nest cannot be visually inspected from the top, it is best to lift it to the water surface and pour the male – and perhaps a mating pair – out of the receptacle before looking inside or placing your hand inside to check for eggs. If the inspection is from the top of the spawning receptacle, the male can be coaxed out from above without having to lift it. If a pair of adults is observed in a spawning receptacle but there is no egg mass, or it appears that spawning activity has not been completed, the receptacle should be gently placed back in position. Again, observing from the top is better as the culturist may be able to do that and not disturb a pair of fish that are about to spawn or are in the act of spawning.

Because the eggs will stick to the receptacle floor and some eggs can be damaged or destroyed when being scraped out, many culturists place a piece of roofing material (tar paper) in the nest to make egg collection easier. Each discovered egg mass is collected by merely removing the roofing material to which the eggs adhere. Another piece of roofing material can then be placed in the nest which can be available to another batch of eggs. Each collected egg mass should be placed in a tub or pail of water for transport to the hatchery. Males may spawn with two or more females during a season, but when pen spawning is used it might be wise to replace males after they have spawned twice and to replace females after they spawn as they only ovulate once a year. When open pond spawning is used, it will not be possible to tell which males have spawned and catching either males or females would require removing the spawning cans and seining the pond, which does not make much sense. When pens are used the adults can be netted quite easily after they have spawned, so replacing them is relatively simple.

The traditional way that channel catfish eggs are incubated is in hatching troughs, which most commonly are small raceways modified for the purpose of providing the proper conditions for egg development. Large egg masses may be broken up into two or more pieces to provide better exposure of all the eggs to oxygenated water. Whether to break a mass up depends on its size – large females can obviously produce more eggs than small ones. The average egg mass will have around 10,000 eggs in it. The egg mass or pieces thereof are commonly placed in hardware cloth baskets that are suspended in the hatching trough (Fig. 6.16). Paddles attached to an axle running down the middle of each hatching trough are slowly turned – at approximately 30 rpm – using an electric motor fitted with a reduction gear. The purpose of the paddles is to move the water through the egg masses, an action that mimics the fin-fanning action that male catfish use during incubation

Fig. 6.16. A channel catfish hatchery with hatching troughs containing hardware cloth baskets full of incubating eggs.

under natural conditions (the male holds his position just above the eggs and moves water through the mass with currents caused by the fin motion). A slow rate of water exchange is used under hatchery conditions and the hatching troughs are aerated. An alternative is to do away with the paddles and just increase the flow of well-aerated water through the trough while still supplying additional aeration at intervals along the trough with air stones.

When the eggs hatch, the sac fry will pass through the openings in the bottom of the hardware cloth basket and fall to the floor of the hatching trough where they can be allowed to remain during yolk sac absorption. At the swim-up fry stage (Fig. 6.5), the fry can be moved to fertilized ponds, raceways or tanks until they reach fingerling stocking size in ponds. Keeping them in culture systems other than ponds after removal from hatching troughs will reduce the chances of mortality, particularly from predation. Catching fingerlings from a raceway to move them to growout ponds when they are several weeks to a few months old is also simpler than seining them from a fry pond for stocking in ponds. Feeding with a finely ground high-protein prepared feed should be initiated as soon as the fry swim to the surface of the hatching trough or other early-rearing container if they have already been removed from the hatching trough. Not too surprisingly, when they swim to the water surface, they are called swim-up fry (Fig. 6.5). Fry should be fed every few hours and waste feed should be siphoned from the troughs periodically, at least daily if the density is high and waste products are visible. Automatic feeders come in handy for the fry stage (see Chapter 8).

When egg hatching occurs in a brood pond, high-protein fry feed is broadcast around the edges of the pond a few times daily after the young fish are observed swimming at or near the water surface. They tend to congregate in schools near the bank so they can usually be observed without much difficulty when they reach the swim-up stage.

In all situations, the first feed offered is finely ground so the fry can easily swallow the particles. Alternatively, some feed mills that produce catfish feed have a variety of feed sizes, from finely ground to pellets. As the fry grow, larger particles (crumbles) are fed, and once the fish are large enough to consume them, pellets can be offered. Advancements in extrusion processing now allow the production of floating pellets with a diameter of 2 mm and even less. Thus, transitioning fingerlings to floating feeds can be achieved rather early in the production cycle. One of the greatest benefits of using floating pellets is being able to accurately monitor feed intake. The formulation of the feed may change with the change in particle size. For example, the protein level is often gradually reduced over time until the fingerlings are fed a more standard grow-out ration. Much more detailed information on nutrition and feeding of catfish can be found in Chapters 7 and 8.

Red drum

Culturists may only spawn red drum (*S. ocellatus*) during the normal spawning season, though, as outlined above, red drum can be conditioned to spawn by exposing them to temperatures and photoperiods associated with the various seasons of the year until the fish are cycled into autumn spawning season conditions. Shifting their spawning activity to spring and summer is often practised because environmental conditions during those seasons are more suited for fingerling production in fertilized earthen ponds.

The successful reproduction of red drum broodstock in hatcheries operated by the TPWD in the USA is a good example of year-round production by government hatcheries. Many private hatcheries, and hatcheries in other states, typically use the TPWD approach to broodstock management and spawning. The broodstock are often maintained indoors in rooms without windows. The solid tops on the spawning tanks keep activity by humans from startling the fish and also prevent room lights from affecting the photoperiod in the tanks, which may differ from one to another depending upon which season of the year is being simulated in each. Each tank is fitted with its own light to control photoperiod. The water supplies to the tanks are independently temperature-controlled, so that different tanks can be in different phases of the conditioning cycle.

Each brood tank is stocked with a small number of fish. Two males and three to four females in a 2–3 m diameter tank is typical. Each tank is equipped with an egg collection box attached to the outside (Fig. 6.17). When the fish spawn, the fertilized eggs, which float on the water surface, are flushed from the tank with the effluent and captured in a fine-mesh bag in the egg collection box. The collection boxes are inspected each morning and when eggs are found they are moved to hatchery tanks in which they will hatch within 2–3 days following fertilization.

Prior to the time the first spawns are anticipated, the culturist prepares fingerling ponds by fertilizing them in a manner that encourages development of a zooplankton bloom. This often involves the use of cottonseed meal or another organic fertilizer in combination with an inorganic fertilizer. Soon after the red drum eggs hatch, the larvae are stocked in the fertilized ponds, though they can be reared in the hatchery for an extended period if provided with live feed (see the section 'Providing Live Food' below) and then weaned to prepared feeds. By stocking them as larvae, the culturist can avoid having to maintain live food cultures. The direct stocking of very small marine fish larvae into ponds is unusual and rather unique to red drum culture, as you will see in later examples on species where a protracted period in the hatchery is standard practice.

Red drum culturists have found that stocking larvae in ponds will typically yield at least 25%

Fig. 6.17. Red drum spawning tanks in a temperature-controlled hatchery room to condition adults to spawn out of season by manipulation of light and temperature (arrow identifies the location of the egg collection box).

survival, which is quite high for any marine/estuarine species with very small eggs and larvae (a good survival rate for highly fecund marine fishes from egg to fingerling would be in the range 5–10%). Much higher yields are sometimes seen in red drum fry ponds, as are smaller yields in some cases; and, interestingly, there may be one pond on a facility that consistently outperforms the others. To date, no explanation for that phenomenon has been identified in terms of differences in water quality, nature of the plankton bloom or various other factors that have been examined. It is worth noting that some individual culturists on a facility may produce higher yields than others if each person is assigned a particular pond or group of ponds to manage (Box 6.9). The difference in production in red drum ponds does not seem to be attributable to the skills of one culturist over another because all the ponds are usually managed in the same way and by the same people; duties related to feeding and managing specific ponds are not typically assigned to individuals but are shared responsibilities.

When red drum are produced for enhancement purposes, the fingerlings are harvested from ponds after about 1 month when the fish have exhausted or nearly exhausted the natural food supply (some prepared feed may also be provided prior to the time of harvest). At harvest the fingerlings should be about 3 cm in length. When used in conjunction with enhancement programmes, they are stocked in nature to supplement wild populations. In the USA, TPWD produces and stocks millions of juvenile red

Box 6.9.

R.R.S. once visited a large goldfish farm where each culturist was responsible for his/her own group of ponds. One of those individuals consistently produced higher yields per pond than any of the others. That is best explained using the 'green thumb' analogy wherein some gardeners are better than others even when all the gardeners being compared employ what appear to be the exact same methods.

drum annually (in the past, the numbers stocked have been as high as 40 million in a year) to augment the recreational fishery; the commercial fishery for red drum in the state was closed in the 1970s. TPWD has initiated studies to determine the efficacy of the stocking programme and its impacts, if any, on other species; it has also looked at the question of whether greater success in recruitment can be achieved by stocking larger red drum fingerlings. TPWD has also initiated stocking programmes with other finfish species that are targeted by nearshore recreational fishermen, including spotted sea trout (*C. nebulosus*) and southern flounder (*P. lethostigma*).

Commercial red drum farmers may keep the young fish in the hatchery until they are well established on prepared feed before stocking them into ponds, or they can use the method previously described and put the newly hatched fry into fertilized ponds. The fish may initially be stocked at high density because their total biomass is low, and they can be captured and graded into groups of similar size and restocked at lower density into several ponds for further growout. The process may be repeated periodically until the fish reach market size; or, as is done with various other species, fish captured from fingerling ponds may be graded and placed into new ponds at the appropriate density for the entire growout period. The latter method involves less handling and accompanying stress, plus it avoids a significant amount of labour and associated costs.

Striped bass and hybrid striped bass

Preparation of striped bass for spawning has been addressed earlier in this chapter. Most commercial culturists produce hybrids between striped bass (*M. saxatilis*) and white bass (*M. chrysops*) as those fish perform better than striped bass under culture conditions. Both types of crosses are made; that is, the male can be from one species and the female from the other. Which cross is used seems to be based on the preference of the culturist as neither appears to have a distinct advantage. However, handling of reproductively mature female stiped bass is more difficult compared with white bass and thus many of the producers of hybrid striped bass for commercial purposes use the reciprocal cross. The eggs of white bass are considerably smaller than those of striped bass but stocking the larvae in fertilized ponds similar to that described for red drum typically provides adequate quantities of zooplankton of suitable size.

Fertilized eggs are often incubated in hatching jars. The larvae can be maintained in tanks in the hatchery and provided live zooplankton after yolk sac absorption. A critical period in the life cycle of striped and hybrid striped bass is the time when the swim bladder is supposed to inflate. Improper inflation leads to heavy mortality in the fry (this has also been a problem with other species, such as European sea bass, *Dicentrarchus labrax*). After swim bladder inflation and establishment of the young fish on prepared feeds has been achieved, they can be stocked into rearing ponds for initial growout with intermittent grading and redistribution to additional ponds for the remaining growout period.

Halibut

Adult Atlantic halibut (*H. hippoglossus*) and Pacific halibut (*H. stenolepis*) are extremely strong animals that have been known to virtually destroy small boats when landed by anglers (Box 6.10). Adult females have been known to reach in excess of 200 kg. Yet, as has been described, the eggs and larvae of halibut are extremely fragile and the period from egg laying to metamorphosis is protracted. We have the opinion that if two halibut larvae even look at one another, both are doomed. It is not quite that dire in reality but getting the young fish through the larval period is not simple. However, techniques have been developed to get halibut through the critical egg and larval development stages, and there is progress in commercial halibut culture in Norway and in eastern Canada. There is also research being conducted aimed at developing commercial culture in Maine, USA. All of that is associated with Atlantic halibut. To date only a limited amount of research has been conducted on Pacific halibut, though results obtained thus far have shown that the two species are virtually identical with respect to culture requirements. Most of the emphasis on halibut culture to date has been focused on enhancement stocking, though, as indicated, a commercial industry is being developed.

Both male and female halibut can be stripped of their gametes. Temperature and photoperiod control can be employed in the laboratory to help promote the development of the adults with respect to bringing them into spawning condition. In Norway, females exceeding 100 kg have been used as broodstock. Female halibut of both species reach much larger sizes than males. In research R.R.S. and his students were involved with in attempts to spawn and rear the larvae of Pacific halibut several years ago, using much smaller adults than those

Box 6.10.

R.R.S. once heard about one not-so-clever recreational fisherman who, becoming concerned that a large halibut he had brought aboard might flop around and damage his boat, took out a pistol and shot the fish. What he failed to consider was the problem that arose because of the hole that appeared in the bottom of his hull when the bullet passed through the fish. Presumably, he headed towards shore before his vessel sank.

used by Norwegian researchers – ours usually weighed no more than 15 kg. We found that all the Pacific halibut we worked with that were more than 1 m in length were females. Because we could not tell the sex of the animals until they developed (at which time the abdominal region of the females would become distended with ova), we retained several fish smaller than 1 m in length on the assumption that at least a few of them were adult males, which turned out to be the case. Today we could use ultrasound to make the distinction between the sexes.

Spawning in nature occurs in the winter and it is during that season the culturists conduct their spawning activities. Maintaining developing eggs under low light levels in static water and providing a salinity gradient in the hatchery tanks so that the eggs can be suspended at the salinity of neutral buoyancy are important during the egg hatching and early larval stages. However, under those conditions bacteria tend to build up in the hatchery tanks so antibiotics have often been put in the water. Other techniques, including keeping the tanks clean, have been developed to keep bacteria under control as their presence can lead to heavy mortalities.

After the approximately 2-month period from egg fertilization until full yolk absorption, the larvae must be provided with food of the proper kind, and it must be of very small size. First-feeding halibut, like many other marine fishes with tiny larvae, require zooplankton that are considerably smaller than the fish themselves. Rotifers are commonly used as a first live food for first-feeding marine fishes, including halibut. The relative sizes between a larval halibut and the rotifers being fed to it can be seen in Fig. 6.18. Once the halibut larvae grow sufficiently, they can be converted to other types of zooplankton, such as copepods, brine shrimp nauplii (*Artemia* spp.) or wild zooplankton that is sieved to the proper size. Weaning to prepared feed is also possible (Box 6.11) and needs to be accomplished as soon as possible so that the culturist will not have to spend so much time producing live food or capturing and filtering wild zooplankton.

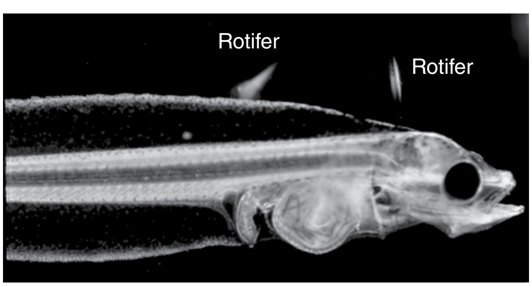

Fig. 6.18. A larval Atlantic halibut and two rotifers (blurry because they are in motion) provided as live food. (Photograph courtesy of Michael B. Rust.)

Flounders and other flatfish

Flounders (e.g. *Paralichthys* spp.), turbot (*S. maximus*) and sole (e.g. *Solea solea* and *Solea senegalensis*), in addition to halibut, represent some of the various flatfish species that are being produced in aquaculture. All flatfish species develop into larvae with one eye on each side of the head and swim with their ventral side down and dorsal side up just as do fish in other orders of finfish (there are several families of flatfishes). During metamorphosis, one eye migrates to the other side of the head and the fish ends up swimming on its side. Depending on which family the fish belongs to, it may swim on its right or left side. Flounders in the family Bothidae (which includes *Paralichthys* spp.), for example, are called right-handed flounders as they swim with the right side down.

In flatfish, the internal organs are located just behind the head. Since the percentage of the body taken up by internal organs is relatively small, the dress-out percentage of flatfish is high compared

Box 6.11.

Weaning is only initiated after the culture animals have grown sufficiently large to take finely ground prepared feed particles. That is typically coincident with when they are being fed brine shrimp nauplii or other zooplankters of similar size. The prepared feed is first added in the presence of the same density of live food that the animals had been receiving. Each day the concentration of live food is reduced as the amount of prepared feed is increased until the live food items are no longer required. This sounds simple but some species are very picky, and it is difficult to get them weaned. Often, if one or a few fish start to feed actively on prepared feed, others will soon follow suit. For some species, larger live foods may be suitable for feeding prior to the introduction of prepared feeds. Examples of such food items include mysid shrimp, gammarid amphipods and nematodes.

with many other types of finfish. When the ovaries develop as adult females approach spawning condition, they extend well back into what essentially becomes an enlarged body cavity (Fig. 6.19).

A major difference between halibut and other flatfish species of interest to aquaculturists is that the eggs and larvae of the latter tend to be very hardy. The difference can be explained by the fact that most flatfish species spawn in relatively shallow nearshore waters where the eggs and larvae are exposed to harsh environmental conditions. Halibut, on the other hand, spawn far out at sea. Their eggs develop at depth where conditions tend to be very stable and calm. The eggs and larvae of halibut do not get tossed around like those of their nearshore cousins.

Taking southern and summer flounders (*Paralichthys dentatus* and *P. lethostigma*) as examples, the two species spawn in nearshore waters where their eggs hatch. As the larvae develop, they move into the estuaries and metamorphose into post-larvae (Fig. 6.20) at about 10 mm long within a few weeks after they were spawned, not several months as in the case with halibut. Once the flounders begin exogenous feeding they will ride the tide upstream near the surface at night, then swim to the bottom and drift downstream with the ebb tide while feeding along the way. As they continue to grow, they adapt to lower and lower salinities and can eventually tolerate freshwater. Halibut, in contrast, are stenohaline and need to be maintained at seawater salinity. Flounders can replicate the pattern of the substrate on which they associate. That ability is exemplified by Fig. 6.21. See if you can find the flounder on the sand in the photo.

Using the same species of flounders as our examples in the previous paragraph, let us look at captive

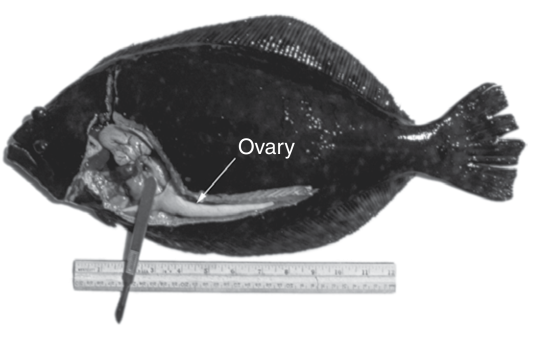

Fig. 6.19. A female *Paralichthys* spp. showing the organs in the abdominal cavity and the developing ovary.

spawning and larval rearing. The process shares aspects from what we have seen with respect to red drum, striped bass and halibut. Summer and southern flounders can be induced to spawn through hormone injections or, most commonly, implants of gonadotropin-releasing hormone analogue (GnRHa). They can also be allowed to develop and

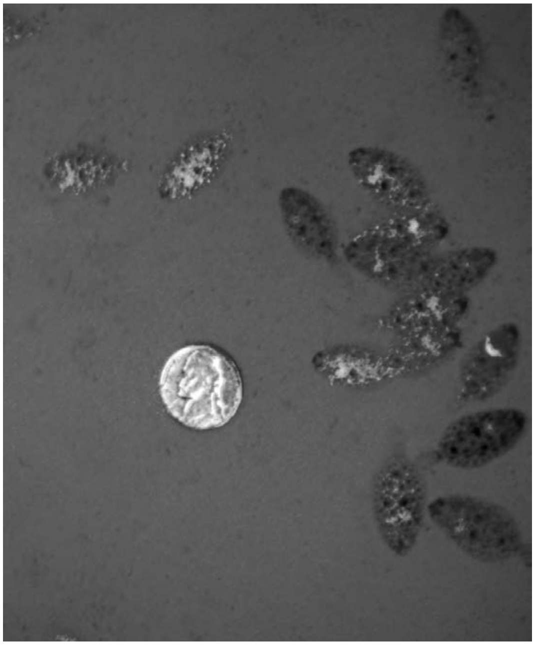

Fig. 6.20. Post-larval flounders, *Paralichthys* spp. These fish were not produced in a hatchery but were collected from a tidal river with a plankton net during the night just below the water surface. The young fish are shown with a US nickel for size comparison.

Fig. 6.21. A young flounder blending in with the sand substrate.

spawn without hormone inducement, which is the method often used in tank spawning. Initial development is induced by the proper temperature and photoperiod regime (which varies to some extent between the two species). As is true of halibut, these two flounder species are cold-season spawners (the normal season begins in autumn or winter depending on species and location), so the culturist can either spawn them during their normal spawning season or manipulate the environment during other parts of the year to induce gonadal development and spawning. Another difference between these flounders and halibut is that the summer and southern flounders are eurythermal while halibut are stenothermal. The fish can be allowed to spawn in tanks volitionally or they can be stripped once they are ripe.

Looking more specifically at southern flounder (though summer flounder should be similar), the eggs, which are about 1 mm in diameter, float in the water and can be allowed to incubate in tanks or aquaria. Hatching in less than 3 days (55 h) has been reported when the incubation temperature is 17°C. At about 5 days post-hatch (dph) the larvae will feed on rotifers. Brine shrimp nauplii will be accepted 15–20 dph. Metamorphosis begins 30 dph at 17°C and is complete at 50 dph. The post-larvae can then be weaned to prepared feed. Once weaned, the fish, which will have reached about 2.5 cm, can be stocked into nursery tanks. They could be stocked in ponds at that size or be reared in nursery tanks to some larger size that the culturist selects. Problems that have been seen with southern flounder include low milt production, low egg fertilization rates, cannibalism among post-larvae, differential growth rates and high levels of ambicoloration.

Other finfish species

The examples presented in this section only scratch the surface of the amount of information that is available on the reproduction of finfishes of aquaculture interest (refer to Table 1.1 to get an idea as to how we have looked at only a small percentage of the finfish species listed). However, except for fairly minor details, the basics about finfish spawning and larval techniques are captured through the examples presented. In addition to the list of books at the end of this and other chapters, you can always search the Internet for copies of scientific papers on your species of interest. Other articles provide recommended hormones and dosages to induce ovulation in the various species. By doing Internet searches, you should be able to find quite a bit of information on any species you might be interested in, including invertebrates, examples of which we turn to now. We caution that searches of the Internet should be focused primarily on articles in scientific journals. Any item that indicates a major breakthrough in association of some aspect of the culture of an aquaculture species should be considered suspect if it has not been published in a reputable journal.

Marine shrimp

The practice of ablating one or both eyestalks of adult female marine shrimp to induce spawning was described in Chapter 4. Another, similar technique is known as enucleation wherein an incision is made in the eye and the fluid is evacuated. That technique will produce the same result as ablation. The hormones involved with reproduction in marine shrimp are located at the base of the eyestalk. That would certainly lead one to surmise that hormone production in marine shrimp is somehow associated with light, which is undoubtedly the case. What ablation or enucleation does is stop the production of a hormone that inhibits maturation of the female gonad. Once the eyestalk is removed (or the shrimp is blinded or partially blinded through enucleation), production of that hormone stops or is greatly reduced allowing gonadal maturation to occur. There is no similar problem associated with sperm production in male marine shrimp, so they do not have to undergo ablation or enucleation.

While the results of research have been somewhat mixed, photoperiod appears to have minimal influence on maturation in marine shrimp. Research seems to show that temperature and light intensity are more important factors than photoperiod.

The female marine shrimp may carry the spermatophore received from the male after which the sperm are ultimately released to fertilize the eggs, which are then broadcast into the water. A single female may produce 1 million or more eggs. In shrimp hatcheries, eggs are hatched under the conditions previously described for marine fish eggs; that is, tanks (usually with conical bottoms) that feature a very slow water exchange rate are used. The larvae moult through several stages before developing into post-larvae. Live foods, usually starting with diatoms and transitioning through brine shrimp nauplii, are offered during the larval development period. The green water technique is often used in shrimp hatcheries; this involves having phytoplanktonic algae in the water along with the shrimp larvae and their zooplanktonic food. Penaeid shrimp begin feeding at the second zoeal stage of development. After additional zoeal stages, they go through several mysis stages before becoming post-larvae. Weaning to prepared feed is as described above for finfish and further described in Chapter 8. At some stage in larval development, or after the shrimp reach the post-larval stage where they look like the adults, the shrimp can be moved to nursery tanks or raceways for growth to stocking size. They are then stocked in ponds operated by the hatchery or sold to other shrimp farmers for stocking. Growout to market size after stocking usually takes about 3 months. In tropical regions, shrimp farmers can obtain as many as three crops annually. A fourth crop is theoretically possible (12 months divided by 3 months/crop = four crops). However, there is some downtime between harvesting ponds and restocking them. They may be left dry for a period and could also require levee maintenance. There is also the need to refill the ponds and establish plankton blooms. So, three crops a year is pretty much the maximum.

Freshwater shrimp

An excellent source of information on the culture of freshwater shrimp is the book by New and Wagner cited in the 'Additional Reading' section at the end of this chapter. The earlier book on the culture of freshwater shrimp by Hanson and Goodwin is another good source of information. The major freshwater-shrimp-producing countries are in Asia, and include Bangladesh, India, Myanmar, China, Taiwan, Thailand and Vietnam. Several US states have some production, some of it seasonal for summer festivals where fresh marine shrimp may not be available. While there are many species in the world, freshwater shrimp culture is dominated by the rearing of the Malaysian giant freshwater shrimp, *M. rosenbergii* (Fig. 6.22). In North America *M. rosenbergii* is almost exclusively the species of choice. It is also the primary species produced in Mexico, though *Macrobrachium americanum* and *Macrobrachium tenellum* are of interest.

In nature, tropical freshwater shrimp such as *M. rosenbergii* can spawn year-round. That will also occur in culture systems established in temperate environments if the proper temperature range is maintained. Recall that females move into brackish water to spawn (the soy sauce story). As a result, laboratory culture methods incorporate low-salinity water as a part of the larval-rearing process. The eggs should be hatched in or moved to brackish water before hatching. A salinity of 12 ppt seems to be optimum for hatching and early rearing. There is a series of 11 moults before the larvae metamorphose into post-larvae. The process from hatching to the post-larvae stage takes from 35 to 40 days at 29°C. When they reach the post-larvae stage, the shrimp can be moved to freshwater. As is true of marine shrimp, freshwater shrimp, which begin feeding 1–2 days after hatching, can be provided a ration of brine shrimp nauplii or some other appropriate-size zooplanktonic species. The animals can later be weaned to prepared feeds. As juveniles they are stocked in ponds. Freshwater shrimp are a good companion species in polyculture with such finfish as tilapia, like *Oreochromis aureus* (blue tilapia), examples of which are shown in Fig. 6.23. Growout

Fig. 6.22. Malaysian giant freshwater shrimp, *Macrobrachium rosenbergii*.

Fig. 6.23. Blue tilapia, *Oreochromis aureus*.

of freshwater shrimp in ponds requires about the same amount of time as marine shrimp. However, they are often grown for longer than 3 months to produce larger-sized animals. Freshwater shrimp can approach 450 g in weight but are normally sold at about 20% of that weight. Worldwide production of freshwater shrimp continues to be significant.

Crayfish

The culture of crayfish is basically focused on pond management. In the southern USA, crayfish are called crawfish (Box 6.12). There is no captive breeding of the shrimp-like crustaceans. The crayfish of interest in the USA are the red swamp (*Procambarus clarkii*) and the white river species (*Procambarus acutus*). The highest levels of production occur primarily in Louisiana, and to much lesser extents in Texas and South Carolina. Crayfish culture has expanded in South-East Asia in recent years to the degree that processed tails are no longer being produced in Louisiana, though there continues to be a good market for live crayfish in that state and others. For example, in the spring in the USA at the height of crayfish harvesting, tons of crayfish – primarily from Louisiana – are sold live for crawfish boils, which are very popular, particularly in Texas (Box 6.13).

Imports now dominate the processed and frozen crayfish segment of the market in the USA. The primary crayfish of culture interest in Europe is the noble crayfish, *Astacus astacus*, though *P. acutus* is now present in Europe and is considered an undesirable invader by some authorities. The most important crayfish culture species in Australia are the marron (*Cherax tenuimanus*) and yabby (*Cherax destructor*).

In the USA, broodstock are placed in shallow ponds (often those are modified or standard rice ponds) during the spring. A few weeks after stocking, the ponds are drained. That causes the adults to burrow into the sediments where reproduction takes place. The mating process involves the male depositing sperm into a receptacle organ on the female. The sperm remains there until September when the eggs are fertilized and extruded from the female to become attached to her swimmerets. The eggs will hatch within 2–4 weeks after fertilization.

During the summer, while the crayfish are in their burrows, the culturist will typically plant forage in the pond which is predominantly rice. However, other plants such as smartweed, water primrose and alligator weed can serve as plant forage. During the early autumn (October–November),

Box 6.12.

The term crawfish is used primarily in the southern USA in preference to crayfish, which is the term used in most of the USA and in other countries.

Box 6.13.

A group of long-time friends of R.R.S.'s son has hosted a large crawfish boil for several years, though R.R.S. has heard that the 2021 boil may be the last one as several of the friends have dispersed. In any event, the boil typically involved 500 or more pounds (227 kg). Much of the crowd arrived early so they could get their fill while crawfish were still available. The crustaceans were boiled in water with seasonings, potatoes and often other vegetables. The ingredients vary by location and the people responsible for preparing the delicacy. In the case of the crawfish boils that R.R.S. attended locally, a table is set up and the piping hot crawfish and other ingredients are dumped out. The edible portion of a crawfish is the tail, which is twisted off and cracked open using the consumers' fingers. The edible portion is small, so many hungry folks stand around the table consuming dozens of the crawfish (also called mud bugs in some places). Holes in the table, which have buckets under them, collect the heads and tails from which the meat has been removed.

Attendees bring side dishes and desserts. Hamburgers and hotdogs are plentiful along with the fixings. Soft drinks and beer are plentiful as well, and a live western band entertains. Usually there are 100 or so attendees of all ages. There are inflatable slides, etc. for the children, horseshoes and cornhole competitions (the latter involves boxes with holes in them that are the target of beanbags thrown from several metres away). One year, the hosts put a sign for the crawfish boil along the road where attendees left the main road to turn on to the gravel road to the parking area and apparently everyone who saw the sign was lured in, as the crowd that year was estimated at several hundred. The hosts had no idea who most of them were.

the ponds are flooded. That activity coincides with the time of crayfish egg hatching. The crayfish are harvested from November to May or June (Fig. 6.24) using baited traps (Figs 6.25 to 6.28). The most common way to harvest is from a flat-bottomed boat – necessary because of the shallow water in the ponds. As the boat reaches a trap, the harvester picks it up, drops in a replacement trap and empties the one that was picked up into a holding tank or tub while proceeding towards the next trap. Traps are usually checked daily. Bait for the traps include so-called trash fish such as shad or small menhaden, though artificial baits have been developed and are used preferentially during warmer temperatures.

Fig. 6.24. Adult crayfish.

Harvested crayfish (Fig. 6.29) are held in holding cages until being packaged live in onion sacks and sold to restaurants, grocery stores and other outlets, including directly to the public. Crayfish are relatively inexpensive when sold live, or already cooked whole. That is because their dress-out percentage in tail meat is only about 15% of body weight. The most expensive operating cost for the crayfish farmer is bait and labour costs associated with harvesting. Broodstock are harvested crayfish that are retained and restocked at the end of the harvest season.

A great deal of research has been conducted over several decades at Louisiana State University on crayfish culture that has been instrumental in the growth of the crayfish culture industry. The book by Johnson and Johnson (2008) in the 'Additional Reading' section at the end of this chapter is recommended for those who want to learn about many more details of crayfish culture.

Fig. 6.25. A typical crayfish pond with traps located several metres apart.

Fig. 6.26. A simple crayfish trap, one of the many designs that have been developed.

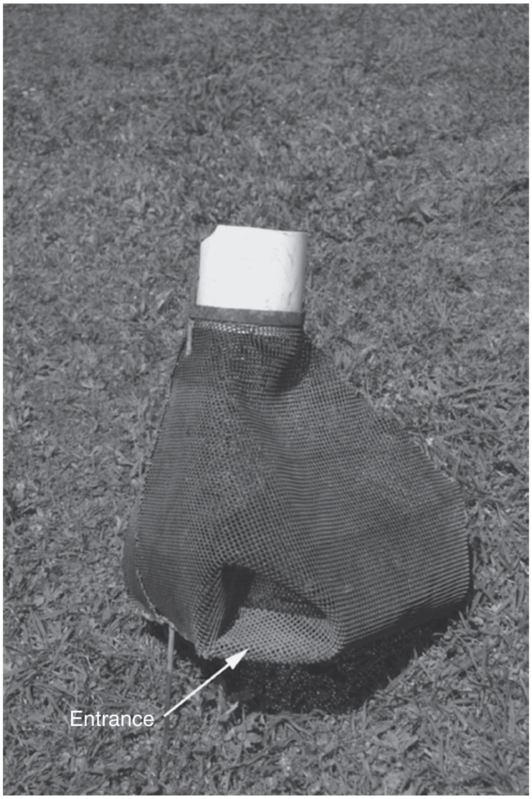

Fig. 6.27. Another crayfish trap, The PVC pipe portion at the top is used to insert the bait and pour out the captured crayfish. The arrow points to the point of entry into the trap.

Oysters

Techniques associated with spawning oysters have been briefly described and will not be repeated here. Since there are species of oysters that spawn in warmwater, coldwater or coolwater, the proper temperature for the species of interest for culture is critical. For the American oyster, *Crassostrea virginica* (Fig. 6.30), which is a warmwater spawner (but is found in nature over a broad temperature range), the eggs will hatch into a larval form called a veliger within about 48 h after fertilization when the temperature is at, or very close to, 30°C. Veliger larvae are planktonic so at that stage the species can be distributed by currents whereby they can potentially colonize new areas. The veliger stage lasts from 10 days to 2 weeks, after which the oysters metamorphose into spat that seek out suitable surfaces on which to attach. Spat have the ability to 'test' sites for suitability but eventually will not be able to return to the water column and must attach to a hard substrate or they will not survive. The source of American oysters is primarily from natural beds or bottoms where substrate (such as oyster shell) is planted to provide areas for spat settlement. In contrast, the Pacific oyster (*Crassostrea gigas*) spawns in water temperatures of 20–22°C. The veliger stage lasts from 14 to 18 days.

In the hatchery, before and during larval development, large amounts of single-cell algae are produced to feed the larval oysters to the spat stage. Recall that the process involves maintaining pure cultures in an incubator to get batch cultures started in carboys, plastic bags, etc., and finally, when the bloom is established, the relatively small batch cultures are used to inoculate large tanks (Fig. 6.31). Once logarithmic growth of the algal bloom slows greatly or ceases, the algae must be used immediately as food or preserved for later use. It is possible to centrifuge the water to separate it from the algae which can

Fig. 6.28. Emptying crayfish from a pillow trap.

Fig. 6.29. A group of live crayfish in a holding cage following harvest.

then be freeze-dried or frozen as paste. A several-thousand-litre tank, such as those shown in Fig. 6.31, can be concentrated to about 1 litre for freezing.

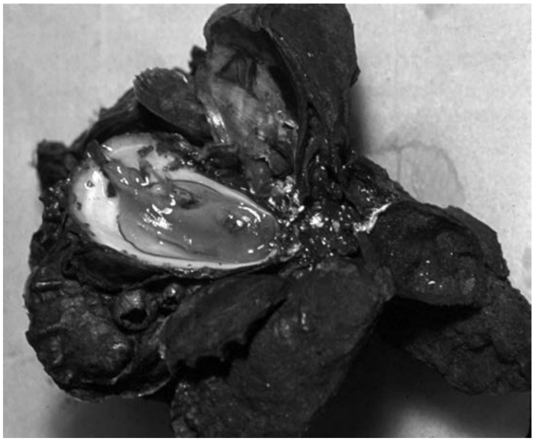

Fig. 6.30. A clump of oysters, in this case American oysters, *Crassostrea virginica*, with one opened to expose the animal.

A cream separator makes a good alternative to a centrifuge for concentrating algae.

Larval development of oysters may occur in either indoor or outdoor tanks, and algae are added daily as food. Once the spat stage is reached, cultch is added, often in the form of oyster shell as shown in Fig. 6.32. The cultch is taken to the grow-out areas after it becomes colonized by the spat. Once the oysters are transferred to their growout locations, no matter whether those are associated with bottom, rafts, baskets, trays or some other culture approach, cultured algae are no longer used; it is important to stock the oysters at the proper density so that they do not deplete the natural phytoplankton population and other food items that they require for rapid growth.

When the approach is to produce cultchless oysters, the spat are allowed to settle on and attach to sheets of plastic or metal from which the oysters are removed once they are several millimetres in diameter. That process is best conducted entirely in the hatchery where food is provided until the cultchless oysters are placed on trays in the grow-out area. In its simplest form, as has been discussed previously, oyster farmers can just let nature do the job of producing spat (Box 6.14).

Clams

There are a number of clams that are of interest to aquaculturists (Table 1.1). Many nations around the globe engage in clam culture, with China being the clear leader in terms of production. For this discussion we have elected to focus on the Manila clam, *Ruditapes philippinarum*. The Manila clam – native to Korea, the Philippines and Japan – is one of the most widely cultured clam species in China and other parts of Asia, and culture of the species also occurs in Europe where it is an introduced species. In Europe, the primary producing countries are France, Spain, Italy, Ireland and England.

In China most of the spat come from nature, where they are collected from beach areas. Shallow ponds are often created in areas of spatfall. Competitors and predators are controlled, and algae may be added to provide food for the larvae and small clams until they reach stocking size.

Fig. 6.31. Relatively small batch cultures are used to initiate the large tank cultures of algae that are shown. Note the overhead lights that are required to stimulate photosynthesis. Aeration keeps the algae in motion.

Fig. 6.32. Outdoor tank cultch is added so that the oyster spat can set.

Box 6.14.

While hatcheries provide a means of controlling the reproduction and larval setting processes, oysters are perfectly capable of taking care of business on their own. An oyster farmer may take advantage of natural spatfall by placing cultch in areas where oyster spat are known to settle. Once the cultch is populated, it can be moved to a growout area where spatfall does not occur or is insufficient. Another option is to leave the cultch in place and allow the oysters to grow to harvest size.

Such ponds are said to be capable of producing 75–150 million clams/ha. In Europe, both natural and hatchery spat are produced to meet the demand. Hatcheries are used in northern European areas because the Manila clam will not reproduce successfully in those waters. The spawning process used in hatcheries varies, but one example is that adult clams can be exposed to 20°C for a few weeks to condition them. The temperature is then raised to 28–30°C after which spawning is induced through cold shocking or by adding sperm obtained through stripping or from a sacrificed male. Once the eggs are fertilized, they are collected with a sieve of the appropriate mesh size and placed in containers for 2 days until the veliger stage is reached. The larvae are sieved again and stocked in containers at a few thousand per litre. They are fed one or more species of cultured algae every other day for 2 weeks until metamorphosis occurs. According to the FAO, optimum salinity for breeding and rearing is 24–35 ppt. A temperature range of 15–28°C is optimal for growth.

The nursery phase may involve rearing the clams to several millimetres in an upwelling system for 2 months in a hatchery after which they are placed in mesh bags placed on racks above the substrate in the natural environment for 2–6 months. If the small clams are harvested from nature instead of being produced in a hatchery, they can be reared in mesh bags to the size of a few millimetres and grown on racks. In some areas, small clams are placed on elevated wooden frames covered with plastic netting instead of in mesh bags. Grading and stocking density reduction occur periodically during the nursery phase.

Growout in the substrate begins when the clams reach 10–15 mm, and stocking ranges, according to the FAO, from 200 to 300/m^2. Protected intertidal areas make good clam beds, though some producers use small ponds. Various substrates, from gravel to mud and shell, will support clams. Predators are removed from the ponds prior to stocking. In Europe, long strips of mesh may be used in intertidal areas to cover the clams as a means of limiting predation by crabs and birds. The work is still done by hand in some regions, though mechanized planting and covering of clams with mesh have been developed in Europe. The nets need to be cleaned of fouling organisms periodically. Harvest size is around 40 mm, when the clams are 2–3 years old. In China small clams are planted at densities as high as 35 million/ha and growers typically do not cover the clams with netting during growout.

Abalone

The various species of cultured abalone can be found in water temperatures ranging from 2 to 30ºC, which probably explains why spawning ranges from late winter to late summer. Thus, determining the temperature at which a particular species spawns is an important bit of information for anyone wanting to culture it. For example, in South Korea, *Haliotis discus hannai* spawns at about 20ºC, which is reached in July or August and lasts until September or October; thus the abalone in that area are late summer spawners.

The sexes are separate, as we have seen with other molluscs. Gonadal development generally first begins when the animals are about 1 year old and have attained a size of about 3 cm. Depending on size, female abalone may release from 1 million to 10 million eggs into the water where they are fertilized. Did you ever wonder what the holes in the abalone shells are for (assuming you haven't studied abalone biology)? Those are exits for water flow past the gills. The current produced ejects the eggs when they are expelled from the ovary.

Over a period of weeks, abalone eggs develop, go through various larval stages of development and settle to the bottom. The larvae exist on egg yolk until the post-larvae stage at which time they can feed on benthic algae (diatoms). Later, they feed on macroalgae, such as species of *Ulva* and *Gracilaria*.

Echinoderms

Sea cucumber

As is common when overexploitation of wild populations occurs, aquaculturists step into the picture with the purpose of producing a species or group of species for enhancement and/or direct marketing. Such is the case with sea cucumbers. Sea cucumbers are highly valued as food, particularly in certain cultures, primarily in Asia. Sea cucumber culture has developed to the extent that it is now a component of IMTA systems in some parts of the world. In those systems the sea cucumbers feed on the waste feed and faeces of fish or shrimp in the system. Culture is not restricted to Asia but is also conducted in Australia and various South Pacific Island nations, among others.

Captive spawning involves holding broodstock collected from the environment by the culturist or commercial harvesters in tanks with several centimetres of sand that provides an opportunity for the animals to bury. They are fed algae. Spawning is induced by raising or lowering the ambient temperature by a few degrees Celsius for a few minutes, after which the temperature is returned to what it was originally. The process stimulates spawning. Larvae hatch after about 48 h and feed on algae for several days. In culture they enter a non-feeding period during which they are induced to settle by adding various types of algae and commercial products. Once settled they are provided with benthic diatoms. Juveniles are reared in tanks on sand substrates until they are several centimetres long, after which they are transferred to ponds or sheltered bays for growout in pens.

Providing Live Food

There has already been considerable discussion about the use of live food, and details of producing algal cultures have been described in the preceding section and other chapters of this book. Therefore, this section focuses on the production of zooplankton species that are used for feeding the early life stages of aquaculture animals in the hatchery.

Larval and early fry stages of many aquaculture species will not accept prepared food at first feeding. Their mouths may be too small to consume the particles, or the animals may not recognize prepared feed particles as food. Prepared feed particles do not 'behave' like living organisms, which could account for the lack of recognition because most of the carnivores being cultured feed by sight. Some species may reject prepared feed particles if they do not have the proper odour and figuring out what that odour should be, can be difficult. Colour may also be important, but that is not a major issue because prepared feeds can be made in virtually any colour by adding the appropriate ingredient to the feed. That might be, as examples, an edible dye (array of colours available), ground marigold petals (yellow), algae such as the cyanobacterial genus *Spirulina* (green) or krill meal (pink). A major problem is that it is difficult to manufacture very small particles of prepared feed that contain all the necessary nutrients, and nutrients will leach from tiny, prepared feed particles much more rapidly than from larger pellets. There has been some research on developing microencapsulated feeds (Box 6.15), but there has been limited success in getting aquaculture species to accept them. Microencapsulation is discussed further in Chapter 8.

It is very important to understand that in cases where zooplankton are produced to provide live food to the early life stages of such species as marine fish and shrimp, there may be three cultures that need to be maintained: (i) algae; (ii) zooplankton; and (iii) the species of fish or shellfish that will ultimately be grown for marketing. If both rotifers and brine shrimp are involved in the feeding protocol, four cultures will need to be maintained. In addition, many hatcheries maintain an array of phytoplankton species, again adding to the number of cultures that require constant time and attention, not to mention expense. A problem that causes any of the three (or more) cultures to fail can spell disaster for an entire hatchery operation. A backup means of providing algae in the event of loss of an algae culture would be to have frozen or

Box 6.15.

Microencapsulated feeds are made by mixing extremely small feed particles with water to produce a slurry that undergoes a process that encases the particles with a proteinaceous membrane to make the microcapsules. Microbound diets also can be produced but are not encapsulated with an outer membrane.

freeze-dried algae on hand to meet the demand until a new culture can be obtained. Such algal slurries as well as dry supplements to feed rotifers are now commercially available. Algae cultures, even the stock cultures maintained in test tubes, can become contaminated and taken over by competing species. A stock culture may be dropped, spilled on the floor accidentally, or after several cycles it may become senescent. There are several other ways to lose a stock culture as well. Maintaining more than one tank of each type of zooplankton species will also serve as a backup for those cultures. If one tank is lost, another one would be available.

Depending on the location of the facility and the characteristics of local zooplankton populations, it may be possible to pump natural seawater and pass the collected zooplankton through sieves to concentrate the animals, sort them to the proper size range and then put them in the culture chambers. This technique, while it can eliminate the need for algae culture, can be dangerous, however, as it commonly leads to the introduction of carnivorous species that will prey upon the culture species. Some sorting out of undesirable species can be accomplished through the sieving process as the carnivorous plankton species are often larger than the culture animals. However, if predators of the same size as the desired food items are present and if they grow more rapidly than the target aquaculture species, they may eventually become large enough to prey on that species or they may be voracious enough to attack, kill and consume the primary culture species even when the predator is the smaller of the two.

Among the most common live food animals provided by aquaculturists to larvae and post-larvae are rotifers, copepods (particularly copepod nauplii) and brine shrimp (*Artemia* spp.). Copepod culture is similar to rotifer culture except that, in most cases, the source of the zooplankton species is from nature using plankton nets as the means of capture (Fig. 6.33). Once the samples are sieved to separate larger organisms from the desired plankton size, they will need to be sorted to eliminate unwanted species. This is obviously tedious work, but if the purpose is to collect broodstock for use in a hatchery, only a few animals from the sample may be required. Both calanoid and harpacticoid copepods have been of interest and techniques for their culture have been developed. An example of a harpacticoid copepod that can be cultured for live food is *Tisbe biminiensis*.

Rotifers

Rotifers within the genus *Brachionus* are widely used by aquaculturists, with *Brachionus plicatilis* being perhaps the most popular. Of course, it is not quite that simple. There are various strains of *B.*

Fig. 6.33. Plankton nets can be used to collect wild zooplankton. The nets are available in various mouth diameters (with 0.5 and 1.0 m being common) and mesh sizes. A cup at the end of the net collects the sample.

plicatilis, and at least some of them have different growth rates and, more than likely, other differences in performance characteristics. Rotifers are very tiny and often serve as the first food for marine fish and shrimp larvae. Starter cultures can be obtained from scientific supply houses or from other aquaculturists. Rotifers can be reared in batch culture or continuous culture. Continuous culture is probably the best method when a consistent rate of supply is required.

Rotifers are usually reared in one or more tanks that have a total combined volume sufficient to produce the number of animals required daily as food for the fish or shrimp being cultured. In fact, it is wise to produce rotifers in excess, so if one culture tank experiences a high level of mortality there will be sufficient numbers on hand to meet the needs until additional rotifers are produced. An alternative that has been used is to rear rotifers in earthen ponds. That might be most appropriate when extremely large numbers are required. If pond culture is used, it is wise to have at least two ponds in the event of a population crash in one of them. Rotifers can be fed either algae or yeast. A properly fertilized earthen pond may provide sufficient levels of phytoplankton and reduce or eliminate the need to augment the algae produced naturally with cultured algae.

Adult rotifers in a tank or pond will actively reproduce and a few animals can become many thousands within a few days. Each female produces only a few eggs at a time, but the offspring will become reproducing adults themselves within less than 24 h, so the population literally explodes. Rotifers should be cultured in warm saltwater – upper 20s to 30°C is a suitable range. Full-strength seawater is not required. The animals may be grown at 15 ppt salinity or, perhaps more desirable, 20 ppt salinity. The lowest temperature that *B. plicatilis* will tolerate is near 10°C. It has been recommended that the pH should be slightly alkaline (around 8.0), though rotifers will grow over a pH range of about 6.5–8.5.

Batch culture of rotifers involves stocking a tank and allowing the population to grow until a concentration of the order of a few hundred rotifers per millilitre of water is reached (500/ml seems to be a reasonable number). Depending on the number of rotifers that hatch and water quality conditions, a batch should be ready for harvest in 2–7 days after inoculation. At that time, fine-mesh nets are used to harvest the entire adult population.

In continuous culture, a portion of the population is harvested each day once the population has grown to several hundred rotifers per millilitre. Rotifers are often cultured without continuous water exchange, which is common given their very small size (a fraction of a millimetre in length for adults); static water and high density make capture of rotifers in fine-mesh nets relatively easy. A percentage of the tank water can be exchanged each day during partial harvest.

While densities at harvest of a few hundred rotifers per millilitre are perhaps standard, high-density cultures of 2000/ml are sometimes maintained. Super-high densities of 20,000/ml have been achieved, but it would probably not be desirable for the aquaculturist to attempt maintaining such densities in a production facility due to the increased potential for water quality problems and subsequent population crashes. Thinking about having up to several thousand rotifers in a millilitre of water should convince you that they are very tiny animals.

Brine shrimp

Cultured shrimp and many species of fishes of aquaculture interest have been identified as excellent consumers of brine shrimp nauplii (*Artemia* spp.) as a first feed as they are large enough at that time so that rotifers are not necessary. Animals that require rotifers or some other extremely small live food items early in their lives are typically converted to brine shrimp as they grow large enough to ingest the nauplii. There is at least one distinct advantage of feeding brine shrimp nauplii – the culturist does not have to maintain an algae culture to feed them unless they are to be grown to the juvenile or adult stage. Even in the latter cases, they could be fed frozen algae paste or freeze-dried algae and eliminate algae culture by purchasing phytoplanktonic algae in one of those forms. Feeding brine shrimp on yeast also avoids the need for maintaining an algae culture.

The reason you do not have to provide algae to brine shrimp that are fed as nauplii is that brine shrimp cysts (sometimes mistakenly called eggs) can be purchased commercially, so there is no need to maintain a self-sustaining population of the animals. The cysts are a resting stage that float on the water surface and are collected using boats. The two original major sources of brine shrimp cysts were the Great Salt Lake in Utah, USA, and the other is San Francisco Bay, California, USA. The first is an extremely salty water body in which the only living creatures throughout most of the lake are brine shrimp and a couple of species of algae upon which the brine shrimp feed (Box 6.16). Brine shrimp collected from the Great Salt Lake are dried and vacuumed-packed in cans. In the San Francisco Bay area, brine shrimp cysts have been cultured in ponds. Aquaculturists in many places around the world have established their own populations of brine shrimp in suitable saltwater bodies and, in a few instances, wild populations have been found in saline water bodies outside the USA, though the major source for cysts continues to be the Great Salt Lake.

Once the cysts have been collected, they are dewatered and canned as previously mentioned. The vacuum-packed cysts have a long shelf life and can be easily shipped around the world. The major problem in recent years has been an unreliable supply while demand has been increasing. That combination of factors has caused the price to increase in some years to the point that the economics of aquaculture, particularly marine shrimp culture, has sometimes been jeopardized. Competition for the cysts that are available is sometimes fierce, thereby driving the price up even more and leaving some hatcheries without an adequate supply.

Box 6.16.

The cysts are produced so the brine shrimp, which are short-lived, can maintain their population during periods when the food supply is scarce. The resting-stage cysts float on the surface and can often be found in windrows far offshore. Because they bring a high price, the competition among people who collect cysts in the Great Salt Lake is very high. They often use spotter planes to find a windrow of cysts and then the race is on to see who can get there first – the company that hired the plane, or a competitor who was keeping an eye on the boat heading out at high speed to get to the spotted windrow. High-rate vacuum systems are used to fill tanks on the boats with cysts. The floating windrows are sometimes so dense that people can literally walk on them.

When the culturist needs live brine shrimp nauplii, all that needs to be done is to place the cysts in well-aerated seawater (35–40 ppt salinity is typical) at room temperature (about 25°C). The cysts will usually hatch into nauplii in 24–36 h. The nauplii are positively phototaxic, so they can be attracted to, and concentrated under, a strong light source that accommodates netting or siphoning them from the hatching tank. The nauplii are immediately used as food in most cases, though they can be reared for a period of up to a few days on an enrichment diet before being offered to the primary culture species. Enrichment of *Artemia* can involve feeding them probiotics, HUFAs, vitamins, purified amino acids, algae (which is a means of providing HUFAs) and other substances that may enhance the performance of the animals that consume them.

Yeast slurries alone or in combination with algae and/or various types of lipids have been used to fortify – that is, enrich – both rotifers and brine shrimp. Culturing rotifers or brine shrimp on properly selected algae or a combination of algae and yeast appears to produce better-quality food, at least for some larval fishes. One purpose of enrichment is to fortify the *n*-3 (also called omega-3 or ω3) fatty acids in the diet (see the section on lipids in Chapter 7).

Controlling Sex

The primary reason an aquaculturist would want to control the sex of the animals being stocked is to enhance the population's growth rate. Sometimes males grow more rapidly than females, as we have seen in conjunction with tilapia (*Oreochromis* spp.). In the case of tilapia species in which the females become reproductively active before reaching market size and may produce so many progenies that overpopulation and stunting occur, the culturist may wish to stock only males. In other species, such as flounders (various genera) and halibut (*Hippoglossus* spp.), the males grow slowly and their growth terminates at sizes much smaller than the females, so it may be desirable to stock all-female populations in grow-out facilities.

There are several methods by which all-male or all-female populations can be produced. All-male populations are desirable with respect to tilapia, as previously mentioned, while the opposite is true of European sea bass (*D. labrax*), so there is interest in stocking all-female populations of the latter species. The oldest method of determining sex involves visual inspection, and that requires the examination of each individual animal if the sexes are different in some aspect of their morphology at an early age. Determining the sex in some species is simple; take shrimp, for example, where the male has a petasma and the female has a thelycum. The problem is that while it is simple to determine a shrimp's sex, there is no advantage in stocking one sex over the other, which also tends to be the case with respect to other species that are easy to differentiate by sex.

Until they are in breeding condition, it is often difficult to sex finfish. There may be visible differences in the vent region of juveniles that allows differentiation. That approach has been used with tilapia, for example. The problem is that it is virtually impossible to eliminate human error, so the approach is not 100% effective, though it will certainly reduce the number of females that are introduced into a growout pond and thus cut down on unwanted reproduction. Another problem is that the technique is time-consuming, labour-intensive and, thus, expensive. The hearty nature of tilapia means that stress-induced mortality is probably not a major issue when sexing by handling and visual inspection is employed.

Sex reversal

Interestingly, the sex of some fishes is not fixed at birth (and, as we have seen, some species are protandrous or progynous hermaphrodites). If the proper hormone is fed to a newly hatched first-feeding fish, it may be possible to control the ultimate sex of that fish. One of the first times, at least with respect to aquaculture, that hormones were used to control fish sex involved research conducted in the Philippines in the mid-1970s. Rafael Guerrero, a Filipino scientist, dissolved a form of the male sex hormone testosterone in alcohol, mixed the alcohol and hormone solution with finely ground feed, dried the mixture to drive off the alcohol (which allowed the hormone to adhere to the feed particles) and offered it to first-feeding blue tilapia. The result was that under the proper conditions, nearly all the treated fish matured as males (the technique tends to be something like 95% or more effective). In his studies, Guerrero determined the proper dosage and amount of time over which the hormone should be fed (21 days) to produce all-male progeny. The most commonly used hormone to develop all-male populations is 17α-methyltestosterone.

The hormone-feeding technique has been widely adopted by tilapia producers, though there have been objections to its use. Some people are concerned that hormone residues may get into humans who consume fish that had been treated early in their lives. Feeding the hormone from first feeding is necessary because if the hormone is not provided soon after the fry tilapia begin to feed, sex reversal will not be obtained. Studies have shown that the natural hormone levels in fish at the time of marketing are many times higher than those to which the fish were exposed during the sex-reversal process, but sceptics remain, so some jurisdictions will not allow production or sale of hormone sex-reversed fish.

Conversion of fish from male to female calls for feeding a female sex hormone. The technique cannot be expected to work with every fish species, nor is there any desire by aquaculturists to sex-reverse the majority of the species that are currently under culture.

Polyploidy

Eggs and sperm have one set of chromosomes and are called haploid. Other cells normally have a set of chromosomes, each obtained from the male and female parents. Those cells are called diploid. There are instances in which organisms have somatic cells with more than the normal number of pairs of chromosomes. That can occur in nature and can also be induced. When it does occur, it is a condition called polyploidy. Having three sets of chromosomes is the most common type of polyploidy and those individuals are known as triploids. Triploidy is sometimes a condition that is desired by the aquaculturist who wants to avoid reproduction in the species being cultured and, because triploid animals are generally sterile, stocking triploids is a convenient way to get around the occurrence of reproduction. In nature, polyploidy is much more common in plants than in animals, but aquaculturists have found ways to create triploids and in some cases tetraploids (fish with four pairs of chromosomes). Triploids can be produced by crossing tetraploids with diploids. Besides sterility, triploids often grow more rapidly than diploids of the same species. Sterility in triploid oysters has an additional benefit in that the gonads of the animals do not develop in preparation for spawning. During gonadal development, which occurs in the warmer months of the year, the quality of oysters is degraded, which is the reason oysters are not desirable as human food in the northern hemisphere during months that do not have an 'R' in them (May, June, July and August).

Mitosis inhibition has been used to create tetraploid rainbow trout (*O. mykiss*). Tetraploids have also been produced in molluscs; the first culture species in which tetraploids were successfully produced was the Pacific oyster, *C. gigas*. Successful tetraploid production of other oyster species soon followed. In addition to producing them by crossing tetraploids with diploids, triploid oysters can be produced using hydrostatic pressure, thermal shock or by exposing their eggs to certain chemicals, such as cytochalasin B and formalin. Both of those chemicals are toxic and pose a health threat to the people who use them, so proper training of involved personnel and proper disposal of water to which the chemicals have been added are required. The percentage of sterile polyploid animals produced varies by species and the technique used. Tetraploid oysters have been produced that, when crossed with diploids, produce nearly 100% triploid offspring. The situation with respect to grass carp has been discussed previously, but because of the controversy surrounding the species, more discussion is warranted (Box 6.17).

Production of grass carp for stocking in the USA – primarily to control weeds, not only in aquaculture ponds but also in other systems, such as weedy lakes, ponds and streams – began in the state of Arkansas. Some of those fish eventually found their way into the Mississippi River and within a few years evidence of spawning was seen. Eventually, some 30 states outlawed the stocking of diploid grass carp. Ultimately, triploid grass carp were produced. One method to accomplish that is by heat shocking the eggs during first cleavage. Once triploid grass carp became available and a method of rapidly ensuring that 100% of a population was certifiably sterile, laws in many states were changed to allow the stocking of triploids.

There has been a controversy raging in the Chesapeake Bay area of the eastern USA over a plan to introduce the Asian or Suminoe oyster (*Crassostrea ariakensis*) to restore eastern oyster (*C. virginica*) beds that have been devastated by the diseases Dermo and MSX ('multinucleated sphere unknown'). One approach would be to employ triploid Suminoe oysters, though there is evidence that triploidy in oysters does not always mean that 100% of the animals are sterile.

Box 6.17.

If a population can be certified as 100% polyploid and sterile, objections to stocking of exotic species can sometimes be overcome. That has been the case with grass carp (*Ctenopharyngodon idella*). Interest in stocking grass carp developed in North America in the 1970s, particularly in the USA, and research indicated that the species could not successfully reproduce in US rivers because the flow rates were not appropriate. However, that turned out not to be the case.

Hybridization

Breeding different species that produce viable offspring (hybridization) is another method that has sometimes produced sterile aquaculture animals. One example is a cross between grass carp (*Ctenopharyngodon idella*) and bighead carp (*Aristichthys nobilis*). A major reason for wanting to stock sterile fish is to avoid reproduction by non-native animals. Non-native does not necessarily mean that the animals are different species from those already present in a region. Geneticists often express concern that genetic integrity may be lost if the genes from one population of a species are mixed with those of another of the same species that comes from a different locale. A good example is stocking Atlantic salmon (*S. salar*) from European waters into North American net pens. In a portion of the east coast of North America, primarily from Maine, USA, northward well into Canadian waters, Atlantic salmon are native, but the wild stocks are in decline, particularly in Maine. Stocks from such places as Norway differ to some extent genetically from their conspecifics in North America and there are stocks of Norwegian Atlantic salmon that have been selectively bred for aquaculture over several generations, so they are genetically distinct from even their native wild populations. Stocking sterile fish will keep the introduced animals from spawning with the natives, should the cultured fish escape. Thus, the genetic integrity of the local stocks can be maintained by introducing only sterile fish. In Maine, some of the fish that were raised in net pens contained the genes from local, Canadian and European strains. In recent years, there has been a regulation in place that allows only native Maine fish to be stocked or cultured in that state.

In many cases the introduction of an aquaculture species represents a truly exotic species; that is, one that does not have an existing natural population in the area. Examples are the rearing of tilapia (primarily *Oreochromis* spp.) outside their native range of Africa and the Middle East; rainbow trout (*O. mykiss*) throughout much of the world outside the western USA where the appropriate temperature range for the species occurs (Box 6.18); Atlantic salmon culture in western North America and Chile; and red drum (*S. ocellatus*) in China.

In some instances, the hybrids produced when two closely related species are crossed will be predominantly or entirely of the same sex when they mature. In many cases, hybrids are also sterile, as previously mentioned. Crosses between some species of tilapia produce high percentages of males, sometimes approaching 100%. Examples are crosses of *O. aureus* with *O. mossambicus* and of *O. aureus* with *Oreochromis niloticus*. There are two drawbacks with the approach. Because hybridization of tilapia does not always produce 100% males, some reproduction can still occur, though it will be far less than in cases where the ratio of males:females is 1:1. Another drawback is keeping the two parental stocks separated when not spawning.

Box 6.18.

During the late 19th century when Pacific salmon were being stocked in the eastern USA and Atlantic salmon were being stocked on the west coast, rainbow trout, native to the area west of the Rocky Mountains, were also being transplanted to other regions of the country. Rainbow trout are now commonly seen throughout the USA in regions where there is cold water throughout the year and are often stocked during the winter for recreational fishing in waters that will not support their survival year-round. The stocking programmes are intended to provide angling opportunities for recreational fishermen with the expectation that most of the fish will have been caught before the water temperature reaches the lethal level. As is true with tilapia in South-East Asia, the population of the USA now considers rainbow trout to be native in regions where they have been introduced and survive throughout the year.

Gynogenesis

If an ovum develops following sperm penetration but without fusion of the gametes, the embryo that is produced has undergone a process known as gynogenesis. In most cases, the number of chromosomes will be haploid ($1n$) because only those contributed from the female will be present. Those embryos will die within a few days. However, in some cases, the second polar body associated with meiosis will be retained and contribute the other half of the chromosomes needed for a diploid ($2n$) individual. Because all the chromosomes originate from the mother in those rare cases, the fish will be XX or female.

Various techniques have been used to produce gynogenetic fish. Using the sperm of a distantly related species has been effective in some instances. For example, using UV light to inactivate the sperm of black sea bass (*Centropristis striata*) males and exposing that sperm to the eggs of southern flounder (*P. lethostigma*) has been used as a first step in producing gynogenetic flounders. Once the eggs have been activated, they can be exposed to the proper pressure so that the second polar body is retained, and the surviving eggs develop into gynogenetic females. However, the presence of sperm is not always required. A needle dipped in whole blood or blood serum of a fish can be used to prick the ova and some of those eggs may develop as gynogenetic animals. Weak electric currents and low levels of UV light or X-ray radiation may also stimulate gynogenesis. The major problem with the technique is that no matter what process is used to stimulate gynogenetic development, only a small percentage of the eggs receiving the treatment ever develop into viable animals.

Induced gynogenesis has been applied to grass carp where the desire has been to introduce unisex fish into an aquaculture situation or into nature for aquatic vegetation control in areas where grass carp had not previously become established or where diploid fish are prohibited. Because all the gynogenetically produced fish are females, they will not be able to reproduce if they escape from aquaculture or if they are intentionally introduced into nature. That assumes an absence of males that may have been introduced into nature by other parties or may have escaped into the wild.

Because of the low rate of success in producing gynogenetic fish, the technique is not commercially viable and is not likely to generate much interest in the aquaculture community unless a simple process that can produce large numbers of gynogenetic fish is developed. However, though the percentage of gynogenetic eggs that develop, hatch and survive to adulthood is very low, it is possible to sex-reverse them in some cases, thereby producing gynogenetic (XX) males, which when mated with normal females will produce all-female populations. Examples of species to which that technique has been applied are tilapia and southern flounder.

There has also been some production of gynogenetic as well as androgenetic tilapia (which develop into YY males). Androgenetic tilapia can be produced by feeding the female hormone 17β-oestradiol to normal fry, using the same procedure as that used to produce all-male populations by feeding 17α-methyltestosterone. Those androgenetic fish have been referred to as pseudofemales. Mating the pseudofemales with normal males will produce a high percentage of male offspring.

Selective Breeding

Selective breeding has led to the development of a range of domesticated animals and breeds of those animals that have little resemblance to their wild ancestors – think about the numbers of breeds of dogs you have seen. While selective breeding of some aquatic animals has been ongoing in some cases for hundreds of years (e.g. koi, which are highly selected common carp (*C. carpio*)), few aquatic species can truly be called domesticated. It has been estimated that less than 5% of global aquaculture production involves genetically improved stocks.

The purpose of selective breeding in aquaculture is to improve the performance (such as growth rate, dress-out percentage, fecundity, disease resistance, or colour as in the case of koi) or some other characteristic of a culture species thought to be desirable by the culturist and/or makes the final product more attractive to consumers. It has been demonstrated that selection for stress resistance in rainbow trout can reduce the amount of feed that is wasted and improve the efficiency of feed conversion. There has also been research that indicates a portion of the fishmeal in feeds offered to selectively bred salmonids can be replaced with soybean meal without negatively impacting performance.

In addition to several species of carp, cultured trout have been selectively bred over many generations. Cultured Atlantic salmon in Europe are genetically distinct from their wild counterparts as previously mentioned and are said to not perform as well as the wild fish if they escape from net pens. Channel catfish (*I. punctatus*) have also undergone several generations of selective breeding, which has sometimes led to unintended consequences.

In the case of channel catfish, one group of fish that R.R.S. and his students worked with several years ago was much more aggressive than others in our research facility. That strain of catfish had undergone many generations of selective breeding before we obtained some of them for our breeding programme. It is theorized that the culturists who had bred the fish before we got them had selected their broodfish from among the fastest-growing fish from each generation – every generation will produce a range of sizes of fish that are of the same age. As that type of selection occurred over several generations, the broodstock always produced offspring that ranged greatly in size at maturity, a result we figured was largely due to competition. The most aggressive fish were undoubtedly able to outcompete the others for food, thus they grew faster. So instead of obtaining steadily improved growth over several generations, we concluded that the culturists were selecting for aggression, which seems to be a reasonable conclusion. That strain was the only one of four or five that we looked at that would aggressively try to bite a person attempting to handle them. The other strains had not gone through several generations of selective breeding (Box 6.19).

Selective breeding can lead to loss of genetic diversity rather quickly if the effective population size of the broodstock is insufficiently large. Just what the effective population size should be depends on the spawning characteristics of the species, the number of eggs produced by each female, the number of egg batches from different females that are fertilized with the sperm from a single male and undoubtedly a number of other

Box 6.19.

During the early 1970s when the channel catfish industry in the USA was growing rapidly, John Guidice, fish a geneticist at the Fish Farming Research Center at Stuttgart, Arkansas (a US Fish and Wildlife Service facility that ultimately was moved to the USDA), began a selective breeding programme with that species. He collected broodstock from a number of sources, including private producers as well as university and government hatcheries. Various pairings from among the sources of fish were made and the offspring were evaluated for performance characteristics. Little improvement in phenotype was detected. Guidice attributed the lack of phenotypic improvement to the notion that if the ancestry of those various groups of broodfish was traced back to their origin, it is likely that all, or at least most, of the fish came from one federal hatchery. John Guidice also conducted initial crosses of channel catfish with other species of *Ictalurus*.

R.R.S. worked during the summer of 1968 at the Stuttgart lab to learn as much as possible about catfish aquaculture in what led to his PhD dissertation on catfish nutrition. One of R.R.S.'s graduate students at Texas A&M University was able to obtain wild channel catfish from a few places in the USA and compare their performance with fish that had been in culture for a least a few generations. Some significant differences among those populations were readily apparent, one of which, as previously discussed, was associated with aggression.

factors. Inbreeding depression can occur quickly when insufficient broodstock numbers are used. Loss of genetic diversity can lead to various problems associated with performance, including reduced survival. Examples of aquaculture species where loss of genetic diversity has been reported include Atlantic salmon (*S. salar*), barramundi (*Lates calcarifer*) and catla (*Catla catla*).

However, selective breeding can also lead to improved performance, which is what the aquaculturist desires to accomplish. One of the best examples of a selective breeding programme that has greatly improved the performance of a fish species is the Genetic Improvement of Farmed Tilapia (GIFT) project. The project took place in the Philippines from 1988 to 1997 and involved eight strains of Nile tilapia (*O. niloticus*). There were four strains from the Philippines and four from their native range in Africa. At the end of the 10-year-long project, improvement in the growth rate of what became the GIFT strain of tilapia was double that of any of the eight strains when spawned within strain (Fig. 6.34). GIFT fish not only grow fast, but considerable production cost savings have also been reported from several nations that have adopted the strain.

Genetic Engineering

Molecular biology has made it possible to transplant genes from one species into another to produce transgenic organisms. Aquaculturists have been applying molecular biological techniques for several years and many view the technology as a means by which rapid improvement in the desirable characteristics of farmed fish and shellfish can be achieved. Gene transfer could, for example, result in greatly improved growth rates (insertion of growth hormone genes) and may provide broader temperature tolerance (insertion of antifreeze genes). Among the benefits for aquaculture predicted from the technology are development of reagents and vaccines from molecular cloning and the expression of specific genes leading to increases in aquaculture production. The latter could be particularly important in developing nations where the income of poor farmers could be improved. However, the environmental risks associated with the use of transgenic or GMO aquatic animals need to be assessed on a case-by-case basis.

Several transgenic species of aquaculture interest have been created and used in research in recent years. Some examples are abalone (*Haliotis* spp.), Atlantic salmon (*S. salar*), coho salmon (*O. kisutch*), channel catfish (*I. punctatus*), common carp (*C. carpio*), rainbow trout (*O. mykiss*) and tilapia (*Oreochromis* spp.). In nearly all cases the growth hormone gene was involved.

The maintenance of transgenic fish in US research facilities is carefully controlled to prevent escapement and the mixing of genetically altered animals with wild stocks. The American Fisheries Society policy statement on the development of transgenic fishes also cautions against uncontrolled releases

Fig. 6.34. An example of a Genetic Improvement of Farmed Tilapia (GIFT) broodfish at an experimental facility in the Central Luzon area in the Philippines.

because the potential ecological impacts on natural ecosystems have not been determined.

Aquaculture, not unlike other agricultural disciplines, is at a crossroads with respect to genetic engineering. The potential exists to greatly increase productivity through the development of transgenic organisms, but consideration of potential environmental consequences and impacts on wild populations of the same species cannot be ignored. Many individuals would prohibit all production of transgenic animals, and some individual nations and groups of nations have prohibited the introduction of transgenic organisms. A seemingly realistic approach appears to be that such animals should be developed under fully controlled conditions where the chances of escapement are minimal, and that they should only be released for commercial production once it has been determined that they pose no undue threat to natural communities. Assurance of the latter requirement may involve the coupling of genetic engineering with the production of sterile individuals. The fear that transgenic animals may affect humans in some way is another issue.

Molecular biology techniques can also be used to develop vaccines to combat diseases. For example, viruses such as IHN of salmon can be obtained from an infected fish, amplified through PCR and the strain of the virus can then be identified. That approach holds promise for the development of vaccines to combat various viral diseases that afflict aquaculture species.

Genetics and genetic engineering are major foci of both those supportive of, and opposed to, aquaculture. As we have seen, there is also a great deal of concern being expressed by geneticists about the maintenance of genetic diversity in hatchery fish destined for enhancement stocking. The book by Beaumont *et al.*, listed in the 'Additional Reading' section, discusses those topics in detail.

Summary

In this chapter you have been provided with an indication of the methods by which various aquaculture species are reproduced. To close the life cycle of a species and make it possible to keep from having to go to nature to obtain animals for stocking, having control over reproduction is required, but sometimes achieving that control is difficult.

Nearly all the species actively being grown for human consumption have separate sexes and with few exceptions once the sex is established, it does not change through the life of the animal, though sex reversal is possible in some species during the early stages of their lives before their sex is firmly established. Most aquaculture species, both fishes and invertebrates, broadcast their eggs and sperm into the water, so fertilization is external and there is no parental care. However, some species, particularly those with relatively large ova, do provide some form of protection for their eggs (e.g. carrying them on the body until hatching in the case of freshwater shrimp and lobsters, nest building in salmonids, protection of the eggs by ictalurid catfish and mouthbrooding in tilapia).

For some aquaculture species, differentiating the sexes is very simple, but for others it is difficult to tell males from females, particularly when the animals are not in spawning condition. Once they do develop and are ready to spawn, they may be allowed to do so in ponds under natural conditions or in hatcheries where a great deal of control over the activity, including selection of specific males and females that will be paired, is practised. Under hatchery conditions it may be necessary to inject females (and sometimes males) with hormones to induce spawning. Specific information for a variety of species was presented to provide an indication of the range of methods and technologies that has been developed for spawning selected species and/or groups of finfish and invertebrates.

Because many primary aquaculture species require live food when they begin feeding – often because they will not accept or cannot recognize prepared rations as food – there was further discussion in this chapter about how to culture such live food items as rotifers and brine shrimp. Algae culture to feed rotifers and other live foods has been covered to some extent in earlier chapters as well as in this chapter. In the case of filter-feeders, such as bivalve molluscs, the only live food that needs to be provided is algae, so zooplankton cultures are not required. Once molluscs leave the hatchery and are stocked in nature, most species will rely completely on natural primary production for their food.

Sex control is often an important consideration. One sex may grow significantly faster than the other, so manipulating the sex ratio to skew it towards the more rapidly growing sex can reduce the time required to grow all the animals in a population to market size and reduce the cost of production. In some cases, it is desirable to produce sterile animals as well. Stocking sterile animals is often a good idea when dealing with exotic species and should be a consideration in the use of transgenic animals. Other techniques associated with sex control include development of polyploid individuals, hybridization and gynogenesis.

Selective breeding has been practised with many aquaculture species ever since the knowledge on how to spawn and rear them in captivity was gained – in some cases hundreds or even thousands of years ago. Selective breeding by geneticists began only a few decades ago, though fish such as koi (colourful *C. carpio*) were developed centuries ago. The purpose of selective breeding may be to improve performance, but it can also be used to develop better dress-out percentage, resistance to disease and various other desirable traits in a species.

Genetic engineering has the potential to accelerate the progress that can be made in enhancing desirable traits through getting new genes incorporated into the DNA of a particular species or strain of aquatic animal. Growth hormone incorporation has been successfully accomplished with many aquaculture species, and other genes such as the antifreeze genes found in some coldwater species are of interest.

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7 Aquatic Animal Nutrition

Introduction

The focus of this chapter is strictly on those aquaculture species that are commonly offered prepared feeds, though we recognize that in some parts of the world various species of carp, tilapia and other finfish are grown primarily in fertilized ponds and may not be offered such feeds. Shrimp are the primary invertebrates that are provided prepared feeds. Mollusc culturists, for the most part, rely on natural levels of plankton in the grow-out areas to provide nutrition for the animals. However, algae paste can be provided, and often is (at least during a portion of the life cycle) if a hatchery is used, as has previously been discussed. Prepared feeds have also been developed for abalone. The use of pelleted bait is an option in crayfish traps but is not used as a feed during the rearing of those animals because of the much more economical use of forages such as rice stubble which serves as the base to support a microbial food web. In any case, aquaculture nutritionists have concentrated primarily on determining the nutritional requirements of finfish and shrimp, but even after several decades of research, a good deal of information is still needed, particularly in the case of species that have recently been commercialized and those that are still primarily at the research stage of development.

Energy and Growth

For living organisms to grow, they require energy, which can come from a variety of sources and different nutrient groups. Plants utilize light as their source of energy, while animals depend upon the energy found in the proteins, lipids and carbohydrates they ingest. Protein, lipids and complex carbohydrates need to be broken down and converted into simple sugars and other metabolic intermediates before they are used as energy. Some organisms obtain their energy from other chemical compounds, but none of these are relevant to this discussion. In this chapter, only aquatic animal nutrition which is based on food energy is discussed.

The energy contained in the food aquaculture animals consume is measured in calories, which for our purposes involves the large calorie or kilocalorie (kcal). One kilocalorie is the imperial term defined as the amount of heat required to raise the temperature of 1 kg of water by 1°C. A small calorie is 1/1000 of a kilocalorie and would represent the amount of heat required to raise the temperature of 1 g of water by 1°C. In the International System of Units, the joule (J) is a derived unit of energy, often expressed as kJ which is equivalent to 0.239 kcal. Aquaculture feeds not only need to provide the proper types of nutrients for proper growth; they also need to contain the proper amount of energy. There is a good deal of variability in terms of the amount of energy required for growth at an optimal rate, so each species and life stage need to be evaluated individually to find the optimal protein to energy (PE) ratio. This ratio is most precisely expressed as a digestible protein (DP) to digestible energy (DE) ratio by considering the fraction of total dietary protein and energy that are digestible and thus available to the fish. The optimum PE ratio may vary not only from species to species, but also with temperature. There are undoubtedly physiological conditions that would be factors as well. We should indicate that if you delve into the topic of the relationship between protein and energy, you may come across discussions in which an author mentions the energy to protein (EP) ratio rather than the PE ratio. It is the same thing, only they are reciprocals, so a low PE ratio would be a high EP ratio and vice versa (Eqns 7.1 and 7.2):

$$DP/DE = \text{Digestible protein (g)} / [\text{Dietary energy from protein + carbohydrate + fat } (\text{kcal} \times 1000 = \text{mcal})] \quad (7.1)$$

$$EP = 1/PE \quad (7.2)$$

DOI: 10.1079/9781800621145.0007

The goal of the aquaculture nutritionist is to balance dietary energy sources such that the protein is used primarily for growth, while lipids and carbohydrates are burned to produce the energy required for various routine metabolic processes. It has been determined that the gross energy levels contained in proteins, lipids and carbohydrates are 5.65, 9.40 and 4.15 kcal/g, respectively; so lipids contain nearly twice the energy per gram as proteins and more than twice the energy per gram as carbohydrates. For simplicity, when calculating digestible energy levels in feeds, researchers often assume values for proteins, lipids and carbohydrates of 4, 9 and 4 kcal/g, respectively.

As mentioned previously, not all of the food energy in the various dietary components is actually available for growth and metabolism. The total amount of energy in a diet is called its gross energy. Following digestion, some of the food energy is absorbed into the animal's body and some is lost in the faeces because some components in feeds are indigestible. Complex carbohydrates, such as starches, are not generally well digested by finfish. The fibrous carbohydrate cellulose is virtually indigestible by finfish. You will see in the carbohydrate section of this chapter that activity from the enzyme that breaks down cellulose, called cellulase, has been observed in the digestive tracts of a few finfish species, and that activity appears to be associated with the presence of gut bacteria that produce the enzyme. We can assume that, even in those instances, the efficiency of the process is low and most of the dietary cellulose passes through the intestines intact and provides little or no benefit to the fish.

The absorbed energy is called digestible energy while that lost in the faeces is, not too surprisingly, referred to as faecal energy. Digestible energy cannot be measured directly, but the other forms of energy can be measured through a method known as bomb calorimetry from samples of the feed and faeces. Bomb calorimetry involves placing dried samples, separately, in the bomb calorimeter where they are ignited and the amount of heat given off is measured. If you know the amount of energy in the two samples, you can subtract the faecal energy from the gross energy. The difference is the digestible energy value.

That is not the end of the story, however. There are a couple of other losses of energy after digestion that need to be considered before the energy that can be used for growth and metabolism (metabolic energy) can be determined. Those additional losses are energy excreted via the gills in the form of ammonia and the energy contained in the urine. Those two can be measured but obtaining those metabolites from aquatic species is rather complicated. In addition, only about 10% of the energy measured as digestible will subsequently be lost in metabolism on average. Therefore, digestible energy is the most common measure of available energy for aquatic species.

The amount of energy burned by or required to maintain an organism at rest is a measure of its basal metabolic rate. When an aquatic animal swims, moves about, is involved in reproductive activity, actively eats, digests its food or is involved in various other activities, additional energy is required. You might think that the best way to grow a fish would be to have it resting at the bottom of the culture unit and expending energy above that required for basal metabolism only to eat and digest its food. On the contrary, as in humans, active behaviour (exercise, if you will) is required for maintenance of proper physiological functioning. There have been suggestions from researchers that maintaining a current in culture chambers so that the animals within have to actively swim provides them with needed exercise that may be somehow beneficial by stimulating growth or enhancing muscle tone. That certainly makes sense with respect to those species which naturally live in flowing waters, though not necessarily for animals that are, by nature, sedentary. Currents may be beneficial to benthic species such as oysters, clams and mussels, but in those cases the benefit is associated with food being carried past the animals, not with exercise. In any case, the situation with respect to how beneficial exercise might be has not been fully resolved.

While many aquatic animals continue to grow throughout their lives (referred to as indeterminant growth), growth does tend to level off (approach an asymptote) at some point in the life cycle, which may actually be several years after the animal becomes mature – at least in long-lived species. Growth is most rapid, however, during the early stages in the life cycle. Post-larval and fry fish may double in size every few days, while young fingerlings may double in weight in about a month and older sub-marketable animals grow at a rate that requires several weeks or months for a doubling. Those rates of growth apply to rapidly growing species. Some species, particularly those that are of the coldwater type, tend to grow more slowly than warmwater ones. Adults maintained as broodstock also tend to increase in size very slowly, adding only a small percentage to their total weight annually, if they grow perceptibly at all.

In general, the aquaculturist would like to be able to rear the species being cultured from egg to market size within one year. For many species that can be done, and it may even be possible to obtain two or more crops per year, as is the case with marine shrimp. In the tropics, shrimp farmers can often get three crops per year by having post-larvae from the hatchery ready for stocking as soon as ponds have been harvested and refilled with water. For fish, one crop a year is possible with many species, though longer growout periods are not uncommon. If three or more years are required to rear the animals to market size, it may be difficult to obtain a profit unless the species brings a premium price. Atlantic halibut (*Hippoglossus hippoglossus*), currently the only commercially produced halibut species, take two years or longer to reach market size, which is typically 5–10 kg. That is a coldwater species, which accounts for part of the long growout period. Also, recall that there is about a five-month period from the time the eggs of Atlantic halibut are fertilized until the post-larval stage is reached.

Many species are harvested before they reach maturity, though we have already seen that there are exceptions, including such tilapia species as the Mozambique tilapia (*Oreochromis mossambicus*), which can mature and begin to spawn well before reaching a size that is accepted in many markets. For such animals as marine shrimp, market size may be from 15 to 20 g or more (depending on consumer demand), while for a variety of finfish, the market will commonly accept animals in the 450–500 g range. Larger sizes of fish dominate some markets, and that is not necessarily a function of species, but relates to consumer preference. Similarly, some consumers will accept fish of quite small size. For some species, different sectors of the market may desire different sizes, not to mention the forms of the product. By forms we mean how it is presented to the consumer. For example, a fish may be sold in the round; gilled and gutted; deheaded, gutted after the fins, scales or skin (in the case of catfish) are removed; filleted; or in various other forms. Shrimp may be sold whole, as tails, or shelled and deveined. Mussels are typically sold in their shells. We could go through additional types of seafoods and varieties of preparation, but we think you get the idea. The edible products which are generated from aquacultural production are typically rich in protein and relatively low in fat compared with most terrestrial animals. The fat typically contains appreciable amounts of long-chain HUFAs which are unique to seafood and provide beneficial effects to human consumers. The dietary components that must be provided to nourish the animal and efficiently produce that edible product are discussed in the following sections.

Proteins

Proteins comprise the muscles and other connective tissues in an animal. They are also important as hormones and enzymes, which are responsible for catalysing thousands of biochemical reactions. As such, dietary protein is extremely important in supporting the growth and metabolism of all organisms including aquatic animals. The dietary protein component, which is composed of various amino acids, is also typically the most expensive constituent in prepared diets.

The estimated dietary protein requirements of some aquaculture species based on research studies are presented in Table 7.1 (see also Box 7.1). A general trend can be seen in which fish with carnivorous natural feeding habits tend to have higher dietary protein needs compared with omnivorous or herbivorous species.

Differences in initial animal size, culture conditions, dietary protein sources, dietary PE ratio, feeding rate, number of feedings per day, stocking density and the response being evaluated (growth, feed conversion efficiency, protein conversion efficiency or some other physiological parameter) are among the factors that tend to confound the results of such studies, and thus produce ranges in values rather than absolute numbers. Perhaps the most important contribution of such studies is that they provide feed formulators with target protein levels or ranges that should lead to acceptable performance.

Amino acids combine in long chains to make up the many thousands of different proteins that are found in the bodies of every aquacultured animal. Each amino acid is comprised of carbon, hydrogen, oxygen and nitrogen. Three amino acids also contain sulfur; those are methionine, cystine and cysteine. While an individual protein molecule may

Table 7.1. A sample of the estimated requirement or range of requirements for protein (as a percentage of diet) for various species of aquaculture interest and importance.

Species	Protein requirement (%)
Abalone (*Haliotis* spp.)	27–44
Shrimp	
Black tiger (*Penaeus monodon*)	35–46
Blue (*Litopenaeus stylirostris*)	44
Freshwater (*Macrobrachium* spp.)	13–25
Indian white (*Fenneropenaeus indicus*)	40–43
Kuruma (*Marsupenaeus japonicus*)	>40–60
Bass	
European sea (*Dicentrarchus labrax*)	40
Striped (*Morone saxatilis*)	45–50
Carp	
Bighead (*Aristichthys nobilis*), fry	30
Common (*Cyprinus carpio*)	35–40
Grass (Ctenopharyngodon idella)	41–43
Silver (*Hypophthalmichthys molitrix*)	37–42
Catfish	
Channel (*Ictalurus punctatus*)	32–36
African (*Clarias* hybrid), fry	<50
African (*Clarias* hybrid), 2–4 g	40
Indian (*Clarias batrachus*)	30–40
Charr	
Arctic (*Salvelinus alpinus*)	37–42
Eel, Japanese (*Anguilla japonica*)	45
Flounder	
Olive (*Paralichthys olivaceus*), larvae	>60
Olive (*Paralichthys olivaceus*), juveniles	46–51
Milkfish fry (*Chanos chanos*)	40
Mullet, Striped (*Mugil cephalus*)	28
Pacu (*Colossoma macropomum*)	35
Plaice (*Pleuronectes platessa*)	50
Salmon	
Atlantic (*Salmo salar*), juveniles	45
Coho (*Oncorhynchus kisutch*)	40
Chinook (*Oncorhynchus tshawytscha*)	40
Sea bream	
Gilthead (*Sparus aurata*)	40
Red (*Pagrus major*)	55
Tilapia	
Blue (*Oreochromis aureus*), fry	56
Blue (*O. aureus*), fingerlings	34
Mozambique (*Oreochromis mossambicus*), fry	40
Nile (*Oreochromis niloticus*)	25
Trout, Rainbow (*Oncorhynchus mykiss*)	40
Yellowtail (*Seriola quinqueradiata*)	55

Box 7.1.

To tell if a particular diet is having the desired effect on protein deposition (increasing it over other diets), and not just increasing weight by adding fat deposits in the visceral cavity, for example, an aquaculture nutritionist would want to know various components that make up the body of the experimental animals. Determination of the levels of protein, lipid, carbohydrate, minerals and water in the body of an animal can be estimated from a series of rather simple chemical tests and is called proximate analysis. Various methods for determining the nitrogen level in a sample of, for example, a whole ground-up shrimp or fish have been developed to approximate the crude protein level. If the researcher is only interested in the proximate composition of the edible portion, that is what would be analysed. The same goes for what remains after the edible portion is removed. That would answer the question: how valuable is the processing waste of this fish? Each fraction is determined from a subsample of a homogenized individual or group of individuals making up the sample. We will not go into how all the components are measured in any detail, but there are standard methods for each of them, with one exception, which is determined by difference – and that is soluble carbohydrate. Vitamins are not measured as part of proximate analysis but make up a small fraction of the biomass of any aquaculture species. Multiplying the nitrogen level by 6.25 gives a good approximation of the protein content in the animal. Lipids can be extracted in one of the organic solvents listed in this chapter and the weight of the material obtained can be compared with the wet or dry weight of the animal to determine the lipid percentage. The mineral percentage is obtained by burning a subsample in a muffle furnace at approximately 600°C for a period of time. What remains after the process is completed are the minerals that were in the sample, or what is known as the ash fraction. The moisture (water) level in the sample is obtained from a subsample that is dried for 24 h at slightly over 100°C. The fibrous carbohydrate level (also known as crude fibre) in the sample is determined by washing in acid and alkali solutions and measuring the remaining organic matter. Add up all the proximate analysis components and subtracting from 100 will approximate the percentage of soluble carbohydrate. It is usually going to be 3% or less of initial dry body weight. The values can be reported on either a wet weight (moisture included) or dry weight (moisture subtracted) basis.

contain thousands of amino acids in its structure, only about 20 different amino acids have been identified and all have the same basic structure as shown in Eqn 7.3:

$$R - \overset{\displaystyle NH_2}{\underset{\displaystyle H}{\overset{|}{\underset{|}{C}}}} - COOH \qquad (7.3)$$

where R can be as simple as a hydrogen atom (as in glycine, which would be the amino acid in Eqn 7.3 if the R was replaced by H) or much more complicated, including some with benzene (six-sided) ring structures.

Some of the amino acids can be synthesized through biochemical manipulation within the animal from carbohydrates, lipids and various nitrogen compounds (including other amino acids). Those are known as dispensable or non-essential amino acids because a dietary supply is not required to support normal growth and metabolism. There are ten generally recognized dispensable amino acids. Indispensable or essential amino acids are those that must be provided in the diet.

There also are ten indispensable amino acids generally recognized for all aquatic species. They are:

- arginine;
- histidine;
- isoleucine;
- leucine;
- lysine;
- methionine;
- phenylalanine;
- threonine;
- tryptophan; and
- valine.

Among these is the sulfur-containing amino acid methionine. The requirement for sulfur-containing amino acids can be met by a combination of methionine and cysteine, though cysteine is not required in and of itself. Another nitrogenous compound derived from cysteine is taurine, characterized as 2-aminoethanesulfonic acid. It does not have a carboxyl group and thus is technically not an amino acid and is not a constituent of protein. However, it has functional roles in conjugation of bile acids, osmoregulation as well as cell membrane stabilization and antioxidant effects. Several studies have found taurine to be conditionally required in the diet of marine fish and shrimp species. In contrast, many freshwater species appear to be able to synthesize taurine by the transsulfuration pathway and thus do not require a dietary supply.

It is important to provide all the indispensable amino acids at the proper levels in the prepared diet given to aquatic animals that are not receiving natural food. Aquaculture nutritionists have determined what those levels should be with respect to some species, though for others, the research is yet to be conducted. Fishmeal is typically derived from the whole-body tissues of marine forage fish and thus has a balanced amino acid composition which, when included in prepared diets, tends to meet the amino acid requirements of aquaculture species. That is one reason why fishmeal traditionally has been often used as an ingredient in prepared diets. Other animal proteins that provide reasonably balanced levels of indispensable amino acids are meat and bone meal, and poultry by-product meal. Shrimp-head meal and krill meal have also found their way into at least some aquaculture diets and can also provide the necessary levels of indispensable amino acids. Plant protein feedstuffs are usually deficient in one or more indispensable amino acids. Lysine and methionine are two that are often present at inadequate levels in the plant protein feedstuffs found most commonly in prepared aquaculture diets (see Box 8.1 for examples of protein source alternatives to fishmeal).

Some plant proteins contain anti-nutritional factors such as protease inhibitors, phytate, glucosinolates, saponins, tannins, alkaloids and gossypol. We will not spend time on each of these, but a few examples will give you a feeling of the kinds of problems that can occur.

Regular cottonseed meal has glands in it that contain the yellow pigment gossypol which serves as a defence against plant pests; however, this compound has been shown to depress growth in various monogastric organisms including fish. For example, channel catfish (*Ictalurus punctatus*) exhibited depressed growth if cottonseed meal was included in the diet at a level higher than about 17% of dry weight. Salmonids seem to tolerate somewhat higher levels of dietary cottonseed meal. A glandless cottonseed meal has been developed in which the level of free gossypol is significantly lower than in glanded meal. Another kind of cotton plant has been produced by gene silencing, in which glands containing gossypol are present in all parts of the plant except the seeds. Higher levels of these cottonseed products can be included in the diet of fish without causing reduced growth.

Soybean meal is widely used in aquaculture feeds, but it too contains an anti-nutritional component in the form of a trypsin (protease) enzyme inhibitor that can limit fish growth. Depressed growth from trypsin inhibitor has been seen in common carp (*Cyprinus carpio*), channel catfish and tilapia (*Oreochromis* spp.). Proper heating of soybeans in the process of manufacturing the meal will reduce or destroy the trypsin inhibitor.

Soybeans and various other plant feedstuffs contain some level of phytate. This is a form of phytic acid, an organic compound that helps the plant store phosphorus. The problem with phytic acid is that monogastric animals cannot digest it and thus its phosphorus has limited availability; also it binds with trace minerals and amino acids, making them unavailable to the animal. Phytate is not well digested, so the attached phosphorus is not available unless the enzyme phytase is added to the diet. One concern is that much of the undigested dietary phytate enters receiving waters in the effluent from aquaculture facilities and can lead to eutrophication. Research has shown that growth of some finfish species fed diets treated with phytase significantly improved, as compared with the same species when they were fed untreated diets.

Lipids

Lipids are a diverse group of biochemicals that make up various tissues of a plant or animal and are chemically characterized as being soluble (can be extracted) in such organic solvents as ether, chloroform and benzene. Several types of lipids may occur in the tissues of an organism including simple fatty acids, triglycerides (three fatty acids esterified to glycerol), phospholipids, glycolipids, aliphatic alcohols, waxes, terpenes and steroids. Fatty acids have the following chemical structure:

$$R - COOH \qquad (7.4)$$

where R is a methyl group (CH_3) and four or more CH_2 groups. The total number of carbon atoms in the molecule is always an even number in living tissue. There can also be one or more double bonds present in the molecule as, for example, in linolenic acid:

$$CH_3CH_2CH = CHCH_2CH = CHCH_2CH = CH(CH_2)_7\,COOH \qquad (7.5)$$

If a fatty acid contains no double bonds, it is saturated. Fatty acids with one double bond are monounsaturated, while those with two or more double bonds are polyunsaturated. Linolenic acid (Eqn 7.5) is an example of a polyunsaturated fatty acid (PUFA).

Fish and crustacean species, like other animals, cannot synthesize PUFAs from monounsaturated fatty acids *de novo* and thus have specific dietary requirements for certain 'essential' fatty acids.

As mentioned previously, there are various health benefits associated with *n*-3 (also known as omega-3 or ω3) fatty acids which are most concentrated in aquatic organisms including fish. Linolenic acid (Eqn 7.5) is the smallest-molecular-weight fatty acid in that family. The longer-chain (>20 carbons) highly unsaturated fatty acids (HUFAs) of the *n*-3 family are the ones most recognized for having beneficial health effects to humans. Other families of PUFAs are the *n*-9 (or ω9) and *n*-6 (or ω6) families, with the lowest-molecular-weight fatty acid in the *n*-9 and *n*-6 families being oleic acid and linoleic acid, respectively. All animals require a dietary source of *n*-6 and *n*-3 fatty acids, while most fish tend to have a higher relative requirement for the latter and terrestrial animals require a greater proportion of the former.

A shorthand notation has been developed for PUFAs in the three families. For example, linolenic acid is presented as 18:3*n*-3 or 18:3ω3. The first number (18) refers to the number of carbon atoms in the molecule. The number after the colon is the number of double bonds in the molecule and the third number indicates the number of carbon atoms from the methyl (CH_3) end of the molecule to the first double bond. Look at Eqn 7.5 and you will be able to see why it has the shorthand notation 18:3*n*-3. Biochemical conversions from one fatty acid to another within a PUFA family can be made within the organism, but the fatty acids that are in any given one of the three families cannot be used by animals to synthesize those in either of the other two families.

As mentioned previously, many terrestrial animals have a predominant requirement for *n*-6 family PUFAs, while the requirement in aquatic animals tends to be for PUFAs in the *n*-3 and sometimes in both the *n*-3 and *n*-6 families. For marine species, eicosapentaenoic acid or EPA (20:5*n*-3) and docosahexaenoic acid or DHA (22:6*n*-3) are often required preformed in the diet. Those two fatty acids are often referred to as HUFAs. PUFAs (including HUFAs) are required for development and proper functioning of cell membranes and a deficiency of HUFAs may be related to impaired vision development in larval fish. The demand for HUFAs can usually be met through a combination of the two fatty acids, or by either alone.

Freshwater fishes seem to be able to convert 18:3*n*-3 to HUFAs somewhat better than marine fishes, so HUFAs are commonly supplied in marine aquaculture diets at a minimum and are often formulated into freshwater feeds as well. Good sources are, as you might imagine, fish oils. Other available marine oils, particularly those extracted from algae, are also good sources of HUFAs. Lipid-soluble contaminants of fish oils can lead to unsafe levels in fish due to biomagnification (a multiplying of the concentration of a contaminant as it passes up the food web from one trophic level to another), so there is concern that some sources of fish oil from wild fishes that are used in aquaculture feed could potentially be harmful to humans. It is possible to decontaminate fish oil before it is used as a feed ingredient.

Marine fishes and anadromous salmonids appear to have a higher dietary requirement for *n*-3 fatty acids, while non-anadromous freshwater fishes and at least some invertebrates appear to require both *n*-3 and *n*-6 fatty acids. One example is tilapia (*Oreochromis* spp.), which have a greater requirement for *n*-6 fatty acids. At least some marine shrimp species appear to be able to perform as well on diets containing soybean oil or poultry fat (high in *n*-6 PUFAs) as on diets supplemented with fish oil (rich in *n*-3 PUFAs). Linseed oil is high in 18:3*n*-3 (nearly 50% of the lipid in linseed oil is in the form of linolenic acid and there is virtually no HUFA in the remaining 50%) and it appears both to be tolerated and to serve as a replacement for fish oil in at least one species of Brazilian catfish (*Rhamdia quelen*). We are not aware of other studies in which good growth has been obtained on diets in which linseed oil was the primary lipid source, but diets with up to 50% of their lipid in the form of linseed oil have shown to have no negative effect on growth in salmon. In conjunction with the PhD research of R.R.S., he fed channel catfish diets containing linseed oil in a large experiment where various lipids and forms of them (triglycerides, free fatty acids and fatty acid esters) were compared. The fish used in that research did not perform well on linseed oil in any of those forms. As the only lipid source in semi-purified diets (see Chapter 8) linseed oil was not a good lipid source. However, studies have shown that stabilizing linseed oil (limiting its oxidation) in practical feed can reduce rancidity in fish post-harvest, making them more acceptable to consumers.

There is increasing demand for fish oil around the world: it is not just used in aquaculture but is a component of margarine in some countries and is in demand as a dietary supplement for maintenance of human health. We have already discussed the notion of feeding mixtures of plant oils during much of the growout period and then providing a HUFA-rich diet for a relatively short period of time prior to harvest. Consumers who want their fish to contain high levels of *n*-3 fatty acids might shy away from fish that were supposed to be rich in those fatty acids, but in fact had lower levels than the wild counterpart. Also, there may be a detectable difference in flavour (Box 7.2).

Over time, the PUFAs in the diet can oxidize and form peroxides. The result can be a rancid diet that may be harmful to the fish that consume it; or can, at the very least, retard their growth. Adding antioxidants to the diet or lipid supplement itself will help protect the fatty acids from oxidation. Ethoxyquin, vitamin E and vitamin C are antioxidants that have been used as feed additives. In the

Box 7.2.

One of the selling points for eating more fish is that they contain high levels of *n*-3 fatty acids, which seem to provide some protection against the development of heart disease, Alzheimer's syndrome and other ailments. However, not all fish are equal in terms of the levels of those fatty acids in their flesh. One of the best sources of *n*-3 fatty acids is salmon, while many very popular species, such as tilapia, channel catfish, shrimp and crabs, have low levels of *n*-3 fatty acids. However, those levels can be increased by feeding diets with higher levels of *n*-3 fatty acids. Several years ago research by D.M.G. demonstrated that the *n*-3 fatty acids in channel catfish could be significantly increased in fillets without reducing the taste or oxidative stability during frozen storage.

case of linseed oil, as previously mentioned, another possible problem is oxidation and the development of rancidity in post-harvest fish during storage before sale.

In addition to providing essential fatty acids, dietary lipid is also the most concentrated source of dietary energy that is generally well utilized by all fish species. However, carnivorous species in particular benefit from rather high lipid levels in the diet due to their more limited ability to use soluble carbohydrate for energy.

The level of dietary lipid that provides good performance varies significantly from one species to another. If the level of dietary lipid is too low, protein may be preferentially used for energy metabolism and not for growth. In finfish, on the other hand, if the lipid level is too high, a lot of it may be deposited in the visceral cavity where it becomes processing waste when the animals are harvested. If too much fish oil is in the diet, while it may provide high levels of HUFAs, it can also give the fish a flavour that many consumers find undesirable. That is, the fish will begin tasting fishy. Of course in some cultures, that is what consumers prefer, but many people seem to like to compare fish with chicken – you can make them taste like anything you want by using various cooking methods, herbs, spices, sauces, etc. to adjust the flavour. They just don't want their fish to taste fishy. Typically, aquaculture feeds contain around 10% lipid, though Atlantic salmon (*Salmo salar*) farmers in Norway use feed that may contains 35% lipid or more.

Carbohydrates

Carbohydrates are relatively simple chemically, being made up of the elements carbon, hydrogen and oxygen. Glucose, fructose and galactose are known as simple sugars or monosaccharides, while combinations of two sugars can form disaccharides such as sucrose (glucose + fructose), maltose (glucose + glucose) or lactose (glucose + galactose). Carbohydrates which have high-molecular-weight and are made up of long chains of simple sugars such as glucose, are polysaccharides. Examples are starches, cellulose and hemicellulose. Given that aquatic animals typically cannot digest fibrous carbohydrates, their levels in prepared diets are generally minimized. Higher levels of soluble carbohydrates are typically included in the diets of herbivorous and omnivorous aquatic species compared with carnivorous species because of their ability to metabolize them for energy.

Carbohydrates are not stored in the bodies of animals to any large extent (if you read Box 7.1, you may recall that the total amount of carbohydrate found after a proximate analysis has been run is of the order of 3% of dry body weight). The major place where carbohydrate can be found is in the liver and to a lesser extent in the muscle as glycogen. The primary uses of carbohydrates are for energy and to serve as a source of carbon for constructing non-essential amino acids. When present at the proper level in the diet, soluble carbohydrate can be digested to glucose and metabolized for energy, thereby allowing protein to be used for growth. This is called protein sparing. Lipids, which are even more energy-rich, can also spare protein, though excessive dietary lipid can lead to fat deposition in the visceral cavity as previously mentioned.

As previously noted, some aquatic animals utilize carbohydrates efficiently, while others do not. Much of the carbohydrate in prepared feeds is in the form of starch, which is not well digested by many species of aquatic animals. Rainbow trout (*Oncorhynchus mykiss*), a carnivorous species, does not digest soluble carbohydrate well and can develop toxic levels of liver glycogen when fed diets too high in carbohydrates, while omnivorous species such as channel catfish and tilapia perform well on diets high in carbohydrates. Turning to crustaceans, freshwater shrimp (*Macrobrachium rosenbergii*) grow poorly when the diet is supplemented with glucose but exhibit good growth on diets with high levels of starch. The same seems to be true of marine shrimp as well. Also, in at least one marine shrimp species, disaccharides and starches appear to be better utilized than monosaccharides.

Dietary fibre sources, such as cellulose, pass through the intestines of most animals undigested. In order to be digested, the enzyme cellulase must be present in the digestive tract of the animal. No vertebrate is known to produce the enzyme, but some finfish harbour intestinal flora able to manufacture the enzyme. Back in the 1970s, one of my summer technicians and I (R.R.S.) examined the intestinal tracts of a wide variety of marine and estuarine fishes collected from nature, along with cultured channel catfish, in an attempt to find cellulase activity. In fact, a few species did have cellulase present in their stomachs, but the conclusion from the research was that the activity was attributed to the natural invertebrates those fish consumed and not an endogenous source of the enzyme. Cultured channel catfish at our laboratory, which had been held indoors and fed prepared feed their entire lives, were found to have a low level of cellulase activity as well, though there was no cellulase activity found in their feed and the activity in the fish could be eliminated by feeding them an antibiotic. The conclusion was that gut flora obtained from consuming insects or some other cellulase-containing organisms that fell into the culture tanks was the source of the enzyme. The fact that antibiotic destroyed the cellulase activity implies that it was from bacterial synthesis and that channel catfish do not violate the conclusion that vertebrates are unable to produce the enzyme cellulase.

Aquatic animal nutritionists have been working on developing diets that employ as much carbohydrate as possible so as to provide protein sparing, but without sacrificing performance. Plants are the source of carbohydrate in aquaculture feeds and also supply protein, as we have seen. The challenge is to develop feeds that provide not only the proper level of protein and energy, but also the proper balance of amino acids. After the lipid, vitamin and mineral requirements are met in the formulation, the remainder of the feed, which is a considerable percentage of the total, is nearly all carbohydrate. That is why aquatic animal feeds tend to contain relatively high levels of plant meals.

Vitamins

The definition of a vitamin is somewhat vague. Classically, a vitamin is an organic compound that is required in small amounts to maintain health and promote normal growth by at least some animal species. More specifically, vitamins take part in biochemical reactions but are not contained in the end products of those reactions. Therefore, vitamins serve as catalysts for chemical reactions. Vitamins also tend to serve as coenzymes in biochemical reactions. Scientists believe that all the vitamins that are required by animals have been chemically identified. Furthermore, each of them can be synthetically produced.

There are two basic kinds of vitamins: those that are water-soluble (vitamins in the B complex and vitamin C) and those that are fat-soluble (vitamins A, D, E and K). There is no uniformity with regard to the chemical structures of any of the vitamins.

As feed pellets sit in water, various nutrients can leach out of them. Included, as one might guess, are water-soluble vitamins and, in particular, vitamin C (ascorbic acid). One hour of submersion of feed pellets in water can lead to loss of that vitamin of the order of 70%. Leaching can be a particular problem in shrimp farming where the pellets may be consumed over periods of several hours.

Animals can show a variety of signs associated with vitamin deficiency (hypovitaminosis) with respect to both water-soluble and fat-soluble vitamins. Signs of excessive levels of vitamins (hypervitaminosis) occur only in conjunction with fat-soluble vitamins. If water-soluble vitamins are fed in excess, they will be excreted in the urine. A few signs of hypovitaminosis and hypervitaminosis in association with fat-soluble vitamins are presented in Table 7.2. Deficiency signs associated with water-soluble vitamins are presented in Table 7.3. Poor growth is a sign associated with all vitamin excesses and deficiencies. Loss of appetite is also a common sign of a vitamin problem. Because those signs are fairly universal, they were not included in the tables. See the book by Halver and Hardy in the 'Additional Reading' section for additional details on this and many other aspects of fish nutrition. The 2011 National Research Council publication on *Nutrient Requirements of Fish and Shrimp* also is a comprehensive reference.

Just because a fish shows one or more of the signs listed in Tables 7.2 and 7.3 should not necessarily lead one to the conclusion that there is a vitamin problem. Pathogens can cause gill and fin haemorrhaging; exophthalmia may be a sign of gas bubble disease or the presence of certain infectious diseases. Changes in blood chemistry can also occur in conjunction with pathogens, as can loss of appetite, and so on. Reduced growth can be caused by any number of factors, including impaired water quality.

Good sources of fat-soluble vitamins are fish oils and meals, some grains and leafy green vegetables. Water-soluble vitamins are found in cereal grains, fresh organ meats, legumes and citrus fruit (rich in vitamin C). Synthetic vitamin premixes are routinely added to fish feed formulations to ensure that the proper level of each vitamin is provided. It is very important to have a vitamin package in nutritionally complete feed. The designation of a nutritionally complete feed refers to one in which a vitamin premix is included, whereas supplemental feeds are often formulated without supplementation of micronutrients.

The potency of vitamins can be expressed in any of four ways: (i) IU, in which vitamin activity is

Table 7.2. Signs associated with excess or insufficient dietary fat-soluble vitamin levels in fishes.

Vitamin	Condition	Signs
A	Hypovitaminosis	Poor vision, night blindness, fin base haemorrhaging, exophthalmia, oedema, retinal degeneration
	Hypervitaminosis	Enlarged liver and spleen, abnormal growth and bone formation
D	Hypovitaminosis	Impaired white skeletal muscle growth, impaired calcium homeostasis
	Hypervitaminosis	Lethargy, dark coloration
E	Hypovitaminosis	Exophthalmia, anaemia, malformed erythrocytes, elevated body water
	Hypervitaminosis	Toxic liver reaction, death
K	Hypovitaminosis	Prolonged blood clotting time, anaemia, haemorrhagic gills and eyes, lipid peroxidation, reduced haematocrit

Table 7.3. Signs associated with deficiencies of water-soluble vitamins in fishes.

Vitamin	Deficiency signs
Thiamin	Loss of equilibrium, lethargy, muscle atrophy, convulsions, oedema
Riboflavin	Opaque eye lens, haemorrhagic eyes, photophobia, dark coloration, poor appetite
Pyridoxine	Nervous disorders, anaemia, flexing of opercles
Pantothenic acid	Clubbed gill filaments, gill exudate, lethargy
Nicotinic acid	Loss of appetite, lesions in the colon, tetany, weakness, oedema of stomach and colon
Folic acid	Lethargy, dark coloration
Biotin	Loss of appetite, lesions in colon, muscle atrophy, skin lesions, convulsions
Cyanocobalamin	Anaemia
Ascorbic acid	Lordosis, scoliosis, impaired collagen formation, haemorrhaging
Inositol	Poor growth, distended stomach, skin lesions
Choline	Haemorrhagic kidneys, enlarged liver, poor food conversion

compared with an international standard controlled by the expert committee on Biological Standardization of the World Health Organization; (ii) US Pharmacopoeia (USP) units, where vitamin activity is compared with standards in the USA (IU and USP units are often identical); (iii) International Chick Units (ICU), where vitamin activity is measured in terms of the response elicited in chickens; and (iv) weight, where vitamin activity is shown as milligrams per kilogram of diet. Most of the vitamin premixes used in aquaculture feed formulations employ weight as the primary measure of vitamin potency, though it is common to see fat-soluble vitamins presented in units of IU or USP.

The comprehensive vitamin requirements of only a few aquaculture animals have been determined in any detail. Good data exist for species that have been commercially produced for several decades including rainbow trout, Atlantic salmon, common carp and channel catfish, for example. There is some information available on tilapia and a modest amount for shrimp. A summary of the available information is provided in Table 7.4. Some of the ranges are very large; in many cases that has to do not only with differences among species, but also differences at various life stages. Undoubtedly, environmental conditions and various other factors (such as the availability of natural food, even when no natural food organisms were supposed to be present) can affect the results of such studies (Box 7.3).

Because some vitamins are degraded by heat, moisture or light, or can be oxidized when exposed to the atmosphere, the apparent requirement for a vitamin can be affected by how a feed is manufactured and stored. Antioxidants commonly added to prepared diets to help protect the vitamins are lecithin (phosphatidylcholine), ethoxyquin, butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), and vitamins C and E. Vitamin C in the form of L-ascorbic acid is such a good antioxidant that it can become depleted in a stored feed very quickly as it is used up to protect other ingredients from oxidation. It is also very heat-labile in the free acid form. Over recent years protected forms of vitamin C that are heat-resistant have been used effectively in aquaculture feeds. Those forms include ascorbic acid sulfate, ascorbyl monophosphate and ascorbyl polyphosphate. To maintain the

Table 7.4. Range of vitamin requirements for a few finfish and shrimp.

Vitamin and units	Range of amount in diet	
	Finfish	Shrimp
A (IU[a])	1000–2000	Not available
D (IU)	500–2400	Not available
E (mg/kg)	30–100	Not available
K (mg/kg)	10	Not available
Thiamin (mg/kg)	1–15	120
Riboflavin (mg/kg)	7–30	22.3
Pyridoxine (mg/kg)	3–20	120
Pantothenic acid (mg/kg)	10–50	Not available
Nicotinic acid (mg/kg)	26–150	Not available
Folic acid (mg/kg)	6–10	Not available
Biotin (mg/kg)	1–1.5	Not available
Cyanocobalamin (mg/kg)	0.015–0.02	Not available
Ascorbic acid (mg/kg)	30–150	100–8000
Inositol (mg/kg)	200–400	200
Choline (mg/kg)	0–8000	600

[a] IU, international unit.

Box 7.3.

One of my (R.R.S.) former graduate students was conducting research on the vitamin requirements of tilapia. In one experiment, the fish grew just fine even though one particular vitamin that we thought was required, pantothenic acid, had been completely left out of the semi-purified diet he was feeding as a control. The culture system he was using was of the recirculating variety and there was some bacterial growth on the walls of the culture tanks. We assumed these bacteria, the source of which was probably the biofilter, were providing the missing vitamin. The experiment was repeated in another laboratory with flow-through water and the same result was obtained. In that case, we observed some algae growing on the walls of the culture tanks, undoubtedly because there were windows in the laboratory allowing sufficient natural light to shine on the tanks to support photosynthesis. The third time was the charm. The experiment was conducted in a flow-through system in a room with no natural light and the requirement for pantothenic acid was finally determined. It is obvious that pantothenic acid would not need to be added to feeds formulated for outdoor culture of tilapia or in many indoor culture systems, such as those in greenhouses. However, as a precaution, we would recommend adding it because the cost of the feed would be minimally increased.

required level of vitamin C in the free acid form of L-ascorbic acid in an extruded feed, the vitamin should be supplemented at about 400% of the requirement, as about 75% of the vitamin will be destroyed by the heat associated with the pelleting process. Alternatively, vitamin C can be added at the requirement level if the vitamin is in the phosphate form, which is one of the forms that is heat-resistant (Box 7.4). Antioxidants are often added to feed formulations to protect some of the ingredients from degradation, or a nutrient may be over-fortified to ensure that it is present at the desired level after the feed mixture is processed.

Minerals

Minerals are inorganic elements required in the body for various structural and/or metabolic purposes.

Box 7.4.

The problem of oxidation of vitamin C was brought home to me (R.R.S.) after one of my graduate students and I developed a series of channel catfish fry diets. As you have seen, it is desirable to change the formulation, along with the feed particle size, in fry and early fingerling feeds to provide the proper levels of dietary protein. We took the results to a feed company that wanted to put those diets on the market, which would have been the first for the industry: typically, trout feed has been used for fry and early catfish fingerlings because it is much higher in protein than standard catfish feeds. That company did not make trout feed and was finding it difficult to convert customers who could obtain both trout and catfish feed from other companies to switch their allegiance from one to the other when they quit feeding trout feed and began feeding catfish pellets. The feed company bought all the ingredients that would be needed, including a vitamin mixture that contained a high level of vitamin C. The ingredients were stored for several weeks prior to the time they would be needed, so the feed had not been manufactured when the problem arose. During the storage period in a warehouse, vitamin C began to oxidize, which heated up the vitamin package and started a fire that nearly destroyed the building. As a result, the catfish fry formulas that we developed have, to my knowledge, never been used by the commercial industry.

As we have seen, marine organisms live in an environment where minerals are plentiful, and in fact excessive amounts need to be continuously eliminated from the bodies of the animals through osmoregulation. As a consequence, feeds manufactured for use with marine animals do not need to contain added minerals but typically do (especially for euryhaline species reared in freshwater, or low-salinity water systems). Freshwater species also may obtain some minerals from the water that contribute to meeting their metabolic needs; however, their diets are supplemented with the proper level of various minerals to meet their requirements for proper tissue development and to support various life processes. Minerals serve a diverse number of functions in the body as components of skeletal tissue and as participants in various physiological processes including respiration, digestion and osmoregulation. Minerals also serve as cofactors when they are a component of protein molecules.

There are seven major minerals and at least nine minor or trace minerals that are required by animals for proper nutrition. The major minerals are:

- calcium;
- chlorine (as chloride ion);
- magnesium;
- phosphorus;
- potassium;
- sulfur; and
- sodium.

As much as 80% of the inorganic material in the ash component of a finfish is contributed by the seven major minerals (about 10% of the dry weight of a fish comprises inorganic material).

The trace elements include:

- cobalt;
- copper;
- fluorine;
- iodine;
- iron;
- manganese;
- molybdenum;
- selenium; and
- zinc.

They are called trace elements because they are required in very small amounts to serve their biological function. If present in excess, they can be toxic. Selenium is particularly toxic but is still required in minute amounts. Copper is a required element for haemocyanin, the chemical in the blood that transports oxygen to the tissues in invertebrates. Haemocyanin in invertebrates serves the same role as the iron-based haemoglobin found in vertebrate blood. The copper requirement for fish is low, perhaps a few milligrams per kilogram of diet, whereas the quantified requirement in shrimp is at least an order of magnitude higher.

As we saw in conjunction with vitamins, the mineral requirements of only a few aquaculture species are known with any degree of detail. Standard mineral premixes based on rainbow trout requirements are commonly used in conjunction with species for which detailed mineral requirement information is not available. The same is true of vitamin premixes, in fact. Mineral as well as vitamin premixes that work well in rainbow trout feed seem to perform well when used in feed manufactured for various other species of finfishes as well. The known mineral requirements of several species are presented in Table 7.5. It is obvious that the most complete data sets are available for rainbow trout (*O. mykiss*), channel catfish (*I. punctatus*) and common carp (*C. carpio*).

Summary

This chapter provided a brief overview of aquaculture nutrition, focusing on finfish and shrimp nutrition. We began with a look at dietary energy that can be contributed by protein, fat and soluble carbohydrate and how maintenance of the proper protein:energy ratio in the diet is required for efficient utilization. Because the desire of the culturist is to use as much dietary protein as possible to produce new flesh in the culture species and not have it burned in support of routine metabolic processes, as much dietary energy as possible that can be used for metabolism should come from carbohydrates and fats.

Proteins are composed of about 20 amino acids, ten of which must be obtained from the diet as they cannot be synthesized by the animals. These are called indispensable or essential amino acids. Different species have somewhat different protein requirements, and the higher the protein requirement, the higher is the price of the feed, because protein often represents the highest-cost component in a finished feed.

Carbohydrates may be individual simple sugars (monosaccharides), pairs of sugars (disaccharides) or larger combinations of sugars in the same molecule (polysaccharides). The latter are such things as starches and cellulose. Many aquatic species,

Table 7.5. Estimated mineral requirements of representative aquaculture species.

Mineral	Species	Recommended level (mg/1000 g diet)[a]
Calcium	Kuruma shrimp	1.0–2.0[a]
	Pacific white shrimp	Dispensable
	Blue tilapia	0.17–0.7[a]
	Channel catfish	0.45–1.5[a]
	Common carp	Dispensable
	Rainbow trout	Dispensable
	Red sea bream	Dispensable
Chloride	Rainbow trout	Dispensable
	Red drum	2.0[a]
Copper	Channel catfish	1.5–5
	Common carp	3
	Rainbow trout	3–3.5
	Pacific white shrimp	32
Iodine	Chinook salmon	0.6–1.1
Iron	Channel catfish	30
	Common carp	199
	Red sea bream	150–199
Magnesium	Kuruma shrimp	0.3[a]
	Blue tilapia	0.023[a]
	Channel catfish	0.04[a]
	Common carp	0.06[a]
	Mozambique tilapia	Dispensable
	Nile tilapia	0.059–0.077[a]
	Rainbow trout	0.05–0.07[a]
	Red sea bream	Dispensable
Manganese	Channel catfish	2.4
	Common carp	12–13
	Mozambique tilapia	0.17
	Rainbow trout	12–13
Phosphorus	Kuruma shrimp	1.0–2.0[a]
	Pacific white shrimp	≤0.34–2.0[a]
	Atlantic salmon	0.6[a]
	Blue tilapia	0.50[a]
	Channel catfish	0.33–0.80[a]
	Common carp	0.6–0.7[a]
	Hybrid striped bass	0.5[a]
	Rainbow trout	0.7–0.8[a]
	Red drum	0.86[a]
	Red sea bream	0.68[a]
Potassium	Kuruma shrimp	0.9–1.0[a]
	Red sea bream	Dispensable
	Channel catfish	0.26[a]
	Chinook salmon	0.6–1.2[a]
Selenium	Channel catfish	0.25
	Rainbow trout	0.07–0.38
Zinc	Blue tilapia	20
	Channel catfish	20–150
	Common carp	15–30
	Nile tilapia	30
	Rainbow trout	15–80
	Red drum	20

[a]denotes levels of g/100g

especially those that are naturally carnivorous, do not tolerate monosaccharides well, so feeds usually have carbohydrates that are starch-based. Various cereal grains provide protein and carbohydrates, as well as some lipid.

Many aquatic animals require *n*-3 (sometimes known as ω3) family fatty acids more than those of the *n*-6 (ω6) family. HUFAs are of particular importance for many species of both finfish and invertebrates. That is certainly true for the marine species that have been studied, as well as for salmonids. Some freshwater species appear to more equally require both *n*-3 and *n*-6 family fatty acids. The level of dietary lipid required varies greatly by species. Some require very little dietary lipid, while others grow well on high levels. The medical community is urging people to eat more fish because of data that seem to be increasingly coming to the same conclusions relative to the link between consumption of diets containing fats that are high in *n*-3 fatty acids and reduction in the incidence of various human health problems. What the consumer is not always aware of is that there is a significant range in *n*-3 from one species to another, with salmon being perhaps the best widely available source of that family of fatty acids, most of which are in the form of HUFAs.

Complete aquaculture feeds normally contain vitamin and mineral premixes to enhance the background levels of those two groups of micronutrients that may be contributed by the other feed ingredients.

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8 Prepared Feeds

Introduction

Economic analyses of modern aquaculture facilities that intensively rear organisms and use prepared feed as the primary source of nutrition for the animals being raised often conclude that approximately 50% of the variable costs associated with their operations are expended on feed. That is even true when at least some fertilizer is used to provide live food during the rearing of early life stages. Feed costs are irrelevant when fertilization is the sole approach to feeding, as is often the case in subsistence culture operations, particularly in developing nations. Similarly, the cost of food is less significant when live food (algae and/or zooplankton) is provided during the hatchery stage of culturing molluscs and echinoderms. After this stage, in cases where the juveniles are placed in the environment for growout, they filter-feed or graze on available organisms.

Prepared feeds are sometimes called artificial feeds meaning they are produced by humans rather than naturally occurring. They are produced almost entirely, if not exclusively, from natural or processed ingredients. Terms such as prepared feed and manufactured feed are preferred. Use of the term feed is preferred over diet because diet is defined as the sum of food consumed and could include natural food items. Of course, feed may also be used as a verb in referring to the act of providing nutrients to the organism. In this chapter and throughout this book, the term prepared feed is used.

The rationale for using prepared feed is rather simple. Assuming that research has been conducted to provide the information needed for the preparation of nutritionally complete feed (Boxes 8.1 and 8.2), the aquaculturist can anticipate good performance from the animals being cultured, unless water quality, disease or some other unforeseen problem intervenes. When performance is poor or fish begin to die, the feed is often blamed for the problem. While there are situations wherein feed is indeed improperly formulated or even contains a substance that is lethal (often due to improper storage), those are rare given the massive amounts of feed that are used in the production of various species in aquaculture.

If there is a feed mill that makes aquatic animal feeds located fairly near your aquaculture operation, and – better yet – is a mill that makes a proven feed specifically designed for the species that you are rearing, then buying from that mill makes eminent sense. It is possible to ship feed long distances, of course, but transportation expenses can significantly increase the percentage of variable costs associated with operating the facility. For some species, the nutritional requirements are relatively similar, so a feed developed for one species might work well on another. For example, rainbow trout (*Oncorhynchus mykiss*) feed will meet the nutritional requirements of a variety of other finfish species. If, for example, an aquaculturist is rearing tilapia (*Oreochromis* spp.) or channel catfish (*Ictalurus punctatus*), trout feed can be used because it contains levels of some ingredients that not only meet but exceed the requirements of the non-target species. Traditional trout feeds have contained significant levels of animal protein, usually in the form of fishmeal. However, researchers have developed formulations in recent years that contain little or no fishmeal, but still produce good growth and other performance characteristics. Feeds with reduced levels or no fishmeal in them have also been developed for tilapia and channel catfish. Culturists can save a good deal in feed costs by feeding formulations that contain little or no fishmeal, but it is important to note that the alternative feeds should meet the nutritional requirements of the species under culture and not negatively impact their performance to any significant degree.

DOI: 10.1079/9781800621145.0008

Box 8.1.

Examples of alternative protein feedstuffs instead of fishmeal that have been evaluated for use or incorporated in aquaculture feeds:

Alfalfa meal (potential ingredient for rotifer feed)
Algae (*Macrocystis pyrifera*, *Scenedesmus almeriensis*, *Spirulina* spp.) and others
Almond meal
Berseem clover (*Trifolium alexandrinum*)
Black soldier fly larvae
Black soldier fly prepupae
Black soldier fly pupae
Blood meal and rumen contents
Brewer's dried yeast
Camelina (false flax) meal (*Camelina sativa*)
Canola meal (rapeseed)
Canola protein concentrate
Caraway seed meal
Carob tree seed germ meal (*Ceratonia siliqua*)
Cassava flour
Chaya leaf (*Cnidoscolus chayamansa*)
Chicken egg concentrate
Cinnamaldehyde (cinnamon tree bark extract)
Coffee pulp
Common caridina meal (*Caridina nilotica*)
Common Indian weed leaf
Corn (maize) meal
Corn (maize) germ meal
Corn (maize) gluten feed
Corn (maize) gluten meal
Crab meal
Date pits
Defatted microalgae protein
Distillers' dried grains and solubles
Dried poultry waste
Egg-waste protein
Ethanol yeast
Expeller pressed soybean meal
Faba bean protein concentrate
Fermented fish silage
Fermented shrimp shell waste
Fishmeal analogue meal
Goat blood meal
Grain distillers' dried yeast
Groundnut cake
Groundnut meal (*Arachis hypogaea*)
Indian mustard meal (*Brassica juncea*)
Indian mustard protein concentrate
Kikuyu grass
Krill meal (deshelled or whole)
Lupin kernel meal (*Lupinus luteus*)
Lupin meal
Lupin seed meal
Maca (*Lepidium meyenii*)
Macadamia presscake
Meat and bone meal (not recommended due to possible transmission of mad cow disease)
Mealworm meal
Microbial floc meal
Moringa tree (drumstick tree) leaf meal (*Moringa oleifera*)
Pea seed meal
Peanut leaf meal
Pearl lupin meal (*Lupinus mutabilis*)
Pistachio meal
Potato protein concentrate
Poultry feather meal
Poultry by-product meal
Pumpkin kernel cake
Rice bran
Rice protein concentrate
Rubber seed meal, defatted (*Hevea brasiliensis*)
Sea urchin meal
Shrimp shell meal
Silkworm meal (*Bombyx mori*)
Soy curd residue
Soy protein concentrate
Soy protein isolate
Spray-dried blood cell meal
Spray-dried blood plasma meal
Squid by-product
Taro leaves (boiled)
Tomato meal
Tuna by-product meal
Tuna waste
Turkey by-product meal
Variegated grasshopper meal (*Zonocerus variegatus*)
Wheat germ
Wheat middlings
White leadtree (and several other common names) leaf meal (*Leucaena leucocephala*)

As an aside, if you try to develop a new finfish or invertebrate species for culture and it will take prepared feed, trout feed is almost sure to provide all the required nutrients at, near or above those of the targeted species. At least, that used to be the case when trout feed contained at least 40% fishmeal. In recent years, the fishmeal level has been reduced to some degree without negatively impacting growth rate. In fact, well-performing feed formulations are still readily available; these

Box 8.2.

The nutritional requirements of any given species are not the same for all life stages. Post-larvae, fry, fingerlings or juveniles, subadults and adults may all have somewhat different requirements for proteins, energy and other characteristics of their feed. In addition, readily available ingredients that will meet the nutritional requirements of a given stage in the life cycle can vary from location to location – a particular ingredient may not be economically available in one region of the world, but some other ingredient that is locally available at reasonable cost may be an appropriate substitute. Also, feed mills often use a process called least-cost formulation, by which they may substitute one ingredient in a feed for another in each batch depending upon the cost of each ingredient on the day of manufacture. Such substitutions, not only in the individual ingredients, but also in the proportions of each that go into a particular batch of feed, are routinely made, but the goal is always to meet the established nutritional requirements of the animals.

contain little or no fishmeal (substituted for with other protein sources, see Box 8.1) compared with high-fishmeal trout feeds. Some species require protein levels higher than 40% so it is important to determine what research, if any, has been conducted concerning the proper level and source of protein to obtain optimum performance of your species of interest. However, at the initial stages of development of a new species, the objective is to keep the species alive and see if you can get it to grow at a reasonable rate. If fish nutritionists have not determined the optimum protein level for your species of interest, trout feed should, in most cases, be able to meet both those objectives.

In this chapter, we look at the types of prepared feeds that are available, as well as the various manufacturing processes that are used to make these feeds. Feed storage is mentioned again, and some feed ingredients are described. Additives are also discussed. We then look at feeding practices and how feeding rates are established. Some of the topics have been mentioned in passing or even in some detail in other chapters in this book, but repetition of some of the material is important to drive home certain points.

Types of Prepared Feed

Prepared feeds come in various physical shapes, forms and particle sizes depending on several factors including processing equipment and manufacturing procedures. There are also differences with respect to nutritional value, which depends on the targeted nutrient levels and ingredients comprising the formulation. Prepared feeds are used primarily for crustaceans and finfish. Most cultured molluscs spend most of their lives, and in many cases their entire lives, in nature and depend upon natural phytoplankton as food. If they are hatched in captivity, they may be fed cultured phytoplankton for a period of time before being put out in nature, but that period is generally brief, as has been previously discussed. Some very simple algae-based feeds have been developed for molluscs, for example abalone. However, use of prepared feeds for molluscs is not very common currently. Prepared feeds have also been developed for sea urchins such as the North American green urchin (*Strongylocentrotus droebachiensis*). More commonly, for abalone and sea urchins, their preferred algae species are grown in conjunction with the animals or harvested elsewhere and transported to the culture facility to be fed.

Supplemental and complete feeds

One of the most fundamental distinctions in the types of prepared feeds concerns their nutrient density, which will dictate if they can be fed in the absence of natural productivity. If there is a considerable amount of natural productivity in the culture system which the targeted species can access for providing some nutrition, and if the stocking rate is relatively low, then supplemental feeds may be used to augment the nutrition provided by that natural productivity. As such, supplemental feeds usually contain lower protein and energy levels than those designed to meet all nutritional requirements of a given species. Such feeds also may lack supplemental vitamins and minerals, though there will be some of those micronutrients present in the practical feed ingredients used in the supplemental feed formulation. The aquaculturist may provide additional nutrition in the form of a supplemental feed. Supplemental feeds should not be used in intensive culture systems (cages, net pens, raceways, tanks, recirculating systems, etc.) where the cultured species has limited access to natural productivity. An exception may be biofloc systems.

When natural productivity is low or absent, and in virtually all cases where stocking densities are high, complete feeds should be employed. Complete feeds, as the name implies, contain all the nutrients required by the animals at levels sufficient to meet their metabolic and growth needs so they can perform optimally. Complete feeds have been developed for a variety of aquaculture species, each having slightly different nutritional requirements, though closely related species usually have quite similar requirements. It is much more common these days to readily obtain complete feeds as opposed to supplemental feeds regardless of the production intensity of the culture system to which it will be applied.

Particle size

The aquatic medium in which organisms are cultured will readily leach nutrients from prepared feeds unless they have adequate water stability. Thus, providing aquatic organisms with feed particles that are water-stable has been a primary focus of various feed manufacturing techniques developed specifically for aquatic animals. For very small larval and post-larvae animals, several different processing techniques have been developed to produce microparticulate diets with adequate water stability. Of course, smaller feed particles are generally more susceptible to leaching due to the increased surface area. Thus, specialized procedures for making microparticulate diets have been developed and will be discussed later.

Feed manufacturing

For feeding fingerling fish and juvenile shrimp to harvest size, pellets are commonly manufactured either by compression pelleting or extrusion processing. The primary differences between these manufacturing procedures are the machinery used and the physical conditions they are able to achieve. Regardless of the manufacturing procedure, the compilation of feedstuffs and other components in the formulation are finely ground, typically in a hammer mill, prior to being manufactured into pellets. Compression pellet mills use steam to moisten (15–18% moisture) and heat (70–85°C) the feed mixture in a preconditioner before passing it through a pellet die of the appropriate diameter to produce a compressed pellet of the desired size. The feed mixture is fed into the machine from a hopper that has an auger at the bottom of it that pushes the mixture through a die, which is a short cylindrical metal object with a large number of uniform-sized holes drilled through it. The feed enters the die through the centre opening, and pressure forces the material laterally through the holes where the material is put under pressure. Steam may be injected into the pellet mill to heat the feed material and add moisture. Pressure and heat, along with some type of a binding agent that is added as a part of the ingredients in the formula, cause the ground particles to bind tightly together as they move through the die. The length of the holes in the die is of the order of a few centimetres, so residence time is short and there is limited heating of the feed ingredients due to pressure as they are being forced through. Heating does occur in the absence of steam due to friction, but the pellets will not be nearly as hot as when steam is provided. As the spaghetti-like strands of material exit the die, a knife cuts them into pellets of the appropriate length. The pellets are dried, often using forced air. Although some cooking of ingredients and gelatinization of starch occur in the conditioning and pelleting process, a pellet binder is typically included to increase pellet durability. Pressure pellets have a specific gravity greater than 1.0, so they sink when placed in water. The pellets need to be water-stable for sufficiently long to allow the culture animals to consume them (recall that for species that swallow the pellets whole, a minimum of 10 min should be sufficient).

The most common means for producing feed pellets today is by extrusion processing. An extruder is a machine with a long barrel (often 1 m or more in length) that has a single hole through the middle of it that is, in most cases, smaller than the pellet that is produced because many products expand as they exit from the machine. The extruder barrel is typically several centimetres in diameter. The shape of the hole translates into the shape of the product. It may be round, square, star-shaped or any of several other shapes. Pasta and breakfast cereals that are produced through extrusion will give you some idea of the variety in shapes. For aquaculture pellets the hole in the barrel is round and the pellets that come out are spherical.

The mixture of feed ingredients, prepared as described above in the pressure pellet discussion, is pushed through the extruder barrel under much higher pressure than is the case in pressure pelleting. The feed mixture is subjected to higher moisture (~25%) and much higher temperatures (135–175°C) as it passes down the extruder barrel and eventually is expelled out the end of a die (Fig. 8.1). An extruder barrel is also many times longer than the width of a die used for pressure pelleting, so the residence time in the barrel is naturally longer as well. Heating elements can be placed at intervals along the length of the barrel (sometimes with different temperatures at different locations). As the material exits the extruder barrel it is cut into spherical pellets. Extruded pellets, like pressure pellets, typically require drying following production.

If the ingredients have a relatively high level of starch included in them, and if the temperature and pressure are sufficiently high, the starch will expand as the material leaves the extruder barrel and it will trap air in the process. The rapid reduction in pressure when the mixture exits the die results in vaporization of some moisture and gelatinization of starch molecules such that the pellets expand and have reduced density. This produces pellets with a specific gravity of less than 1.0, resulting in floating feed. Less heat and/or pressure can be used to produce sinking extruded pellets, such as those often used for feeding shrimp and other species that will only feed at the bottom. Those may be cut longer than floating pellets.

Single-screw extruders are most used for manufacturing aquatic feeds because they are much less expensive than twin-screw extruders. However, twin-screw extruders have greater adaptability for extruding a variety of feed mixtures including those with high levels of endogenous lipid. After pellets are produced either by compression pelleting or extrusion processing, they are passed through a drier to reduce moisture to typically less than 10% and thus is considered a dry feed as mentioned in the next section. At a moisture level of 10% or less the feed can be stored at ambient temperatures for extended periods, although storage for less than 90 days is typically recommended.

For most species, the pellets used for growing fish to marketable size are usually 3–5 mm in diameter

Fig. 8.1. Several extruders operating at a commercial feed mill.

and approximately 1 cm in length, though there is some variability. For broodfish of large fish species, pellets of sizes other than the standard ones may be appropriate (Fig. 8.2), though even large fish can, in many cases, easily consume standard-size pellets.

Feed moisture

Historically, the three most common types of prepared feeds for aquaculture species have been in the form of moist, semi-moist and dry feeds. Moist feeds were developed and have been used primarily in salmon hatcheries in the USA, and most of those hatcheries have been associated with state and federal enhancement stocking programmes. Moist (sometimes called wet) feeds are produced from the processed carcasses (frames) of commercially captured fish or from the whole bodies of low-value fish to which dry ingredients are added at a relatively

Fig. 8.2. Some large fish require large feed pellets. The pellets shown here were developed for feeding brood Atlantic halibut (*Hippoglossus hippoglossus*) in Norway.

small percentage. Dry ingredients may include fishmeal, soybean meal, ground grains, vitamins, minerals and other items. After mixing, the material still contains a high percentage of water. It can be made into soft pellets by passing the mixture through a meat grinder. These feeds were very palatable to salmon and similar moist feeds have been used with other carnivorous species due to their acceptance by the fish. The large pellet shown in Fig. 8.2 that was developed for feeding adult Atlantic halibut (*Hippoglossus hippoglossus*) is also a moist pellet. The same kinds of feed are widely used in Japan where they are prepared daily to feed such species as red sea bream (*Pagrus major*) in net pens (Fig. 8.3). While it is desirable to use the feed immediately after preparation, as is done in Japan, in some instances such large amounts of moist pellets are produced that much of the feed needs to be stored for a period of time before it is used. Because of their high water content, which can lead to mould contamination, moist pellets that are not going to be used within 1–2 days after manufacture should be frozen to keep them from deteriorating.

Semi-moist pellets have the consistency of ground beef and resemble that product, except that they may be in any number of colours, depending on the ingredients used, and are cut into lengths that are convenient for the target fish species to swallow whole. They contain a high percentage of preservative to retard the development of microorganisms that can cause the feed to become mouldy, so it does not have to be refrigerated. Semi-moist feed pellets are often placed in vacuum-packed plastic bags to further protect them from degradation. Such feeds are expensive to produce, and thus expensive to buy, so their primary use is in conjunction with feeding young animals. To our knowledge they are not currently in use as growout feeds by commercial aquaculture ventures involved with producing human food species because of the prohibitively high cost.

Dry feeds are the most popular and commonly used in the production of various aquatic species. As previously mentioned, dry prepared feeds are manufactured in pellet form, principally by compression pelleting or extrusion processing. While there is some variability as a function of the manner in which the pellets are manufactured, typically the amount of moisture present in dry feed is 10% or less. While moist and semi-moist pellets sink, dry feeds can be made to either sink or float as previously mentioned.

Fig. 8.3. Manually feeding fish in a net pen.

We have already seen that some fishes will consume prepared feeds when they first begin to take food after yolk sac absorption. Examples are rainbow trout (*O. mykiss*), Atlantic salmon (*Salmo salar*), channel catfish (*I. punctatus*) and tilapia (*Oreochromis* spp.). Those species have large eggs compared with most fishes and, therefore, large fry that can accept prepared feed of the proper particle size at first feeding. Smaller fry are often first provided with live food organisms as discussed in Chapter 6 and are weaned to prepared feed when they are large enough to consume the particles.

Traditionally the pellets manufactured by compression pelleting or extrusion were ground into fine particles or sieved into discrete particle sizes to be fed to fry and smaller fish before they were large enough to consume an intact pellet (Fig. 8.4). This diet form is called crumbles and represents particles that are intermediate between finely ground meal (sometimes referred to as mash) and normal-size pellets. After the pellets undergo grinding, they can be sieved to separate out the various sizes that will then be bagged for sale. The idea is to provide the fish with particles that are representative of the entire array of ingredients in the feed. That will not be entirely possible as the very small particles of ground pellets will not necessarily be uniform with respect to their composition; however, they are certainly better than just broadcasting the various raw ingredients instead of pelleting and regrinding the mixture. Presumably, the small fish will eat enough particles of reground pellets to provide them with the suite of nutrients they require. Having natural food available, as in a fertilized pond situation, can help ensure that the animals receive the proper combination of all required nutrients (as described in Chapter 7).

Advancements and refinements in extrusion processing equipment have made it possible to produce intact pellets of less than 0.5 mm diameter that will

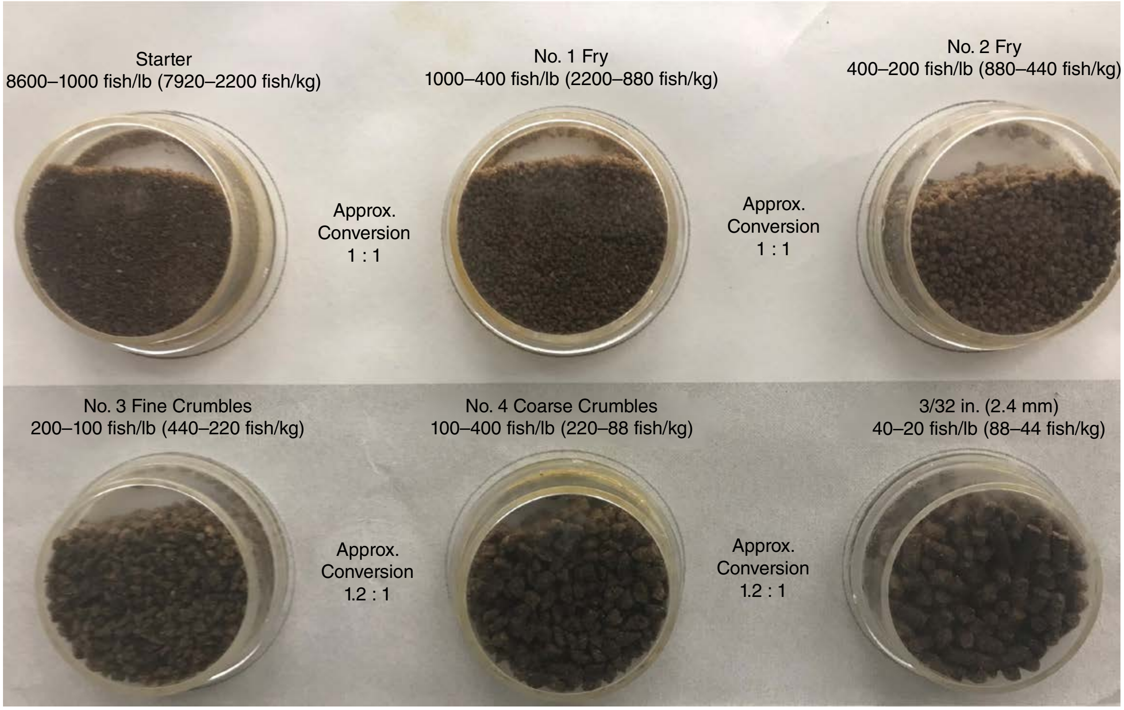

Fig. 8.4. Examples of fry meal and crumbled pellets of different sizes.

float or very slowly sink. Transitioning fry and fingerlings to such feeds early in the production cycle and gradually adjusting pellet size as the fish grow has greatly improved the efficiency of feeding small fish. Once the animals are sufficiently large – actually, once their mouths are large enough to accept it – the feed particle size should be increased. Examples of various pellet sizes are shown in Figs 8.5 and 8.6.

In addition to changing the particle size, the feed formulation may be changed as the animals grow. Fry and early fingerlings usually require higher protein levels to meet their nutritional requirements than is the case with larger fish. Specific feed formulas designed around the size of the fish that will receive them have been developed, such as for channel catfish (*I. punctatus*).

Weaning aquatic animals from live food to prepared feeds may be a relatively simple process, or it may require a considerable amount of time and effort. In most cases, the process begins by providing the prepared feed as particles of a size the young animals can ingest while still providing live food. As time passes, the proportions of live to prepared feed can be gradually changed so the amount of live food is decreased as the amount of prepared feed is increased. Eventually, it should be possible to stop feeding the live food entirely and the weaning process will have been completed successfully. The culturist should closely observe feeding behaviour and may wish to dissect individual animals once in a while to look for feed in the stomach, to ensure that the weaning process is proceeding satisfactorily (this topic was also described in Box 6.11).

Many years ago when we were first trying to develop culture methods for southern and summer flounder (*Paralichthys lethostigma* and *Paralichthys dentatus*, respectively), we collected post-larval flounders with a plankton net and took them into the laboratory. Capturing wild fish was a necessity at the time because the technology for spawning flounders was still under development. We first fed the post-larval flounders brine shrimp nauplii, and then very finely chopped fresh or frozen penaeid shrimp. After that we fed freeze-dried shrimp muscle that was crumbled into suitable-sized particles. Once the fish had been converted from live to

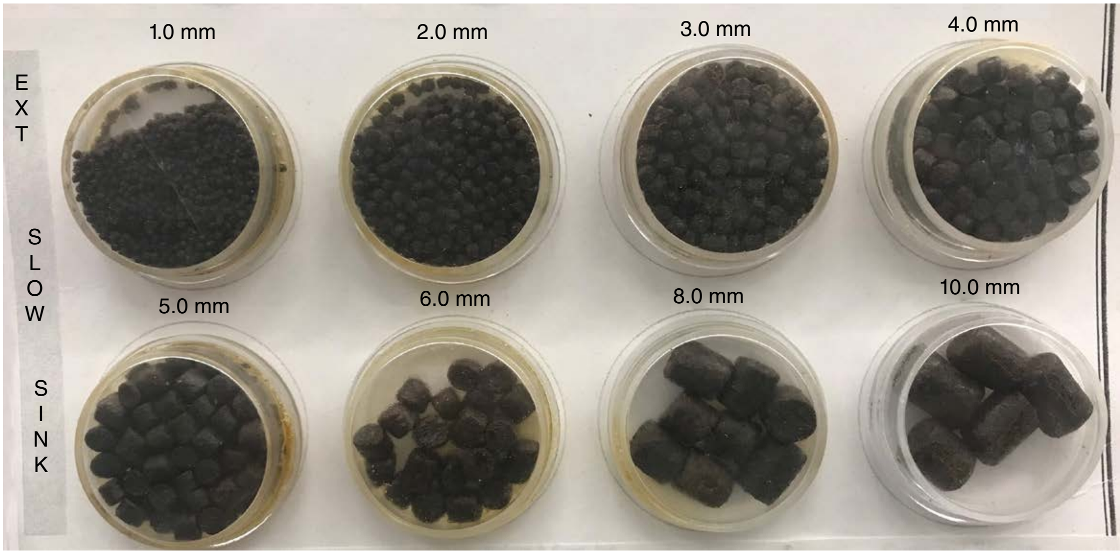

Fig. 8.5. Examples of various manufactured pellets of different sizes.

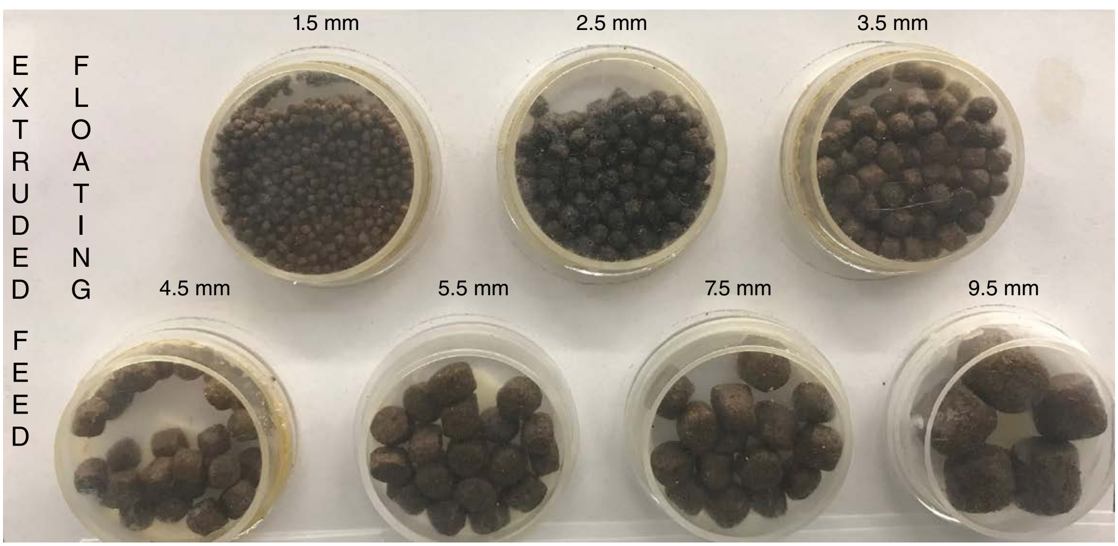

Fig. 8.6. Extruded floating pellets of various sizes.

freeze-dried food, we introduced finely ground dry feed particles and were ultimately able to wean the fish on to only the prepared feed (a trout formula, once again demonstrating the capability of trout feed to support a variety of species). The process took a few weeks and involved a lot of labour. It ultimately proved unnecessary to go through all the steps, as in subsequent research trials we were able to use the technique previously discussed and skipped the shrimp phases of the process. However, during the preliminary stages of trying to learn how to keep the post-larval flounders alive, we did not want to take any more chances than necessary.

The weaning process tends to be similar for most species, though some details will vary. Among the species for which weaning techniques have been developed are cod (*Gadus morhua*), eels (*Anguilla* spp.), milkfish (*Chanos chanos*), sharptooth catfish (*Clarias gariepinus*), sole (*Solea solea*), striped bass (*Morone saxatilis*), striped bass hybrids (*M. saxatilis* × *Morone chrysops*), halibut (*Hippoglossus* spp.) and, of course, southern and summer flounders. The list is much longer, but it should be apparent from the species listed that they are all species that have very small eggs, and thus very small larvae and fry. Shrimp larvae, both marine (penaeids) and freshwater (*Macrobrachium* spp.), also undergo a weaning process to get them off live food and on to pellets.

Let us look in a bit more detail about the development of prepared trout feed, because it has been mentioned as a good first feed for a variety of culture species. It turns out that much of the early work on fish nutrition, which really began in earnest in the 1950s, was focused on trout and salmon. Salmonids require relatively high protein and energy levels in their feeds as you already know (at least in the case of trout, and true for salmon) and also require substantial levels of vitamins and minerals. Any good trout feed seems to work well during the early stages of rearing other species, though the minerals can be eliminated from rations fed to marine species because they obtain their minerals from the water by drinking (the topic of osmoregulation was mentioned in Chapter 4 and is elucidated in Chapter 7). There will certainly be differences among non-salmonid species. Many require less protein than salmonids, while others seem to have higher protein requirements. Some of the flatfishes apparently have protein requirements of more than 50% and that is also true of fish with very high metabolic rates, such as tuna (*Thunnus* spp.). Research using a salmonid feed as a control will often help researchers develop feed formulations that are species-specific, a process that can take several years and remains to be completed for many species currently being successfully reared by commercial aquaculturists. In the meantime, commercial culturists may begin by using a trout diet and then adopt feeds specifically formulated for their particular species as researchers develop new information.

Microparticle feeds

Microparticulate feeds such as microencapsulated feeds (mentioned in Chapter 6) traditionally have not been widely used in aquaculture; however, advancements in feed manufacturing technology have made it possible to produce such feeds for early life stages of various aquatic animals. The microencapsulation process involves dissolving the nutrients in liquid and forming very tiny ball-shaped particles with proteinaceous membranes surrounding the ingredients. The particles can be as small as a few tens of micrometres in diameter. Microencapsulated diets have been used as food for rotifers, molluscs, marine shrimp larvae and some marine finfish species, and they have, for example, been developed for gilthead sea bream (*Sparus aurata*) and other marine fish larvae. Other forms of microparticulate diets include those formed by microbinding, in which the binding agent is dispersed with the feed mixture, and microcoating, in which a coating enrobes the feed particles. All these manufacturing procedures are capable of producing larval feeds ranging from 25 to 400 μm in diameter.

Flake feed is another form commonly used in the ornamental fish industry for feeding tropical fishes. Flakes can also be used to feed young, cultured fish that will ultimately be grown for human consumption, though they are not in widespread use at the present time. To make flake feed, very finely ground feed ingredients are made into a slurry by adding water and mixing thoroughly. The mixture is then passed between two heated rollers of a double-drum dryer that rapidly dries the slurry and forms it into paper-thin sheets. Next, the sheets are broken up into smaller pieces for packaging and sale. Commercial products are usually a mixture of flakes of different colours (pink, red, brown, yellow and green being the most common). The colours are conferred to the flakes by dyes or by natural ingredients that impart colour to the flakes. Feed formulations containing shrimp or krill meal, for example, will result in pink or red flakes while various algae meals produce green flakes (Fig. 8.7). Some fish take up the colours from the feed into their flesh (e.g. salmonids) or on the body surface (e.g. tropical fishes such as guppies, swordtails and many others). The topic of colour as an attractant was discussed in Chapter 6, where you can find some other examples of natural ingredients that add colour to feed.

Purified, semi-purified and practical feeds

Not all aquaculture feeds are equal in terms of their intended uses. Researchers who are trying to determine the nutritional requirements of an aquaculture species

Fig. 8.7. Examples of different diet forms including flakes, extruded pellets and sinking pellets of various sizes.

sometimes formulate feeds that contain exclusively highly purified ingredients. Such ingredients can be manipulated in feeds to alter the primary nutrient of interest without changing the levels of several other nutrients. Such formulations are called chemically defined, or purified, diets or feeds. Once the basic requirements for nutrients are known, a research formulation may contain mostly ingredients that are commonly available as commodities in the marketplace and use a variety of levels of a particular highly refined or purified ingredient to determine the specific requirement for the nutrient(s) contained in that ingredient – for example, an amino acid or fatty acid. Such a feed is called semi-purified. A feed that is entirely based on ingredients used in the manufacture of commercial feeds is called a practical feed.

Purified diets are rarely used in aquaculture research except when the absolute requirement for a specific nutrient is being investigated. The researcher may want to know which amino acids or fatty acids are required and in what amounts. The simple fact is that such diets are extremely expensive to prepare. A purified diet will contain each of its ingredients in a chemically refined form, except for the nutrient that is being investigated in the study. Such diets are typically prepared in rather small quantities with laboratory-scale equipment (Figs 8.8 and 8.9). Let us say the researcher wants to know if a specific high-molecular-weight fatty acid, such as DHA, is required and the level at which the fatty acid should be incorporated into a feed (see Chapter 7 to learn more about fatty acids). To answer these questions, or at least get some information that will begin the process of answering the questions, a series of purified diets should be prepared. In one of these diets, the fatty acid of interest will not be included, but may be replaced by another fatty acid that is not required. Other diets would be prepared that contain DHA at a series of levels, let us say 0.5%, 1.0%, 1.5% and 2.0% of the diet. A truly purified diet would contain a highly refined protein feedstuff or individual amino acids, other lipids in the form of free fatty acids, and soluble carbohydrate in the form of one or more simple sugars, along with a group of vitamins and minerals. A filler of indigestible material, such as cellulose, is added to make up the remainder of the formula. Each diet should be formulated to contain the same amount of energy in the form of caloric content. That is done by manip-

Fig. 8.8. Experimental V-mixer for homogenizing small quantities (up to 3 kg) of dry ingredients.

Fig. 8.9. Laboratory-size food mixer for making experimental diets.

ulating the level of one of the fatty acids that is not required so that the total lipid content of each diet is the same. Such diets will usually produce relatively poor growth because most animals perform better on feeds that contain more complex ingredients than they do on highly purified ingredients. If DHA is required, fish fed the diet lacking that fatty acid should perform even more poorly than fish fed diets containing the fatty acid. As the level of DHA in the diet is increased, fish performance should improve relative to the diet lacking DHA, until the requirement level is reached at let us say 1.0% of dry diet. Higher levels would not lead to increased growth, everything else being equal (protein and energy being the major determinants, so they are maintained as constants in all formulations). So, with the series of diets that were prepared, the researcher can conclude that DHA appears to be required and that it needs to be in the diet at the level of about 1.0% by weight. It could be a bit higher or lower, and to determine that for sure, the researcher would want to run another experiment with diets containing a range around 1.0%, let us say 0.6%, 0.7%, 0.8%, 0.9%, 1.0%, 1.1%, 1.2%, 1.3% and 1.4% DHA. While all that work would allow the researcher to better determine the requirement, there may be a synergistic effect taking place that further complicates the situation. For example, another fatty acid such as EPA may also be required, and the total of DHA and EPA may be more important than the absolute level of each. It looks like another series of very expensive experiments is going to be required to address that issue.

Many researchers have indicated that they used purified diets in their studies but have used semi-purified diets. Such formulations will be designed to look at the requirement for a specific type of ingredient by using that ingredient in purified form while incorporating the other dietary ingredients in a form that is much less expensive than if purified ingredients were used. A few examples of what this means follow.

Evaluation of an amino acid requirement

1. Each diet contains all but one essential amino acid in purified form, except for the control diet, which contains all the essential amino acids.
2. A control diet with a complete protein, such as milk protein (casein), is used.
3. All diets have the same protein and energy levels (i.e. they are isonitrogenous and isocaloric).
4. The carbohydrate may be in the form of starch, for example maize starch.
5. The lipid may be in the form of fish oil, some type of vegetable oil or a combination of the two.
6. A vitamin and mineral package is included.
7. An inert ingredient such as cellulose is used to complete the formulation of all diets.

Evaluation of a carbohydrate requirement

1. A protein source such as casein, which contains no carbohydrate, is used in all formulations.
2. A series of diets containing a variety of carbohydrates at various levels is prepared. Among them may be simple sugars or more complex carbohydrates such as disaccharides or the polysaccharide starch.
3. The lipid may be in the form of fish oil, vegetable oil or a combination of the two.
4. A vitamin and mineral package is added.
5. An inert ingredient such as cellulose is used to complete the formulation of all diets.

Evaluation of a mineral or vitamin requirement

1. A protein source such as casein is used in all formulations due to its low level of most vitamins and minerals.
2. The carbohydrate in all formulations may be in the form of refined starch.
3. The lipid may be in the form of fish oil, vegetable oil or a combination of the two.
4. Vitamin or mineral packages that eliminate one vitamin or mineral in each formulation are used.
5. A control diet containing all the vitamins and minerals that are being evaluated individually is formulated.
6. An inert ingredient such as cellulose is used to complete the formulation of all diets.

Aquatic animal nutritionists often use semi-purified formulations to determine nutritional requirements. In most cases, a practical diet formulation is used as another control in such studies to compare responses of the subject organism and gauge the suitability of the environmental conditions under which the trial was conducted. Typically, the control performs better than the semi-purified diet in such experiments because the ingredients in the control diet may be more palatable and/or the nutrients they contain may be better absorbed than those in the semi-purified diets.

Commercial or practical feeds are those formulated with readily available commodity feedstuffs, many of which are locally available and may be found in the marketplace in most locations around the world, or if they are not locally available, have been imported specifically for use in aquaculture (and perhaps in terrestrial livestock) feeds. Use of imported commodities can add significantly to the cost of feed. Also, humans and terrestrial livestock often take precedence over aquatic animals when it comes to utilizing imported feedstuffs, so there is often a good deal of effort made to find alternative feedstuffs to those that have proved to be very effective if the more commonly used commodity is not available.

Feed Ingredients and Additives

Most of the feedstuffs included in aquatic feeds are by-products from the processing of plant and animal products for human consumption. Most of these ingredients have limited levels of nutrients, and in some cases may also contain anti-nutritional factors which may limit their inclusion. However, by combining a complementary blend of feedstuffs in the feed formulation, the nutritional requirements of the targeted species can be met. Most of the feedstuffs included in fish feeds are either protein supplements, which are defined as containing more than 20% crude protein, or energy feedstuffs containing less than 20% crude protein but less than 18% crude fibre. The most common sources of protein in aquaculture feeds are fishmeal derived from various species, a few terrestrial animal by-products such as meat and bone meal and poultry by-product meal, and a significant number of plant meals, concentrates and so forth (Box 8.1). Many of the aquaculture species being reared today are carnivores that appear to require at least some animal protein in their diet. Fishmeal is the most common source of animal protein in aquaculture feeds because it contains all the required amino acids in sufficient quantities to meet the nutritional requirements of both carnivorous finfish and crustaceans. Plant-protein feedstuffs tend to be less protein-dense and may be deficient in one or more of the amino acids (see Chapter 7 for more detail on proteins and amino acids). Herbivorous species and some omnivores can perform very well on feeds devoid of animal protein or containing only minute amounts – tilapia (*Oreochromis* spp.) and channel catfish (*I. punctatus*) are examples – but many species still are being fed feeds containing animal proteins at some level or supplemented with ingredients high in the deficient amino acids or with purified amino acids to meet their requirements.

The most common fishmeals are obtained from such fishes as anchovies (*Engraulis* spp. and *Anchoa* spp.), and particularly Peruvian anchoveta (*Engraulis ringens*), sardines (various genera), menhaden (*Brevoortia* spp.), capelin (*Mallotus villosus*), sand eel (*Hyperoplus* spp.), pollock (*Pollachius* spp.) and herring (*Clupea* spp.). The world's largest fishery for fish used for fishmeal is the Peruvian anchoveta fishery off the coast of the country for which it is named. The meal produced from that fishery is typically one-quarter of annual global fishmeal production and is used around the world in livestock and aquaculture feeds. Because the fishery declines significantly in El Niño years, and much of the world's fishmeal supply comes from that fishery, the price of fishmeal in the marketplace can fluctuate significantly during periods when the Peruvian fishery fails. Because of that and the fact that fishmeal is one of the most expensive ingredients in aquaculture feeds, other sources of protein that will work as well or nearly as well as fishmeal have been sought. Particularly over the past two decades, efforts have intensified to find suitable alternatives to fishmeal because its prices have continued to increase with greater demand exerted from the expanding global aquaculture sector.

Opponents of aquaculture – or more correctly, those who oppose the use of fishmeal in aquaculture feeds – indicate that feeding fish to fish makes no ecological sense and that other users need the fishmeal more than aquaculturists. It is true that current use of fishmeal by aquaculture amounts to a significant percentage of the annual global supply; it is increasingly being replaced by other protein sources, including fish processing waste, which might be considered an ecologically sound way of recycling material. Let us see who those 'other users' are. Currently, another significant amount of annual fishmeal production goes into terrestrial livestock and poultry (primarily chicken) feeds. It should be noted that chickens do fine, thank you very much, on feeds containing no animal protein, and in the USA, all-plant-protein feeds for chickens are the rule, not the exception. Much of the fishmeal used in poultry feed is fed in developing countries where maize, which is a major ingredient in US poultry feed, is not available, at least in the quantities required. The remainder of the world's fishmeal supply is used for fur animal and cat foods. With respect to aquaculture species, by far the most fishmeal goes into carp, with catfish, tilapia and milkfish following in that order. Since little or no fishmeal is used in channel catfish feeds in the USA, the majority of that used for catfish involves other such species as walking catfish (*Clarias* spp.) and catfish in other families than Ictaluridae, for example basa (*Pangasius bocourti*). Carp, non-ictalurid catfishes, tilapia and milkfish are primarily produced in developing nations, and although the inclusion percentage in the feeds of these species is relatively small, the vast quantities of these fish species produced accounts for a large percentage of the fishmeal used with respect to aquaculture. By the way, the same four groups of species also account for most of the fish oil used in aquaculture. Fish oil is another commodity for which there is a limited supply and strong competition among buyers who use it for various purposes.

Some alternative animal-protein feedstuffs that have worked well are meat and bone meal (from cattle or swine) and poultry by-product meal (primarily from the chicken industry). Meat and bone meal is an excellent protein source for at least some species (Box 8.3), but because of mad cow disease in some parts of the world, the use of meat and bone meal in fish feeds or any other type of livestock feed is now often limited or prohibited. Feather meal (from poultry feathers) was evaluated

Box 8.3.

Several years ago, a feed company asked me (R.R.S.) to conduct a feeding trial with channel catfish using fishmeal in one feed and meat and bone meal (made from the leftovers after cattle are butchered) in another. Aside from the animal-protein source, the two feeds had the same formulation. At the end of the trial in which the fish were stocked as fingerlings and grown to market size (about 450 g), the average size at harvest and the rate at which they converted feed into flesh were identical for fish on the two feeds. I later had an opportunity to develop some feeds in China to determine if meat and bone meal would work well with such species as tilapia in that nation. I never did see the results of those feeding trials as the Tiananmen Square protests in 1989 prevented me from returning to obtain the data. It was years later that the threat of passing mad cow disease to humans through feeding aquaculture species became a concern. Thus, the use of meat and bone meal from cattle has largely shifted to products rendered from swine.

during the 1960s as a protein ingredient in channel catfish feed, but its nutritional value was seen as being poor. However, that ingredient has found increasing use in recent years in fish feeds, perhaps due to changes in processing, including better hydrolysis procedures.

Among the common plant-protein feedstuffs in fish feeds are soybean meal, canola meal, distillers' dried grains with solubles from corn processing, and cottonseed meal. Wheat, maize and various other grains have also been extensively employed. Rice bran is commonly fed in tropical nations, either directly by spreading it over pond surfaces or as an ingredient in pelleted feeds. Its nutritional value is low, though it may have value in supplemental feeds. It is still widely used in countries where rice is grown as it is readily available and not costly.

Because the cost of protein often represents the highest cost among the ingredients in an aquaculture feed, and because many of the most desirable forms of plant protein that work well in aquaculture feeds are not locally available in developing nations, aquaculturists have looked at a wide variety of alternatives to the protein sources mentioned thus far. A partial list of alternative proteins that have been evaluated in aquaculture feeds is presented in Box 8.1. More information on the use of alternative proteins in aquaculture feeds can be found in the book by Lim *et al.* listed in the 'Additional Reading' section of this chapter.

Protein sources are not devoid of other nutrients. They typically contain some level of lipid (fat), a significant level of carbohydrate in the case of plant proteins, and various levels of vitamins and minerals.

Because mixtures of fishmeal and plant-protein sources are deficient in certain nutrients, it is common practice to add various additional nutrients to feed formulations. Lipids of various kinds are often added, sometimes at very high levels (lipid levels of 35% or more have been used in Norway for feeding Atlantic salmon, *S. salar*). Vegetable oils are commonly employed, though many species do not perform as well on these types of fats as they do on fish oil (see Chapter 7). During my (R.R.S.) PhD research, I found that beef tallow and fish oil outperformed corn (maize) oil in channel catfish (*I. punctatus*) feeds. That was a strange result because beef tallow has very low levels of the highly unsaturated fatty acids required by many fish species. I have never gone back to repeat that study, but the issue certainly deserves more investigation. Some of the common lipid supplements used in aquaculture feeds are presented in Box 8.4.

Carbohydrate is the other energy-yielding nutrient contributed in prepared feeds primarily in the form of the complex polysaccharide starch, which is abundant in a variety of cereal grains such as maize and wheat as well as tubers like potatoes and cassava. Starch not only may be digested to provide metabolic energy but also imparts binding properties when gelatinized in extrusion-processed pellets. Fibrous carbohydrate such as cellulose is typically restricted in aquatic feeds due to lack of digestibility by aquatic animals.

Supplemental vitamins and minerals are also added to complete aquaculture feeds. These nutrients may be contributed by practical feedstuffs but are also added as premixes to ensure adequacy. Vitamin premixes commonly include both fat-soluble and water-soluble vitamins. Phosphorus is the primary macromineral supplemented in aquatic feeds while various trace minerals are included in premix form.

Several other items may be added to prepared feed formulations. Often important among them is some type of binder to help retard dissolution of feed pellets when the feed is put in the water. As a

Box 8.4.

Some lipids that have been evaluated and/or are being used to replace or partially replace fish oil in aquaculture feed formulations:

- Algal oil
- Camelina oil
- Corn (maize) oil
- Canola oil
- Crude palm oil
- Flaxseed oil
- Grape seed oil
- Linseed oil
- Oregano oil
- Palm oil
- Palm oil distillate
- Peanut oil
- Poultry oil
- *Schizochytrium limacinum* (heterotroph thraustochytrid)
- Soybean oil
- Sunflower seed oil
- Tallow
- Vegetable oil

Box 8.5.

The mouth size of a shrimp is never large enough to consume a pellet, but because shrimp feed very slowly – one small particle chewed off a pellet at a time – the same size pellet can be used throughout their growout period. Pellets used for shrimp feed need to contain a significant level of binder, so they do not quickly fall apart when put in the water. They need to stay largely intact for up to several hours. Because shrimp feed so slowly, pellets also need to be overfortified with some nutrients, such as water-soluble vitamins, that will leach out of them over time. Finally, there is the probability that because feed pellets may be in the water for hours before they are fully consumed, colonization by microflora may be a source of additional nutrition for shrimp.

rule of thumb, a feed pellet should remain intact in water for at least 10 min to provide the animals with an opportunity to find and eat the feed. As shown in Box 8.5, shrimp feed slowly by removing small pieces from feed pellets. Therefore, shrimp feed needs to remain intact for several hours, not just a few minutes. That means shrimp feeds need to be heavily fortified with a suitable binder.

Even if a feed only remains intact for several minutes and the pellets have not dissolved, some water-soluble nutrients may leach from them. Water-soluble vitamins can quickly leach from feed pellets (see Chapter 7 for details on which vitamins are water-soluble). Wheat, which is not a terribly good source of nutrition for aquatic animals, does make a good binder as mentioned above and is sometimes used in feeds primarily for that purpose. Some other materials that have been used as binders in semi-purified and practical diets are agar, alginate, carboxymethylcellulose, gelatine and guar gum. In most cases, binders are a form of starch, though that is not always the case.

If the culture species is reluctant to accept a prepared feed, the situation can sometimes be remedied by incorporating some type of attractant into the pellets. That may involve a small amount of an ingredient such as shrimp meal, krill meal, fish oil or some other supplement that imparts an odour that is attractive to the culture species. Incidentally, one of the benefits of fishmeal in aquaculture feeds is that it can serve as an attractant. Extracts from a variety of sources have also been used, as have certain amino acids. The amino acids alanine, aspartic acid, glutamic acid, glycine, histidine, lysine, proline and serine have all been shown to attract certain aquatic species, as have a number of other chemicals including nucleotides such as inosine monophosphate.

Chemicals such as carotenoids (examples are astacene, astaxanthin, canthaxanthin, xanthophyll and zeaxanthin) have been used to impart colour to the flesh or integument of fish. For example, to make trout appear more like salmon, some producers have added carotenoids to give a pink colour to the flesh. Carotenoids have also been added to sea urchin feeds to impart colour to the gonads. Sources of carotenoids include many crustaceans and algae. Carotenoids not only provide colour to species that can utilize those chemicals in that role; they have also been shown to enhance egg and juvenile production in sea urchins.

As we have seen, good management of the culture system can help reduce stress and disease. Certain substances in the feed may stimulate the immune system of fish and help them avoid disease epizootics. Some immunostimulants that have been evaluated with respect to aquacultured fishes are vitamins C and E, β-1,3-glucan, nucleotides and levamisole. Bakers' yeast, *Saccharomyces cerevisiae*, which is a rich source of β-1,3-glucans and nucleotides, has been shown to have growth-promoting and immunity-promoting effects in several finfish when added as a dietary supplement.

Probiotics and prebiotics were discussed in Chapter 5 in conjunction with their role in disease prevention and enhancing immunity to diseases. Probiotics and prebiotics can also enhance performance in other ways by influencing the microbiota of the gastrointestinal tract. The beneficial bacteria used as probiotics can help control and compete with detrimental bacteria in the intestinal tract. They may also improve growth rates, possibly by making nutrients that are indigestible by the host animal available for absorption. Improved food conversion efficiencies have also been observed when probiotics were used. Probiotics can be administered by incorporating them into dry feed or by rearing live food organisms in a medium to which probiotics have been added. The live food organisms become enriched with the probiotic. Probiotic bacteria have also been effective at reducing pathogenic bacteria after being applied to ponds, and they can improve water quality by reducing the biochemical and chemical oxygen demands and by breaking down complex organic compounds in the pond environment. A list of several aquaculture species on which the effects of probiotics have been evaluated is presented in Table 8.1. Several reviews concerning probiotic and prebiotics have been published in recent years. Some are included in the list of additional reading.

Table 8.1. Some invertebrate and finfish aquaculture species that have been evaluated to determine the benefits that can be obtained through the use of probiotics. Includes enhanced live food organisms.

Common name	Scientific name
Invertebrates	
Rotifer	*Brachionus plicatilis*
Black tiger shrimp	*Penaeus monodon*
Pacific white shrimp	*Litopenaeus vannamei*
Finfish	
Atlantic salmon	*Salmo salar*
Ayu	*Plecoglossus altivelis*
Catla	*Catla catla*
European sea bass	*Dicentrarchus labrax*
Olive flounder	*Paralichthys olivaceus*
Rainbow trout	*Oncorhynchus mykiss*
Red drum	*Sciaenops ocellatus*
Turbot	*Scophthalmus maximus*

While many people currently monitor their cholesterol levels and attempt to keep them as low as possible through controlling their diets and in many cases taking medications, at least some species of cultured invertebrates require cholesterol in their diet. Research on various shrimp species, for example, has shown that they have a dietary sterol requirement that can generally be met by including 0.5 to 1% dietary cholesterol. Crustacean species also require dietary lecithin, also known as phosphatidylcholine, a phospholipid which interacts with cholesterol metabolism. Other research led to the conclusion that a combination of dietary plant sterols is as effective as cholesterol in meeting the 0.6% requirement for total sterols in juvenile Malaysian giant freshwater shrimp (*Macrobrachium rosenbergii*). Shrimp are not the only invertebrates known to have a cholesterol or lecithin requirement. Larval mud crabs (*Scylla serrata*) require dietary cholesterol at a level of something less than 1% for proper development and metamorphosis into juveniles. Thus, unlike fish, crustaceans must have a dietary supply of cholesterol and phospholipid in their diet due to limited ability to synthesize those compounds.

The role of dietary lecithin to satisfy the sterol requirement of at least some species of shrimp is not the only benefit that can be obtained from that compound. Dietary lecithin has been shown to improve survival of both shrimp and finfish larvae and the growth of juveniles. There are also indications that dietary lecithin increases stress resistance and food conversion efficiency. It may also serve as an attractant in feed as well as an emulsifying agent and antioxidant.

Feed Formulation

Commercial prepared feeds are manufactured in feed mills from a variety of commodity feedstuffs. While some fixed formulations of aquaculture feeds are used – those are formulations that remain constant from one batch to another – it is common practice to allow substitutions, particularly in the case of certain plant-based ingredients, to accommodate changes in the cost of those ingredients. For example, it may be less expensive to use cottonseed meal as an ingredient one day and groundnut meal another day as the market price fluctuates. This is known as least-cost formulation. It is important that an ingredient used as a substitute still provides the proper characteristics so that the final product will meet the nutritional requirements of the species that will be consuming the feed. Mill operators and nutritionists can develop computer spreadsheets that will automatically evaluate which ingredients can be used and the amounts to be included in each formulation to maintain the desired levels of energy, amino acids, fatty acids, vitamin, minerals, appearance (colour) and, if necessary, odour of the finished feed.

The various feedstuffs arriving at the feed mill may or may not have received some pre-processing before delivery. Fishmeal arrives at feed mills in a processed form. After the fish used for fishmeal have been received at a fishmeal plant, all but a very small fraction of the oil is removed through either pressing or solvent extraction and the remainder is dried and ground into meal. Many aquaculture feeds call for fish oil as well as fishmeal, so both products are often shipped from the fishmeal plants to feed mills.

Cotton is sent to cotton gins where the seeds are removed and may be ground into meal and extracted with solvent before being shipped to the feed mill. Soybeans may have the oil removed at a soybean processing plant, after which they are ground into meal before being sent to the feed mill, though full-fat soybeans have sometimes found their way into aquaculture feeds, in which case they might be ground at the mill instead of being shipped as full-fat soybean meal. Wheat is processed into several fractions, some of which (e.g. wheat middlings and wheat germ) are often found in aquatic animal feeds. Rice bran, as previously mentioned, is often used in feeds in developing countries. That ingredient may be used as a supplemental feed by just adding it directly to ponds, or it can be incorporated into manufactured feed.

As demonstrated in Box 8.1, there is a wide variety of alternative protein feedstuffs that can find their way into aquaculture feeds. Many of those are locally available and are not being shipped internationally. Soybeans, corn (maize) and wheat are examples of commodities that are commonly shipped internationally, though they may not find extensive use in aquaculture feeds in developing countries because their primary use is often directly for human consumption or in products manufactured for human consumption. While local fishmeal is often used in aquatic animal feeds in developing countries, its quality can sometimes be relatively poor, so it is not as expensive as the higher-quality fishmeals such as those obtained from Peruvian anchoveta (*E. ringens*) and menhaden (*Brevoortia* spp.).

Feed mills generally purchase vitamin and mineral premixes to supplement the levels that occur naturally in the various commodities used in a feed formula. The added vitamins and minerals usually comprise no more than about 1–2% of the total diet (less if a mineral supplement is not included in the formula). Lipid may be mixed into the diet prior to pelleting and/or it can be sprayed on after the pellets have been manufactured. Up to about 5% lipid can be added by spraying it on the feed pellets after manufacture. When large amounts of lipid are added, it may be necessary to both add it to the mixture prior to pelleting and spray additional lipid on the pellets after they have been dried. Vacuum infusion is often used to incorporate a high percentage of lipid in salmonid feeds. This process involves exposing the extruded pellets shortly after manufacture to oil under a vacuum. Once the vacuum is released, it allows the high levels of lipid to be infused inside the porous extruded pellet.

Prior to pelleting, any ingredients that did not arrive already ground are subjected to a grinding process, then all the ingredients (except for lipid that is to be sprayed on after pelleting) are placed in large mixers where they are blended. They can then be made into pellets by passing them through either a pressure pellet mill or an extruder (an example of which is shown in Fig. 8.1). Figure 8.10 shows a feed mixer along with a small pellet mill labelled with the location of some of the components. Alternatively, microencapsulated, flake, moist and semi-moist feeds can be manufactured as previously described.

They are then either bagged, usually in paper bags that each contain about 23 kg (Fig. 8.11), or they can be hauled in bulk for delivery to feed bins (Fig. 8.12).

Storage and Presentation

Bags of prepared feed need to be stored in a cool, dry place, particularly if the feed is not going to be used within several days or a few weeks after purchase. The problem associated with mould formation in improperly stored feed has been mentioned previously. There are also potential problems associated with insects such as weevils getting into the

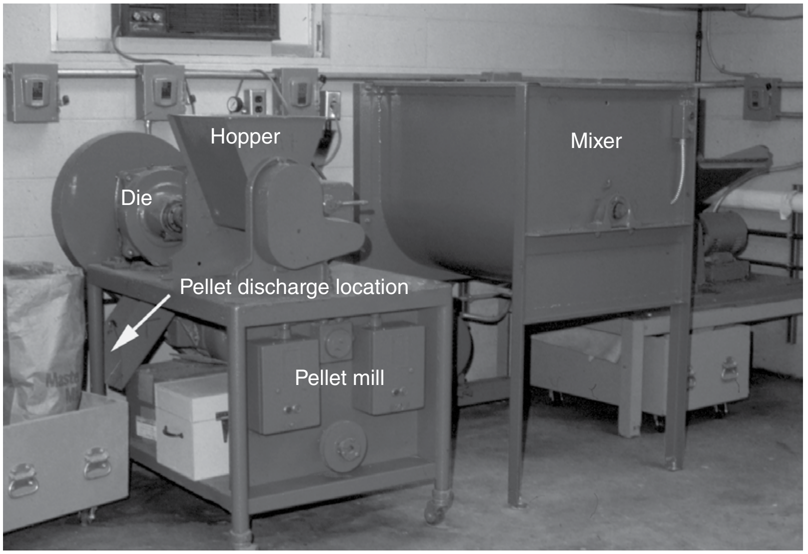

Fig. 8.10. Examples of mixer and pellet mill.

Fig. 8.11. Pallets of bagged feed.

feed. Some insects will burrow through the bags to gain access. Mice and rats can also try to access the feed, so in addition to being kept under cool and dry conditions, it should be stored in a secure location. Bagged feed should be used within 90 days of purchase. Stock rotation is important. That means that the culturist should use the feed in the order of date purchased.

Bulk feed is stored in bins such as those shown in Fig. 8.12. During the growing season, deliveries of bulk feed are made at intervals of a few days to perhaps 2 weeks depending on the size of the facility and the feed storage capacity, so heat is not as much of a problem because the feed is stored for a relatively short period of time. What is of greatest concern is oxidation of lipids and certain vitamins, which takes more time than the interval between delivery and use of the feed. That is, there should be no problem assuming the stock of feed is used in the order that it was manufactured and delivered and that there is not a large excess on hand that is not fed for some weeks after it was purchased. Moisture should not be a problem in feed bins unless there is a leak in the bin in a location that would allow precipitation to enter. Also, during periods when not much feed is being used – early in the growout period and during winter in temperate areas – the feed in bins should not become overly heated, except in tropical regions where seasonal temperature changes are typically small (depending largely on the altitude at which the culture occurs).

By ‘presentation’ (see the section heading above), we are referring to how the feed is provided to the species under culture. The basic methods of presentation are hand feeding and mechanical feeding. Hand feeding is simple to understand. It's what the home hobbyist does when he/she puts a few flakes of feed into his/her aquarium or a handful of pellets into his/her backyard koi pond. The commercial culturist feeding prepared feed can merely pour the feed from a bucket into cages, tanks or raceways that contain the animals. In small ponds, feed can be thrown in from various spots along the pond banks using scoops or buckets. Hand feeding of moist pellets by shovelling them into net pens or cages is an option as well (see Fig. 8.3). Adequate distribution of the feed is another important consideration. Feed is easily distributed in small culture systems such as raceways, net pens, cages or recirculating aquaculture systems. In contrast, distributing the feed in ponds of several hectares can be much more challenging. It is recommended that feed be distributed down one of more sides of the pond to make it accessible to as many fish as possible. This is usually accomplished with feed blowers mounted on or pulled behind trucks. Feed should be distributed from the upwind levee of the pond to ensure feed pellets will be dispersed out into the pond as opposed to being blown next to the shoreline.

Mechanical feeding involves the use of demand feeders (Fig. 8.13), automatic feeders (such as the disc feeder shown in Fig. 8.14) or feed blowers (Fig. 8.15). The latter can be mounted on boats, pickup trucks or pulled along the pond bank by trucks or tractors as previously mentioned. Demand feeders are those that the animals activate because of triggering the feeder to drop a few pellets at a time into the culture chamber, while automatic feeders are on timers, so they drop pellets either continuously or at set intervals. Automatic feeders have also been designed for use with finely ground and crumbled feeds, so they can be used with fry and early fingerlings in a hatchery.

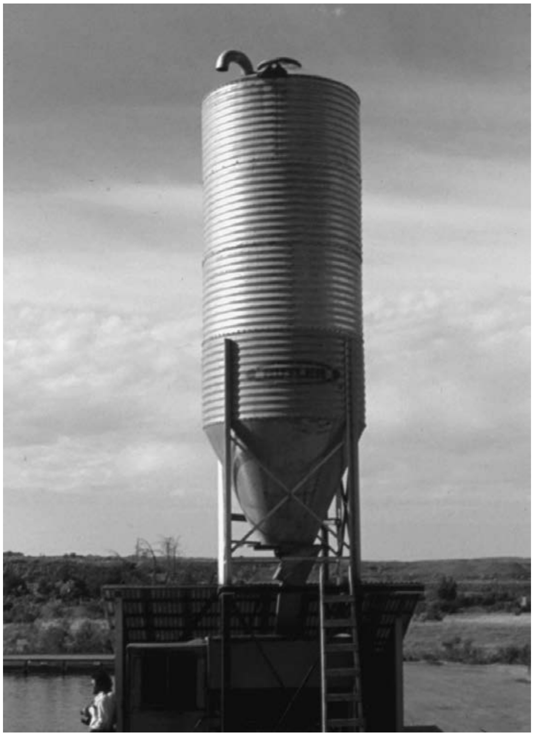

Fig. 8.12. Bulk storage bin for feed at an aquaculture facility.

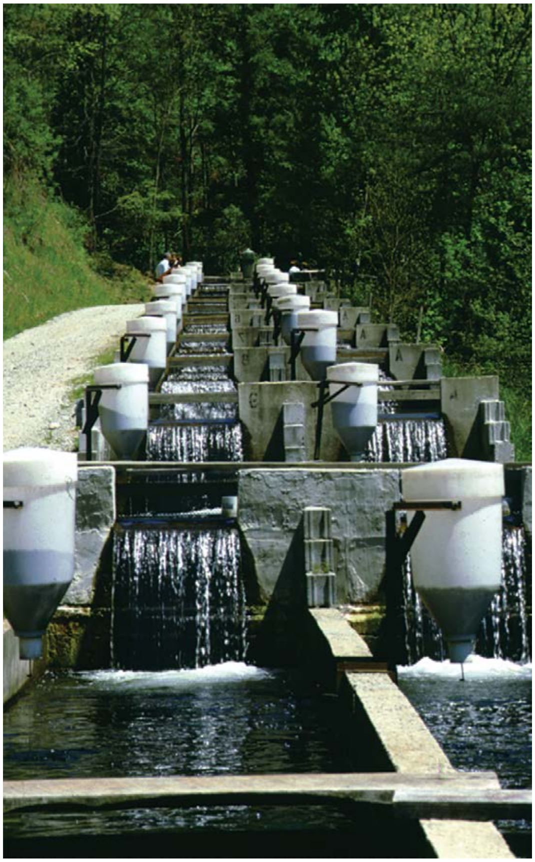

Fig. 8.13. A series of demand feeders located on trout raceways. Note that the feeder is translucent so the aquaculturist can easily determine when to refill it.

A typical demand feeder for fish involves a feed reservoir mounted over the culture chamber from which a rod or chain extends into the water. At the bottom of the rod or chain there may be a piece of metal mounted perpendicularly – a foot plate, if you will (though feet are not a common feature of fish) – to provide more opportunities for fish to activate the feeder by bumping into the activation mechanism. When the rod or foot plate is moved, a few pellets are released and drop into the water. Thus, the fish can obtain feed at will or on demand. Once a fish or two activate such a device, others quickly learn to use the device. Some typical demand feeders are shown in Fig. 8.13. Note that these raceway systems are subject to considerable water flow. The way demand feeders are designed needs to take account of the amount of pressure it will take to activate them. If they are too sensitive, they may be activated by even small currents, which would lead to wasted feed and give the illusion that the fish are consuming more feed than is actually the case.

Fig. 8.14. Vibrating feeder with timer. The frequency of feeding can be controlled by the timer and the quantity of feed dispensed is adjusted based on the gap above the vibrating plate and cylinder which contains the feed.

Automatic feeders are those that deliver feed in batches at certain times of day or continuously deliver small amounts of feed. Automatic feeders are used, for the most part, in conjunction with feeding post-larval and fry fish in the hatchery or in circular tanks, raceways, net pens and cages when larger animals are being reared. Various designs are available

Fig. 8.15. A truck pulling a mechanical feed blower on a pond bank.

commercially, and various designs of home-made feeders have been crafted by practising aquaculturists. Figure 8.16 shows a continuous automatic feeder in which a very slowly moving belt constantly adds feed to the culture system. Most are powered by electricity, though a belt timer could also be powered with a hand-wound spring mechanism.

Fig. 8.16. Belt feeder which can be loaded to dispense feed on a continuous basis. Such feeders are available commercially and can also be built relatively easily by the aquaculturist.

Various types of automatic systems are commonly used to distribute feed to salmon net pens, as previously mentioned. These often move pellets by means of forced air. Often, there is a floating or land-based structure that contains the bulk feed, which is distributed by a blower system through pipes leading to each of the net pens in the system (Fig. 8.17). Such systems can use a computer to send feed out to each net pen several times a day, as mentioned above. Again, video cameras and television monitors may be used so that culturists can monitor feeding activity (Fig. 8.18). In some cases, the cameras are located underwater, but they may also be mounted above the water. As offshore aquaculture using submerged cages in the marine environment has developed, it has been necessary to come up with novel feeding systems that can supply feed under water to the fish. Some of such systems currently being developed are engineered to send the feed from the surface to the submerged cages in a water stream rather than with air pressure.

Feeding Practices

Proper feeding involves providing feed of the appropriate formulation at the optimal time or times of day, in the proper amounts and adequately

Fig. 8.17. Feed barge with pneumatic tubes for conveying the feed to various net pens.

Fig. 8.18. Feed monitors at a salmon net pen facility.

distributed in the proper form, so the culture animals will accept it and perform optimally. Environmental conditions in many culture systems change over time and feeding practices may have to be altered as those temporal changes occur. For example, the amount of feed that is offered daily during periods when the water temperature is in the optimal range for growth may be considerably higher than during periods when the temperature is higher or lower than optimal. During winter in temperate areas, warmwater fishes such as channel catfish (*I. punctatus*) may not be fed at all or are fed only a very small amount daily, every other day, every third day or only on relatively warm days.

Floating pellets are the form preferred by aquaculturists who grow fish that will feed at the water surface. The primary reason is that the farmer can observe the animals feeding. These animals would be finfish without exception unless there are some invertebrates that come to the surface to feed. This is important in that the farmers can feed *ad libitum* (Latin for 'at liberty') or to apparent satiation; that is, they can continue to offer feed until the fish appear to be satiated. Ideally feed should be provided in relatively small amounts over the course of 20–30 min or until feeding activity slows. This approach gives all fish in the culture system ample opportunity to obtain some feed, especially after the more aggressive fish have consumed all they want. However, this method does require a considerable amount of time when multiple culture systems are being managed.

With fish that are first stocked and fed, whether in a raceway, pond or other type of culture chamber, the culturist can first offer somewhat less than what has been estimated as about the right amount, given the number of fish stocked and their size. The culturist would observe the fish until the originally presented feed is gone and then additional feed can be provided. The process would be continued until feeding rate declines appreciably or stops. Knowing how much feed was present before it was offered and how much was left after the fish became satiated, the farmer would have a good estimate of how much to feed the next time feed is to be offered. Increasing slightly the amount offered each day will compensate for growth. It is still necessary to observe the fish and add additional feed if the fish are still actively seeking pellets when those in the initial offering have all been consumed. Generally, it is better to underfeed than to feed too much because the uneaten feed will not only be wasted but also might degrade water quality. If water quality is not good, in terms of low DO or high nitrogenous waste levels, the fish likely will not be willing to feed aggressively.

In some aquaculture systems, feed is typically offered twice a day to maximize utilization by the fish: once in the morning after it has been determined that the DO level is sufficiently high and once in the afternoon before dusk, though feeding advanced-sized fish in large production systems such as growout ponds may be limited to one time per day. In some cases, demand or automatic feeders are used (discussed previously and in more detail below). In the case of marine cages and net pens used for salmon culture, the fish are often fed several times a day with automated feeding systems that can be turned off and on by the culturists or are programmed to provide certain amounts of feed to each unit periodically (Fig. 8.19). Many farms employ remote video cameras located above and/or below the water surface so the culturists can observe the feeding activity and know when apparent satiation is reached. Slow-sinking pellets are typically used in those culture systems. The size of marine cages and net pens can be so large that not all the fish can get to the surface before the pellets have been consumed but, as the pellets begin to sink, fish below the surface have the opportunity to consume them. Cameras below the surface of the cages can determine the extent to which there is feeding activity within the water column.

One benefit of feeding floating pellets, particularly in ponds, is that any diminution in feeding activity can quickly be spotted. For example, if the fish have been stressed or are experiencing the initial stages of a disease outbreak (which may be the result of a stress event), they will not consume as much food as normal, and the farmer can not only save on the amount of food offered, but also can begin looking for the cause of the problem and thus have the opportunity to address it in its early stages.

If the farmer uses sinking feed and cannot see the fish feeding and there is a reduction or cessation of feeding, the problem may not be recognized until it has become acute. In addition to perhaps not being able to avoid losing fish to mortalities, the farmer will also waste a lot of feed between the time that feeding activity is reduced and when the problem becomes apparent. Also, if the farmer cannot observe feeding activity, it will be necessary to sample the culture chambers (typically ponds) at intervals (often weekly or every other week) so that growth rates and feed conversion efficiencies can be calculated. Based on those calculations, feeding rate can be adjusted as discussed below. For some species that have been cultured for many years,

Fig. 8.19. A rotating feed distributor at a net pen.

feeding tables are available that have been empirically derived by monitoring feed intake of a species over several different size ranges and under different water temperature conditions.

In the case of shrimp that are commonly cultured in ponds where their feeding activity on sinking pellets cannot be readily observed, other means of estimating feeding rates and monitoring feed intake have to be employed. For many farms, feeding charts have been empirically derived in which feed quantities are progressively increased over time based on the initial size of the shrimp and stocking biomass, as well as the projected growth of the animals over time. The shrimp may be sampled periodically to monitor their growth. This can be conveniently accomplished by harvesting shrimp from lift nets or feeding trays which are routinely used to monitor intake of the shrimp. Feed is placed on these trays during normal feeding and at certain time intervals the trays are lifted from the water to observe how much feed has been consumed. Based on those observations, feed quantities can be adjusted accordingly. In recent years, the use of hydrophones to monitor the sound of shrimp actively feeding has been implemented to increase the precision of feeding shrimp under pond culture conditions.

In general, juvenile aquaculture animals in grow-out culture chambers will consume prepared feed at a rate of about 3–4% of body weight daily. There are exceptions to that, of course. If fertilization is used and there is a good supply of natural feed (plankton, benthic organisms, etc.), the amount of prepared feed that is required will be less than 3–4% of body weight and may be in the form of a supplemental rather than a complete ration. That will depend upon species and whether the fish are still consuming natural food items (they may, for example, become too large to capture and swallow zooplankton; or, on the other hand, may have gill rakers that are able to filter zooplankton from the water even when the fish become large).

Some species have very high metabolic rates and require much more feed than the percentage range mentioned above. Examples are tuna (*Thunnus* spp.) and dolphinfish or mahi-mahi (*Coryphaena hippurus*) as well as juvenile red drum (*Sciaenops ocellatus*) which will consume up to 6 or 7% of body weight as small juveniles. Other species may have low metabolic rates, especially at less-than-optimal temperatures, and require less than 3–4% of body weight daily.

It is common practice to feed post-larval and early fry far in excess of what they can possibly consume. Culturists may, for example, feed fry fish as much as 50% of their biomass daily but distributed over several feedings. That approach helps ensure that each fish will be able to find food. The culturist usually tries to disperse the feed as evenly as possible throughout the culture chambers, so the animals do not have to move very far to find it. The total amount of feed provided (even at 50% of biomass) is rather insignificant, because the total biomass of fish in the culture system is small. Thus, while much of the feed is wasted, it does not represent a great expense to the culturist. In tanks and raceways, excess feed is usually siphoned out daily or even more frequently to help preserve water quality. In ponds, the excess feed helps fertilize the system. In fertilized ponds, excess feed can still be provided, but at a level considerably less than 50% of the biomass present.

Having just indicated that feeding to excess is acceptable for very small animals, the first rule in feeding juvenile and larger animals, including broodstock, is do not overfeed! On a production facility, those larger stages of aquaculture species receive plenty of food each day when they are fed at the proper level. Feeding more than the animals will consume is wasteful, expensive (feed typically accounts for as much as 50%, or even more, of the variable costs of an aquaculture operation, as previously indicated) and may lead to impaired water quality due to the increased BOD imposed on the system by decomposing feed. Broodstock can typically be fed at only 1% of body weight daily because they tend to grow very slowly after attaining adulthood. You may want to increase the feeding rate and feed some live food or frozen animals (such as small fish, squid or shrimp) or organ meats (e.g. beef or poultry liver, kidney or heart) as carnivorous brood animals are developing prior to spawning. That approach is thought to improve gamete quality and has been used by the channel catfish industry; though, with the development of complete feeds, it may not be necessary and is certainly less convenient than feeding prepared feed. Broodfish formulations may also be available, depending upon species. Typically, a broodfish diet will provide higher levels of certain fatty acids and vitamins than feed used for grow-out. The approach is designed to increase gamete quality. Such feeds would be provided during the pre-spawning period as the gonads develop, so it would be provided seasonally. An exception would be tilapia that can spawn year-round. Standard feed formulations should be provided to tilapia broodfish, which can filter-feed to supplement their nutrient intake.

As the animals grow from their early life stages (where they are overfed) to early juveniles, and from there to later life stages, the amount of feed offered is reduced over time until the final growout feeding rate is reached. Early fingerling fish are typically fed 5–10% of body weight daily and that level is gradually reduced until the 3–4% rate is reached.

Feed particle size also should be increased as the size of the animals allows them to take larger particles. Once the animals can accept full-size feed pellets, they will be fed those exclusively thereafter in most cases. Pellets larger than standard can, if desired, be produced by using larger dies in pressure pellet mills or an extruder barrel with a larger-than-normal aperture. Large soft (moist) pellets, such as shown in Fig. 8.2, can be made by passing the feed mixture through a meat grinder fitted with a die of the proper size. Post-larval shrimp, fry and very small juveniles may be fed several times daily or even continuously using automatic feeders such as those shown in Figs 8.14 and 8.16. The fry and early fingerlings of carnivorous species prone to cannibalism are typically fed at high frequency, which could mean several times daily – often every 1–2 h and in some cases every several minutes for a period when a very high rate of cannibalism occurs – or even continuously to reduce the rate of cannibalism. Frequent grading of carnivorous species to maintain culture chambers with fish of similar size will also cut down on cannibalism, because many carnivores do not exhibit much cannibalistic behaviour if there is not much size variability in the population. It is hard to get your mouth around the animal you are trying to eat if it is the same size as you are. That does not apply to crabs, shrimp and lobsters with chelae that tear their food apart and have culture-chamber mates that become helpless when they are soft after moulting.

Many aquaculturists can enjoy the fact that quite a few of the carnivorous species under culture – and some of the crustaceans, along with many of the finfishes that are carnivorous or omnivorous in nature – are not cannibalistic, or do not demonstrate that characteristic to any extent if they are properly fed in a culture situation.

Determining Feeding Rate

For culturists who sample their animals periodically to adjust the feeding rate, it is necessary to estimate two things: the number of animals in the culture unit and their total weight. If you think that is simple, you are only partially correct. It is certainly relatively easy to capture, count and weigh all the animals in a small culture chamber such as a tank or raceway of limited dimensions (many of these are used in research laboratories and can sometimes be found in commercial hatcheries, but they have little use as growout units on commercial aquaculture facilities). Capturing all the animals in relatively large hatchery culture units or in large raceways and tanks used for fingerling production or even growout is also possible, but how does one count and weigh them in such an expeditious manner that the stress placed on the population is not severe? The problem is compounded further in conjunction with animals reared in cages, net pens and ponds. In those situations, it makes little sense to even attempt capturing all the animals to obtain number and weight estimates.

The only time the culturist has reliable information on the numbers of animals that are in a culture chamber and their biomass is when they are first stocked. It is not a good idea to try and count each individual that is going to be stocked because of the time that would take, the stress that the animals would be exposed to and the impracticality of the process, which may in some cases involve thousands, tens of thousands or even hundreds of thousands of animals in a single culture unit. The typical method of obtaining the required data is to count out 100 individuals and weigh them. If they are very small (fry fish or post-larval invertebrates), in addition to weighing them, the culturist can determine how much water they displace. The sample of known weight is put in a graduated cylinder that is partially filled with water and the amount of water that is displaced by the sample is determined. Let us say that the initial volume in the cylinder was 60 ml and the 100-fish sample of known weight caused the new level of water in the cylinder to rise to 110 ml. We now know that 100 of the fish or invertebrates of known weight in the sample displace 50 ml (110 – 60 = 50). The process should be repeated with at least a few other samples of 100 to determine that you have a good estimate of both the average weight and water displacement. Thereafter, the numbers and weights of the remaining animals to be stocked can be determined from water displacement alone. No further counting or weighing should be necessary.

For larger animals, the system for determining numbers and biomass would be most easily accomplished strictly on a weight basis. Count out 100 fingerlings, weigh them and record the weight. Stock them and repeat the process with another batch or more of 100 to get a reliable average weight. Then you can weigh large batches of the remaining fish and from their biomass you can calculate their numbers. It is best to do all weighing in water, again to reduce stress. That is done by partially filling a suitable container (a bucket, pail or tub, for example) with water. Weigh the container and water, and then record the weight. This is known as the tare weight. Waterproof electronic scales are excellent for this type of activity. And do not worry about getting the weight down to the nearest milligram. We would say for most applications get the weight to the nearest 1–10 g. Then, add 100 animals to the tared container and record the weight. Again, the difference will be the weight of 100 fish. Stock the weighed fish, then repeat the process by getting a new tare weight and the weight of 100 fish. Again, repeat a few times so you have a good average of what 100 fish weigh. After that, you can weigh larger uncounted groups and easily determine how many animals were in each large group by dividing the average weight into the total minus tared weight of the large group. The number of animals in the large groups should obviously not be so great that the container overflows, nor should it be so great that any thrashing about by the animals causes water to splash out. What you will find is that even if the animals are not thrashing wildly, it will be difficult to get an accurate number because there will be some water movement that will cause the numbers on the scale to move up and down. You may need to estimate the midpoint in the swing of weights and record that number. Yes, it is slightly inaccurate, but it will be close enough to the actual total biomass.

While a culturist may have a fairly high level of confidence in the number of animals initially stocked in a particular culture unit, one problem associated with estimating subsequent feeding rates is that the culturist will often not have a good estimate of mortality. Any dead animals that are found can be subtracted from the total number of animals thought to be in the system, but rarely are all the mortalities that occur observed, particularly in ponds, large cages and net pens. Those lost to cannibalism or bird predation, and dead animals that do not float where they can be observed, will not be counted in many instances, particularly in ponds. Fish with swim bladders will often float to the surface after they die. Those without swim bladders, along with invertebrates, do not float to the surface after death, so good mortality estimates are difficult to obtain. The culturist can use an estimated mortality rate as an adjustment factor when calculating feeding rates, but that can introduce a considerable error factor as it is a guess, at best, because mortality can vary dramatically from culture unit to culture unit and from year to year. When the animals reach harvest size, the culturist may be surprised that their numbers are much lower than anticipated because the mortality estimate was well off the mark. On the other hand, there may be the surprising result that there are more fish in the system than anticipated, though they may be stunted from insufficient feed. It is usually easier to get a better handle on mortality from raceway and tank systems than from ponds.

Once you know the initial numbers and weight in each culture unit, you can determine how much feed to provide initially (often 3–4% of the total weight of the fish in each tank, pond, etc.). Adjustments to feeding rate are then typically made at 2-week intervals by obtaining subsamples from each culture unit, from which average weight of the animals can be determined. For purposes of our calculation, we will assume that you were able to identify all the mortalities, so you have a reliable estimate of the existing number of animals in each culture unit at the time the new feeding rate is developed.

Every 2 weeks since you stocked the fish, you have adjusted the feeding rate and accounted as best you could for mortality. Now a few months have passed since you stocked your fingerlings. Let us assume that you have a 5 ha pond with a population of 10,000 tilapia/ha averaging 200 g/fish. You determined the average weight by subsampling the pond. You did that by taking seine samples, counting out and weighing a minimum of 30 fish and repeating that process a few times to get a reliable average weight (Box 8.6). Let us say you want to feed the fish at 4% of their body weight daily until the next scheduled adjustment in their feeding rate, which will be 2 weeks in the future. Note that because the fish will presumably be growing from one day to the next, the actual feeding rate will be less than 4% after the first day and

Box 8.6.

Experience has shown that a subsample of 30 animals is sufficient to obtain a reasonably reliable estimate of average weight, even from a large culture chamber. To be more comfortable with the estimate, we like to weigh two or three subsamples of 30 animals and compare the averages. If they are quite similar, then we are satisfied that we can multiply the average weight by the estimated number of fish in the culture unit and obtain a reasonable estimate of total biomass. If there is a wide range among the subsamples, continue the process until you are satisfied that you have obtained a reasonable estimate. The level of difficulty increases when there is a wide range of sizes in a pond, in which case you would have been better off feeding *ad libitum* or you may need to capture all the animals, grade them into a few sizes and restock each group in a separate culture unit.

will decline slightly each day thereafter until the new adjustment is made. The question is, how much feed will you be putting in the pond each day for the next 14 days before you are scheduled to adjust the rate again? Oh, yes, and this is important: do not feed the fish before you weigh them! While your 30-fish subsamples may represent only a small fraction of the fish in the pond, you will have stressed the fish just by pulling that seine around the pond. Also, the stress will be compounded if they have bellies full of feed, not to mention that they will weigh more than before they fed. Sample in the morning, calculate your feeding rates and feed the fish in the afternoon on the day of weighing.

Okay, let us go back to the example:

$$10{,}000 \text{ fish/ha} \times 5 \text{ ha} = 50{,}000 \text{ fish}$$

$$50{,}000 \text{ fish} \times 200 \text{ g/fish} = 10{,}000{,}000 \text{ g} = 10{,}000 \text{ kg of fish}$$

$$10{,}000 \text{ kg} \times 0.04 = 400 \text{ kg of feed/day}$$

Your feed cost per day is already significant and will grow considerably as you continue feeding the fish to a market size of 450–500 g on average. Assume that the feed cost is US$0.40/kg:

$$\text{US\$}0.40\text{/kg} \times 400 \text{ kg/day} = \text{US\$}160\text{/day}$$

Now you can begin to see why feed costs can amount to such a high percentage of the variable costs of production. At this point you have already used a lot of feed to get the fish to 200 g average, and you have another 250–300 g/fish to go.

After 2 weeks have passed, you take another subsample of at least 30 fish from the pond and find that they weigh an average of 210 g. What is the new feeding rate? Let us assume no mortality:

$$50{,}000 \text{ fish} \times 210 \text{ g/fish} = 10{,}500{,}000 \text{ g} = 10{,}500 \text{ kg of fish}$$

$$10{,}500 \text{ kg} \times 0.04 = 420 \text{ kg of feed/day}$$

$$420 \text{ kg/day} \times \text{US\$}0.40\text{/kg} = \text{US\$}168\text{/day}$$

The fish are growing and so is your cost of feeding them. Over the previous 14 days you have spent US$2240. That will increase by US$112 over the next 14 days (US$8.00/day).

It is possible to project what the feeding rate should be over time by using feed tables or formulas that predict growth. If those approaches are used, it is still a good idea to do some sampling periodically to ensure that the projections that have been used are in line with actual fish growth. Feed tables have been developed for a few species, such as trout and channel catfish, but are not available for most of the species produced in aquaculture. Because environmental conditions vary from culture unit to culture unit, particularly in ponds, the animals in an aquaculture facility can be expected to grow at somewhat different rates in different culture units and in different locations.

The system of determining feeding rates described here will not work if the culturist is using the partial harvest and restocking system for channel catfish (*I. punctatus*) that has been previously described. Recall that, with that method, selective harvesting of marketable animals is conducted periodically. After those fish are harvested, a similar number of fingerlings is introduced. Over time, some fish will stunt and because there is a wide range of sizes in any event, getting a reasonable estimate of average weight becomes very difficult. Also, because some such systems may be operated for years without being drained, not having any reasonable chance of keeping track of mortalities makes estimating the number of fish present virtually impossible. In this case, the only reasonable way to feed the fish would be using floating pellets and going to an *ad libitum* system. Of course, *ad libitum* or 'at liberty' feeding is technically not correct for aquatic species because the aquatic medium does not allow feed to be available to the fish for their consumption all the time such as with some terrestrial livestock. Instead, feed may be offered periodically to aquatic species during which time they may be fed to 'apparent' satiation based on an active feeding response which eventually subsides and at which time feeding should cease to prevent uneaten feed being wasted.

Feed Conversion

Looking back at the growth of your fish over the 2-week period when they increased from an average weight of 200 to 210 g, you might be interested in knowing if that is a reasonable growth rate or not. You should be interested because if the fish are not growing well, something is probably wrong. There are a number of possibilities. You may be overfeeding or underfeeding them because you have not obtained a reasonable estimate of the number of fish in the pond. If the fish are growing slowly and are not being underfed, they may not be consuming the feed and may be suffering from the onset of a disease; or perhaps the feed is not as nutritionally complete as you were told by the feed company (though that is rare – it's common to blame the feed company for your problems but is rarely the case if you deal with reliable feed company). Maybe you came up with your own super feed formulation and gave it to the feed company, not realizing that it was lacking in some key nutritional factor. In any event, how do you determine if the fish are performing well?

A properly designed feed should provide all the nutrients required by the species being fed and those nutrients should be present at the proper levels. Further, the feed should be utilized efficiently by the animals; that is, it should be highly digestible and what is digested should be highly absorbed into the tissues. Realizing that only the protein in the feed is used for somatic growth, the goal of the nutritionist who develops aquaculture feeds is to allow the fish to convert as much of the protein provided in the feed to tissue as possible. Some protein is always going to be utilized as an energy source and will be broken down, converted to sugars and burned for metabolic activity. However, if the lipid and carbohydrate components of the feed provide the appropriate amount of energy, protein can be more effectively used; that is, it can be spared and used for growth.

Determining how efficiently a fish is converting feed into new tissue – defined as growth – is accomplished by calculating the feed conversion ratio (FCR) or feed efficiency (FE). There seems to be some controversy among aquatic animal nutritionists over which of those two is the proper parameter to report, though, as you will see, one can be derived from the other. That being the case, we have elected to not select one term over the other and have provided you with both in the examples below. The formulas for the two are:

$$\text{FCR} = \text{Dry weight of feed consumed}/\text{Wet weight of gain} \quad (8.1)$$

$$\text{FE} = 1/\text{FCR} \times 100 \quad (8.2)$$

FE is typically expressed as a percentage, whereas FCR is a ratio that is dimensionless (Box 8.7).

If we look at a very efficient terrestrial animal, the chicken, we can get some idea of what a good FCR should be. Chickens will have an FCR of about 2.0; that is, for every 2 kg of dry feed consumed there will be about 1 kg of wet weight gain. The FE for that FCR is 1/2 × 100 = 50%. Thus, 50% of the dry weight of feed consumed goes towards growth. That looks pretty good when compared with other livestock species that often have FCRs in the neighbourhood of 8.0 or even higher. An FCR of 8.0 would mean the animal is only 12.5% efficient at converting feed to growth (typical of cattle on pasture, as an example).

Now let us look at how the tilapia (for which we determined a new feeding rate in the preceding section) are doing with respect to growth.

The total amount of gain over the 14-day interval was 10,500 kg – 10,000 kg or 500 kg. The total amount of feed offered was 420 kg/day – 400 kg/day × 14 days = 20 kg/day × 14 day = 280 kg. Thus, the FCR is calculated as follows:

$$\text{FCR} = 400 \text{ kg fed}/280 \text{ kg gain} = 1.42$$

$$\text{FE} = 1/1.42 \times 100 = 70.4\%$$

Box 8.7.

Note that we use dry weight of feed and compare that to wet weight of gain by the animal. Because feed pellets contain some moisture, they can be dried, and the moisture level can then be determined and that amount (some percentage of the weight of the feed) can be subtracted from the fed weight of the feed and used as dry weight.

Given that a good FCR for most aquatic organisms is between 1.5 and 2.0, the value calculated above is not bad, and is probably not typical for tilapia which are efficient – they also cheat as they are species that can consume plankton, which will always be present at some level in ponds. But a step has been omitted. Recall that the FCR and FE are based on dry weight of feed and fish gain. The fish gain (wet weight) is correct, but we did not take the water in the feed into account. Fish farmers often do not consider the water in 'dry' pelleted feed to be significant, but the typical feed pellet contains something like 9–10% moisture. Let us recalculate the FCR and FE using a moisture content in the feed of 9% to see if it makes a difference:

$$400 \text{ kg of feed} \times 0.09 \text{ moisture} = 36 \text{ kg of moisture}$$

$$400 - 36 = 364 \text{ kg of dry feed}$$

$$\text{FCR} = 364 \text{ kg fed}/280 \text{ kg gain} = 1.3$$

$$\text{FE} = 1/1.3 \times 100 = 76.9\%$$

Thus, by taking the water into consideration, the FCR and FE improve, though not by a large amount (Box 8.8). So, if you wish to ignore the moisture correction, you can do so; unless you are feeding moist or semi-moist feed, in which case your FCR and FE will not look good at all if you do not subtract the water.

Summary

The rearing of live food organisms used in the feeding the early life stages of aquatic animals reared for human food was discussed in Chapter 6. This chapter has focused on prepared feeds; the types of prepared feeds that were described include purified, semi-purified and practical formulations. Practical feeds are those used in commercial culture; the other two are used in research to help determine nutritional requirements. A practical feed may be complete or supplemental, in which case it should only be used when there is a sufficient supply of suitable natural food available. Practical feeds are manufactured from various feed ingredients such as animal protein (e.g. fishmeal), plant feedstuffs (various grains and protein concentrates), along with added fat, vitamins and minerals.

Prepared feeds may be in the form of very finely ground particles that are usually made from larger forms, such as pellets. Between those two extremes are various sizes of crumbles, which are also made by crushing or grinding pellets. Other forms are microparticulate feeds for larvae and flakes which

Box 8.8.

In some laboratory experiments, the FCR for tilapia and other species has been calculated at <1.0 (we have seen as low as 0.7 or 0.8), meaning that the FE reached or exceeded 100%. How is that possible? In a pond where there is natural food available, it is certainly conceivable that growth can exceed 1 kg for each kilogram of feed offered because the animals may be supplementing their diets with natural foods. In the laboratory, this is less likely to occur unless the culturist makes natural food available or conditions are such that algae and/or bacterial growth occurs in the culture tanks (given sufficient light, such as natural light through windows). Algae can grow on the sides of culture tanks, and bacteria can slough off biofilter media and get in the culture tanks. Either or both can be consumed by some species of fish, with tilapia being an excellent example. The answer lies in the fact that, in determining FCR and FE, we look at dry weight of the feed compared with wet weight gain. A finfish, for example, may be 70% water, so that a considerable amount of the observed weight gain is in the form of water. Thus, FCRs of 0.7–0.8 can easily occur, though in commercial culture the figures previously provided (1.5–2.0) are reasonable, if not very good. When a farmer calculates an FCR of 3 (equating to 33.3% FE), the animals can be significantly underperforming – at least in the case of several the species currently under culture. Animals that burn a lot of food energy for rapid and continuous swimming, such as mahi-mahi and tuna, may have high FCRs and low FEs because of their high rates of metabolism. For those species, feed costs may be a considerably higher percentage of total variable expenses associated with culture, though if the final products bring premium prices, such as would be the case for sushi-grade tuna, the added expense will be recuperated at the time of sale.

are typically provided to ornamental fish. Each has found use in various types of aquaculture. Pellets can be wet, semi-moist or dry, and they can be made in various sizes.

There are two common ways in which feed pellets are manufactured. One is by pressure pelleting, which produces feed pellets that sink when placed in the water. These are produced with pellet mills that subject them to some pressure and perhaps heat over that caused by friction if steam is used in the process. The ingredient mixtures that make up the pellets should contain some type of binder to help keep the pellets intact in water for at least several minutes so the animals have a chance to eat them. The second pelleting method is extrusion. In that method, the ingredient mixture is passed through a long extruder barrel during which time the mixture is exposed to high pressure and heating in the form of stream. Under the right conditions the starches in the pellets that are formed expand and trap air, making the pellets float when they are placed in water. Altering the conditions in the extruder can also lead to the production of sinking pellets.

Finished feeds need to be properly stored in a cool, dry place that should be secure to keep out rodents and other undesirable organisms that may like to consume it. Bulk feed should be used within a few days of purchase, particularly during warm weather.

Feed can be provided to the cultured organism in a variety of ways, ranging from scooping it into the culture unit by hand to having elaborate feeding mechanisms. Some species will use demand feeds while others can be fed with automatic feeders. Boats or tractor-drawn trailers with feed blowers are commonly used to feed fish in large ponds.

Young, rapidly growing culture species require higher feeding rates (as a percentage of body weight provided daily) than do older animals. During the growout phase, the typical feeding rate is 3–4% daily. Some culturists feed the animals to apparent satiation. That works well when floating feed is used, and it is relatively easy to determine when feeding activity slows or ceases.

Feeding rates need to be adjusted every 2 weeks if the animals are being fed a percentage of body weight daily. Adjustments are made by sampling the culture units to determine how much the animals have grown since the last adjustment. Initially, the culturist needs to determine the number and weight of the animals stocked. FCR and FE can be determined from one feed adjustment period to the next. For many aquaculture species FCR ranges from 1.5 to 2.0, leading to FE of 50–66.7%.

Additional Reading

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9 Additional Topics

Introduction

As one wise individual said about the work of an aquaculturist: 'You're not finished with your job until someone wraps a lip around the product.' In other words, raising the crop is not sufficient. The quality of the final product that gets to the consumer must be sufficiently high that it is readily accepted by consumers and, in many cases, can compete effectively with its wild-caught counterparts taken in commercial or even recreational fisheries. The culturist not only needs to maintain a good environment for the plants and/or animals being reared; care must also be taken during harvesting, processing, packaging and storage of the product. Some of these steps are beyond the control of the average aquaculturist, but the first one – harvesting – is usually overseen, if not conducted, by those who raised the product. In many cases, the producer also delivers the product to a processor, or may process and market the product directly, thereby bypassing the various middlemen who might otherwise be involved. Regardless, it is incumbent upon all who rear and ultimately handle the produce of aquaculture to take great care to protect the quality of the products until they reach the consumer. That said, it is also a fact that most of the problems associated with seafood spoilage, development of odours, illness and so forth are because of mishandling in the kitchen, with the vast majority being household kitchens, not those in restaurants. We will come back to the steps from harvesting to marketing shortly, but first, let us look back at some of the earliest material in this book.

By now, we hope you are convinced that aquaculture truly does encompass the many fields incorporated in business, science, engineering and skilled labour that were outlined in Chapter 1. To us, that is what makes aquaculture so interesting and stimulating, and why it stimulated our interest in devoting most of our professional careers to the subject. The aquaculturist is constantly faced with new challenges and is continuously trying to develop ways to do things better. The dedicated aquaculturist is always in search of new knowledge to apply to his or her profession. Today's aquaculturist also needs to have the goal of not only producing high-quality products but doing so in an environmentally and socially sustainable manner – not a trivial goal by any means.

This chapter discusses harvesting and some other topics that have not been covered in detail (or mentioned at all), which still are not only associated with aquaculture, but integral to the discipline. Included are live hauling and a somewhat related topic, anaesthesia. Fee fishing represents an option that can be lucrative in some places. Processing and marketing are discussed and, since we have not focused on non-food species or species produced in hatcheries specifically for enhancement stocking, recreational fish species, bait and other topics, there are a few sections on these as they are important contributions to global aquaculture. The chapter concludes with some of our thoughts about the future of aquaculture.

Some of the information in this chapter has been mentioned earlier in this book. While that is the case, we don't believe that it is inappropriate to be a bit repetitive to refresh your memory and to provide additional information.

Harvesting and Live Hauling

Harvesting may involve all the animals in one or more culture units or, as has been discussed with respect to channel catfish (*Ictalurus punctatus*), there may be intermittent harvesting of marketable fish followed by restocking with fingerlings. That technique is also called partial harvesting and does not involve draining the pond. In fact, catfish farmers

DOI: 10.1079/9781800621145.0009

who use that technique may not drain and completely harvest their ponds for as long as 10–15 years. Perhaps you have heard about that before.

Live harvesting and hauling are conducted with some species. That technique involves harvesting in a way that does not damage the animals, or at least keeps damage to a minimum, and is followed by hauling the animals to the processor alive in trucks designed for that purpose (Figs 9.1 and 9.2). The size of the vehicle used naturally depends on the quantity of finfish or invertebrates being harvested and the distance to the processing plant. There is a limit to how many animals can be hauled per unit volume of water and still be kept alive. Density needs to be reduced for long hauls as compared with short ones. If the processing plant is nearby, making several runs with smaller vehicles during harvesting is an option, as is the use of two trucks – one delivering fish while the other is being loaded, by which time the first truck may be returning for another load. For very small harvests, delivery of fingerlings and moving fish around a facility, a tank designed to fit in the bed of a pickup truck is a common approach. Hauling tanks are often fitted with baffles to reduce sloshing of the water, which can make handling the vehicle dangerous (Box 9.1). Insulated hauling tanks are often used when fish are hauled long distances, particularly in hot or cold weather (Fig. 9.3).

Live hauling is not just associated with taking harvested animals to the processing plant. Fingerlings are hauled from hatcheries to growout facilities, and fish of various sizes are hauled to stock recreational and fee-fishing lakes or ponds, for enhancement stocking and so forth. In some parts of the USA, and perhaps other countries, trout are stocked during the late winter or spring in regions where the water will eventually become too warm in the summer to support them. The idea is to provide recreational fishing while the water is cold enough for trout survival, and the expectation is that most of the trout will have been caught and removed from the water bodies into which they had been stocked before the temperature becomes too warm. More detail on live hauling is presented later in this chapter.

Fig. 9.1. A medium-sized fish-hauling truck.

Fig. 9.2. A tractor-trailer unit with tanks that is used to haul live fish.

Fig. 9.3. A tractor-trailer unit with insulated hauling tanks.

Box 9.1.

Hauling fish can lead to some interesting moments, which can be terrifying and sometimes humorous. When you accelerate the hauling truck with a load of water in the onboard tank or tanks, that water moves to the back of the tank(s) and when you hit the brakes, the water moves forward. If either acceleration or braking is aggressive, the force of the water movement may cause the driver to lose control of the vehicle. Swerving the vehicle will cause the water to move from side to side, which can also be very dangerous. In one case, a graduate student and I (R.R.S) had picked up a load of striped mullet from the Gulf of Mexico coast of Texas to see if we could grow them in inland freshwater ponds at our research facility near College Station, Texas. We were hauling them in a fibreglass tank in the bed of a pickup truck. At one point along the way back to the laboratory, the driver of the car in front of us slammed on its brakes, and I had to do the same in order to avoid a collision. As the truck slowed, the water kept moving forward with a great deal of inertia. It then reversed course and sloshed to the rear, blowing open the lid on the hauling tank and causing much of the contents to be expelled. When the sloshing stopped, there was water all over the road, along with flopping mullet. I got out of the truck and walked back, only to find a stopped highway patrol car directly behind our truck. A few mullet were lying on the hood of the officer's car. He just looked at me, shook his head and drove off.

In another instance, I was delivering catfish fingerlings to stock a pond. The hauling tank I was using was designed for a long-bed pickup truck, but the one I was driving had a short bed, so I could not close the tailgate. I was following the pond owner who had two boys riding in the back of his truck. A hat blew off the head of one of the boys, and I slowed down planning to stop and retrieve it. A colleague riding with me suggested that I should just slow down, and he would open the door, reach down and grab the hat as we went by. I slowed and steered the vehicle so he would have a chance to grab the hat. The plan worked perfectly. The truck was moving very slowly when he opened his door and grabbed the hat, after which I hit the gas. The water, which had been moving forward as the truck slowed down, reversed course when I sped up and its weight caused me to drive right out from under the fish tank, which landed on the highway. As luck would have it, we were very close to our destination and were able to net the fish, put them into buckets and carry them by foot to the pond bank for stocking. It was also fortunate that we were on a rural road with no traffic appearing while we completed the fish recovery and stocking process. Once the fish were stocked, we drained the tank and loaded it back on to the pickup. Another scary incident that was quite hilarious, though we did have to make some repairs to the hauling tank.

Harvesting extensive culture systems

Proper pond design, as discussed in Chapter 3, becomes very important when it comes to harvesting. Rectangular ponds that are no more than 2 m deep, have properly sloping sides for easy access and all-weather roads on the pond levees on at least two sides (which should be opposite to one another) are features that will help facilitate harvest. Also important is having no debris in the pond levees or bottom on which nets can become hung. Some watershed ponds have been constructed without removing trees, making harvest extremely difficult if not virtually impossible using seines. Large net enclosures in estuaries or lakes (such as are used for milkfish and tilapia in Laguna de Bay, a large low-salinity bay in the Philippines) may even have some types of snags associated with them that inhibit easy harvesting of the crop. Trapping, gill netting or some other form of harvest will have to be used in such situations, and that is inefficient in most cases. The one type of culture where trapping is the primary, if not the only, capture method used is that of crayfish production. What about crab and lobster trapping? Chinese mitten crab culture has increased significantly in recent years, reaching 750,000 tonnes in 2018 (8% of total crustacean production). Crabs are typically harvested with traps and lift nets. With respect to lobsters, that also may be a possible means of capturing spiny lobster in culture facilities. With respect to homarid (clawed) lobsters, there is virtually no commercial culture, though lobsters are sometimes trapped, put into what are called pounds and held until they are sold during the period when there is little or no production by the capture industry, which is seasonal and highly regulated in the USA. The lobsters may also be fed during the period when they are in the pounds.

Having a drain in each culture pond is also important as the water can be removed by gravity when the water level is to be lowered during harvesting. In some cases, such as with shrimp harvesting, it is even possible to place a net over the end of the drainpipe where it comes through the levee on the outside of the pond to capture the shrimp as they are flushed out of the pond. It is certainly possible to pump water out of a pond, but that involves the use of an electric, gasoline or diesel pump, which means additional expense to the producer that can be avoided through installation of a gravity drain when the pond is constructed – a one-time expense.

While partial harvesting may allow the culturist to maintain a pond in production for up to several years, eventually complete draining will ultimately be necessary, so having drains in ponds that are operated using the partial harvesting technique is still important. You might want to at least crack the valve on each pond drain periodically – perhaps every 6–12 months – to prevent it from freezing up to the point it becomes difficult or almost impossible to open. Leave the valve open partially for a few seconds and then shut it again so loss of the aquaculture species is eliminated or at least minimized. There will be very little water lost and you might be glad you took that step when the time to drain the pond eventually comes.

After some time, pond levees may become eroded and organic matter will build up on the pond bottom. When conditions deteriorate to the point that access becomes difficult or water quality is impaired, the pond should be harvested with complete drainage, and reworked. Reworking involves drying the pond bottom and reshaping the levees after the organic matter is oxidized. It is often necessary to clean out the pond bottom as the soil from slumping levees will have accumulated, thereby making the pond shallower than desired. Once the bottom is dry, it is common practice to disc the bottom to turn over the soil and expose more organic matter to the air, assuming you have not removed all the organic matter when you removed accumulated sediment. The bottom may then be smoothed and limed, after which the pond can be filled and put back into production.

During warm weather, it is wise to harvest during the early morning before daytime water heating becomes a problem. This is particularly important when a pond is partially drained before harvest. If the pond is to be completely harvested, it is common to begin draining it several hours or even a day or more in advance of harvest. The time that draining should begin will depend upon the size of the pond and the size of the drain line, because drain size will control how rapidly the water can be released. It is common to drain a pond about halfway before harvesting begins. Caution should be used to ensure that the pond does not drain completely. For example, the culturist may open a valve in the afternoon, thinking that by the next morning the pond will be down about halfway. When returning after a nice evening and night at home, the culturist may be shocked to find that: (i) the pond is empty, and all the fish are dead or flopping around in the sediments; or (ii) the pond is down only a few centimetres instead of a metre as was planned. About that time the seine crew will show up to either find many dead fish and any remaining live ones flopping around in the sediments; or they will be required to stand around for several hours waiting for the pond to be lowered to a level that they can start harvesting.

The presence of a harvest basin is useful, particularly during the final stages of a complete pond harvest. New water running continuously into the harvest basin until the last fish are removed provides them refuge in water that is not too warm for their survival and is oxygen-rich, until they are captured.

A harvest seine should be one-third longer than the width of the pond to allow it to form a semicircle as it is being pulled through the water (Fig. 9.4). The seine needs to be of a height that the cork line floats easily at the water surface and the lead line or mud line is in contact with the bottom. It is common for one of the seine crew to follow the seine through the pond and help ensure that the lead line remains in touch with the pond bottom (Fig. 9.4). The float or headline of a seine typically consists of a rope to which floats, made from cork, plastic, Styrofoam® or some other buoyant material, have been attached at intervals of no more than a few centimetres. The so-called lead line is typically a nylon rope that may or may not have lead weights spaced at intervals along its length. Seines with lead lines work well in sandy-bottom ponds, but not so well in mud-bottom ponds. A mud line – which does work well in mud-bottom ponds, as the name implies – is a series of small ropes, often made of cotton, braided together to make a larger rope of 3–4 cm diameter that, when water-soaked, tends to hold well on top of muddy pond bottoms without collecting balls of mud.

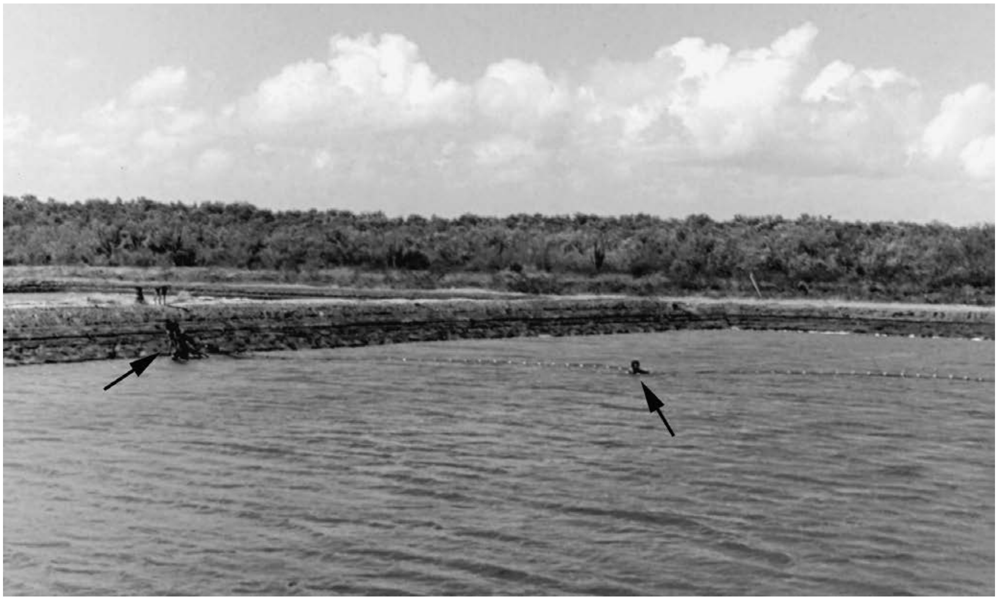

Fig. 9.4. Seining a pond in Jamaica. Note the float line which indicates that the seine forms a semicircle across the pond. The arrows point to a person pulling one end of the seine along the pond bank and another person who is holding down the lead line of the seine so fish cannot escape underneath the net.

In small ponds, seines can be pulled by hand, though in larger ponds trucks or tractors are commonly used to pull the seines slowly through the water. Bag seines are popular. They have a compartment – the bag – in the middle into which the fish are gathered. Some seines are designed so that the bag can be emptied directly into a live car (also made of netting) from which they are later loaded on to a hauling truck.

One pull of a seine through a pond will not result in total harvest. In the partial harvest process, the size of the mesh is sufficiently large that unmarketable fish can escape so the bulk of the catch will be fish of the desired size range for marketing (Fig. 9.5). That still means the seine should be passed through the pond two or more times, unless the intention is to collect only a fraction of the harvestable animals, and this was achieved in the first seine haul.

During total harvest, smaller-mesh seines can be used because the object is to collect as many of the fish as possible on each seine pass and, ultimately, to collect them all. Following the first seine haul the water level, which should be at about half the volume of a full pond when you started seining, may be reduced further, after which a second seine haul is made. The process is repeated until the pond is virtually empty. That is when it is very helpful to have a harvest basin into which the last of the fish (or most of them, as some may become stranded in water-filled depressions or will be found flopping in the mud) are confined. Having a steady inflow of new water at the harvest basin is also important during the final stages of harvesting, as the small amount of water in the basin will heat rapidly under full sunlight during warm weather, thereby severely stressing the fish, unless cooler water is consistently provided. The last of the fish can be removed from the harvest basin with dip nets. Those that are out in the mud or in depressions in the pond bottom can be netted or picked up by hand. They should be flushed with clean water to remove the mud before being placed in the hauling tank or being put on ice.

I (R.R.S.) have found that tilapia not caught in a seine are prone to bury in the pond bottom mud as the harvesting process is completed when the water has been nearly or totally drained. The fish give themselves away by movement. One would think that, with their gills clogged with mud (often for several minutes before they are discovered), they would be asphyxiated, but as you now know, tilapia are hardy animals, so if they are washed off and their gills are flushed, they seem to be unaffected by the experience. Even more interesting with respect

Fig. 9.5. Net full of harvested catfish.

to the toughness of tilapia is that we often found tilapia still flopping on the pond bottom the morning after harvest. Many of those fish survived after being placed in tanks of clean water.

We previously mentioned that seining a pond is difficult if there are stumps or other obstructions that may snag a seine. Large amounts of aquatic vegetation in the form of either algal mats or vascular plants can also hamper seining operations. The net can become clogged with vegetation – often referred to by the more common term, 'weeds' – and the effectiveness of the seine to capture fish is greatly reduced (Fig. 9.6). The fish that are captured must be pulled from the vegetation by hand. Additional photos of ponds with various kinds of aquatic vegetation are located in Appendix A at the end of this chapter.

Several techniques have been employed in getting the crop from the seine to the hauling vehicle. Sometimes, a holding cage placed in the pond is used to collect the fish from one or more seine hauls (Fig. 9.7). The cage can be pulled to the pond bank (Fig. 9.8) and the fish then can be transferred to hauling tanks or totes of ice using nets, baskets, tubs or, in the case of Fig. 9.8, a barrel. Nets, baskets, barrels, etc. of fish may be hand-carried up the levees and handed up to workers who put the animals in the live-hauling tank or in totes of ice. That tends to be back-breaking work, and when there are steps along the side of the pond to assist workers in climbing out, the activity is greatly facilitated though still labour-intensive. Some live haulers have cranes attached to their trucks or bring along a truck with a crane that can be used to lift large baskets of fish or shellfish from the harvest area up to the hauling truck. I (R.R.S.) have also seen conveyer systems used to bring fish from the pond bottom to the top of the pond bank. One such system is shown in Figs 9.9 and 9.10.

One device that is a real labour saver is the fish pump. Fish pumps basically suck the fish out of the seine bag, holding cage, harvest basin, raceway, tank, cage or net pen and transfer them to the hauling truck, sorting area or, in the case of cages and net pens, more often to a boat equipped with a hauling tank. Various designs have been developed (Fig. 9.10), with the major standard feature being that they are gentle enough that the animals are not damaged when they pass through the pump.

Because there are so many different pond sizes and producers around the world who have different capabilities with regard to mechanical assistance with seining and hauling the catch to market, the descriptions above and those shown in the figures

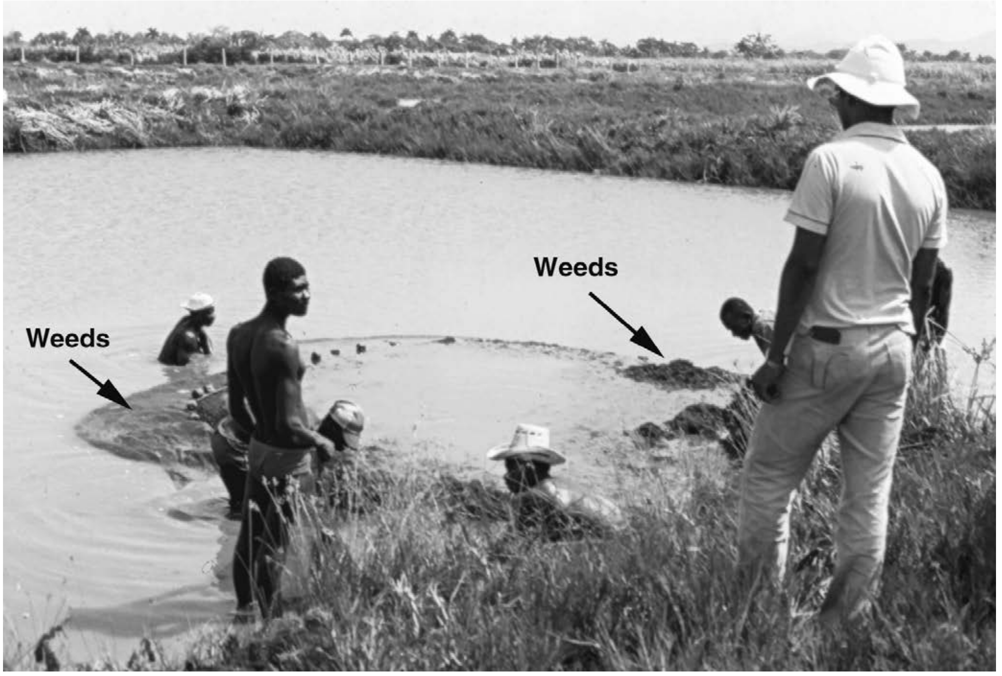

Fig. 9.6. This pond in Haiti had a significant aquatic vegetation (aquatic weed) problem, making seining difficult.

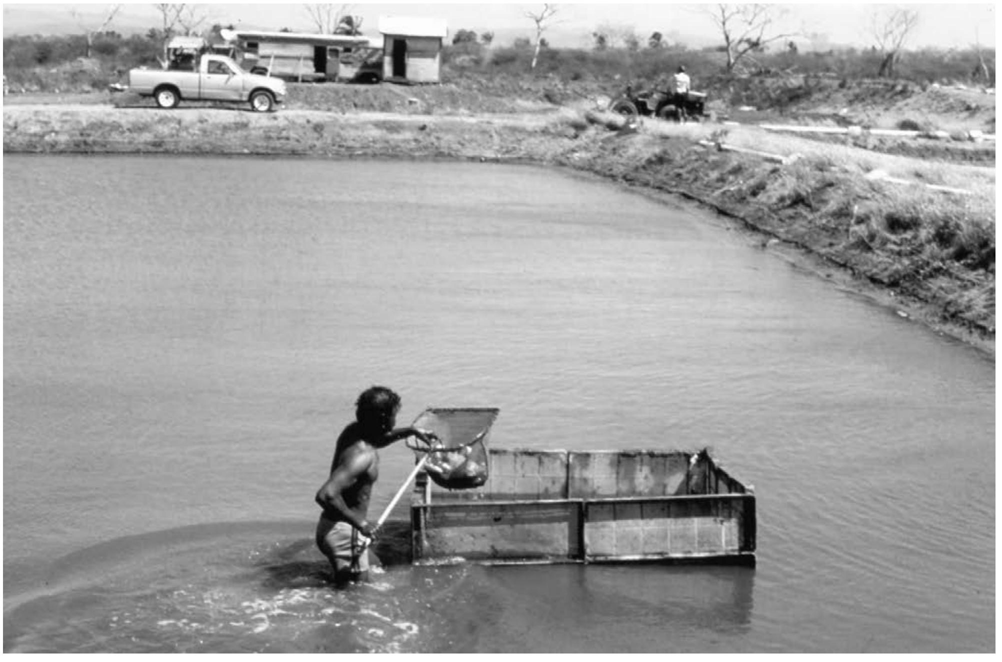

Fig. 9.7. A holding cage in a pond being harvested in Jamaica. The worker is transferring tilapia captured in a seine (not shown) into the cage.

Fig. 9.8. Seined tilapia being moved from a holding cage in Jamaica and transferred to barrels from which they can be loaded into a hauling tank for transfer to the market.

Fig. 9.9. A cart loaded with tilapia (see arrow) moving up the conveyer to be loaded into a live-hauling truck.

cover everything from small operations to large-scale ones. Modifications in harvest methodology to suit local conditions are often necessary. In some cases, the catch is carried in reed baskets to the local market by hand, perched on a person's head, or on a cart, motorcycle or small truck, and is not even kept on ice between the pond and the local point of sale. The catch may not even be transported in water. The animals are frequently sold in the round in a village or town market without any processing whatsoever.

Harvesting intensive systems

Harvesting tends to be relatively easy in tanks and raceways, though it may be a problem with respect to large cages, and perhaps less so with net pens. Crowders can be used in raceways and tanks to

Fig. 9.10. An example of a fish pump. There are many designs and sizes used around the world. This one happens to have been in Israel.

force the culture animals in a small volume of water (Fig. 9.11) from which they can be removed with dip nets or fish pumps. The amount of crowding can be increased as animals are removed so their concentration within the reduced available water volume remains high. A device to crowd animals in a raceway may be a metal frame with vertical bars placed at intervals close enough that marketable animals cannot escape, while allowing sub-marketable animals to pass through to undergo additional grow-out. Alternatively, frames with screens attached may be used, though these may not separate harvestable from smaller animals, depending on mesh size. The crowder is pushed from the upper (inflow) end of the raceway toward the lower (drain) end, forcing the fish or invertebrates to move to the lower end of the culture unit. In a circular tank, two crowders may be used. Initially they would be placed in contact with one another, then one or both would be moved around the tank (in opposite directions if two are moved simultaneously), so the animals are eventually crowded between the devices. In deep tanks, the water level may need to be reduced before the animals are crowded, depending on the configuration of the crowders.

One trout hatchery I (R.R.S.) visited in the state of Utah, USA, used a fish pump to remove the fish from its raceways. The fish then travelled through

Fig. 9.11. Red tilapia have been crowded at one end of this raceway in Jamaica where a worker with a dip net (right edge of photo) is capturing them for loading on a hauling truck.

a pipe to a sorting machine that separated them into size classes after which they were taken, by means of a system of pipes through which the individual size groups passed, directly into the processing plant that was located not far from the raceways. In Illinois, USA, I visited a state hatchery where fish in raceways were pumped down one storey level from the rearing area to a loading dock where they could be sent directly into hauling trucks (Fig. 9.12).

If the harvested animals are loaded on to a truck within a building, the aisles between culture chambers need to be sufficiently wide (and the ceiling and doors sufficiently high) to accommodate transport vehicles. While that seems obvious, it may slip the mind of the designer of the facility who could be thinking about maximizing production space and not about how to handle the harvested product.

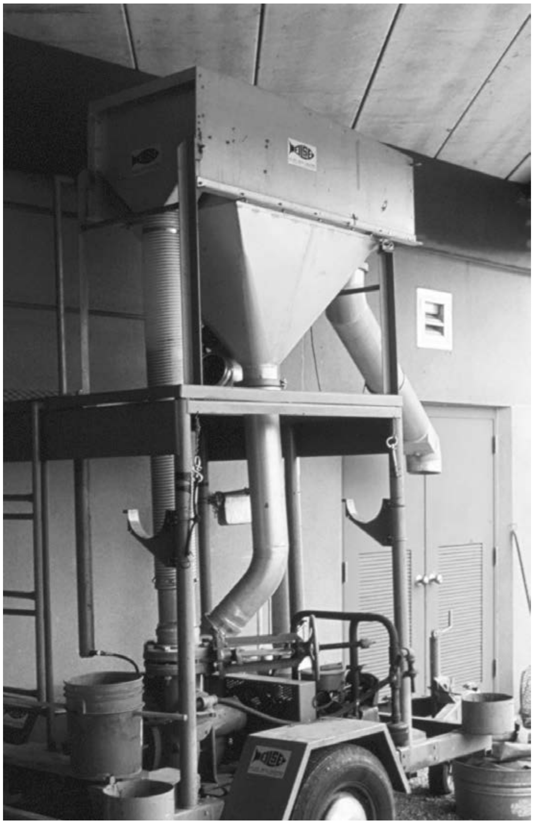

Fig. 9.12. A fish pump at a state hatchery in Illinois, USA, removes fish from raceways located on the floor above and delivers them to the location where the pump resides and from which the animals are loaded into hauling tanks.

Using architects and engineers who are experienced in designing aquaculture facilities or fish processing plants is extremely important.

Small cages can be harvested with dip nets or fish pumps. Harvest is facilitated by having cages tied to a floating platform, or which can be floated to such a platform at the time of harvesting. Having a winch and gantry on the platform so the cage can be partially lifted and tilted during harvest will come in handy. As some of the culture animals are removed, the cage can be increasingly lifted and tilted to reduce the volume of water it contains, thereby facilitating removal of the remaining animals with dip nets. Lifting cages from the water when they are full of fish is generally not practical because cages are not typically designed to accommodate the weight of the fish that have grown to harvest size. Rupture of a cage would create the problem of recapturing the fish, having a backup cage and other challenges.

Large marine cages, some of which now measure in the thousands of cubic metres in volume, pose a new problem for those involved in harvesting fish. Again, some type of crowder can be used to concentrate the animals. This would usually involve a net that is moved through the cage by divers to drive the fish into a relatively confined space from which they can be removed with fish pumps.

Net pens can be harvested by reducing the volume of the pen by gradually hauling in the net. Having two layers of netting within a pen will reduce the chances of loss of fish if the internal net were to rupture during the harvesting operation. Again, as the volume of the net is reduced, the fish can be dip netted or pumped from the net pen and put into hauling tanks. In the case of pens that are not attached to the shore via walkways, but are in an open bay or offshore, boats equipped with fish pumps are usually used to collect and transport the fish back to land where they are transferred to trucks; or the boats may sail directly to a shoreside processing plant (Fig. 9.13). Sedation with isoeugenol (AQUI-S®) has been used in conjunction with Atlantic salmon (*Salmo salar*) harvests from net pens to reduce stress. The technique has also been evaluated with respect to harvesting channel catfish (*I. punctatus*). In Chile, R.R.S. visited an Atlantic salmon facility where the culturists put fish harvested from production net pens into a nearshore 'resting' pen where they were allowed to recover from the harvesting stress. They were then pumped directly into a chilling tank where they were cold-shocked immediately before being processed (Fig. 9.14).

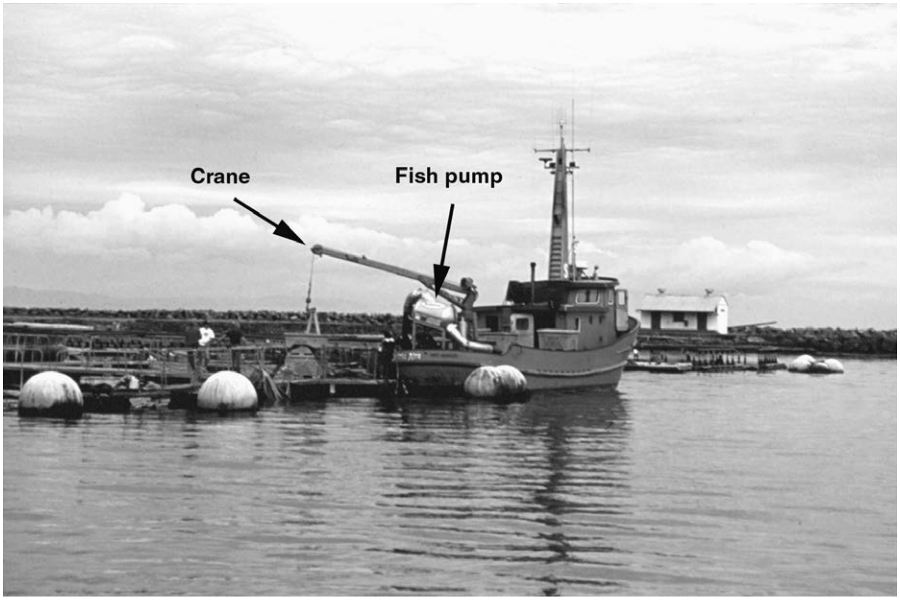

Fig. 9.13. A salmon harvesting boat in the state of Washington, USA, has a crane that is used to pull up the netting to concentrate the fish, which are then pumped aboard the vessel and into a holding tank.

Fig. 9.14. A fish pump at an Atlantic salmon net pen facility in Chile pumps harvested fish from a 'resting' pen into a chilling tank outside the processing plant.

Sub-marketable individuals captured from raceways, tanks, cages or net pens can be transferred back into the culture chambers from which they were captured. A more common technique would be to place the animals in a different culture chamber, perhaps in one that already has similar-sized fish but was understocked, for further growout. If sub-marketable animals are immediately returned to the culture chamber from which they were captured, the same animals might be handled several times before all the marketable ones are removed. No matter the harvest method, repeated handling can be stressful on the animals.

Specialized harvesting methods

Harvesting sessile marine animals such as oysters and mussels requires harvesting techniques different from those used for motile species. Oysters reared at the bottom can be harvested manually by picking up intertidal clumps at low tide or by tonging or dredging for subtidal clumps. Some states have regulations on harvesting oysters that have even been applied to those reared by aquaculturists. Florida, USA, has long restricted oyster harvesting from leased beds to tonging, while clam harvests in some areas have historically only been allowed using sailing vessels, not motorized ones. One state in the USA once even restricted shellfish harvesting in aquaculture facilities on Sundays. In other states, fish raised on private properties were once deemed property of the state, and thus were not owned by the individual culturist. Over recent years, many of the regulations that were promulgated long before aquatic farming became an industry have been amended to accommodate private aquaculture.

Oysters grown in trays and on longlines suspended from rafts are harvested manually, though mechanical devices are used to raise heavy strings of animals to the surface. Mechanical harvesters to collect oysters from the seabed have also been developed. Mussels are typically grown on poles or longlines suspended above the substrate. Harvesting technique is based on how the mussels are grown, but generally mirrors the methods used for oysters. Scallops are sometimes grown in lantern nets (a type of basket) attached to longlines. Scuba divers are commonly used for harvesting benthic animals such as abalone. Commercially geoducks are harvested with water hoses that are under high pressure. Geoducks are several centimetres deep in the sediments with only their siphons reaching the surface, so while recreational harvesters use manual digging with shovels, commercial harvesting is much more efficient by using water pressure to wash the clams out of the sediment. Having had experience digging geoducks, R.R.S. can confirm that it is strenuous activity. Collecting one or two recreationally is probably enough for most who dig them.

Clams can be dredged, mechanically harvested, or grown in trays. In the case of tray culture, marketable clams are harvested manually. One technique is to plant young clams in the intertidal zone under netting, which helps keep predators from attacking them. When the clams reach market size, the net is removed, and the clams are gathered. On firm sediments in the intertidal zone, tractors can be used to pull a specialized apparatus (like a rake) designed to collect the clams at low tide. This saves a great deal of manual labour and is an efficient means of covering a large area during the intertidal period when the harvesting equipment has access to the intertidal area.

As we have seen, crayfish are harvested using baited traps such as the one shown in Fig. 6.27. The trapping season is up to several months long because it involves: (i) the recapture of the adults that were stocked for reproductive purposes; and (ii) the capture of the 'young of the year' crayfish when they recruit into the harvestable population. The traps are run at least once a day using a small, shallow-draught (flat-bottomed) boat with an outboard motor. Specially designed motors are used in Louisiana, USA, which can be operated in the very shallow water of the crayfish ponds. As the boat approaches a trap, the trap is lifted from the water and a second baited trap is taken from the boat and put in the pond. While the boat moves to the next trap, the one just removed from the pond is emptied into a holding container and then bait is added before the trap is put back in the water. Often, the entire process is conducted by one person, though having two people in the boat – one to drive and the other to retrieve, empty and reset the traps – can expedite the process.

Factors that can affect the efficiency of trapping include the amount of natural food (forage) present, water quality, crayfish density, climate, trap design, the bait being used and trap density. While only a few trap designs have been presented in this book, for example in Chapter 6, several designs are currently in use. Many traps are home-made and may be designed by the user.

Traps are baited with dead fish or commercially manufactured baits. Commercial baits have the advantages of being easy to handle, not having noxious odours and having long storage lives without requiring refrigeration. Manufactured baits appear to be most effective when the temperature is above 14°C, though much of the harvest period occurs when the water temperature may be lower than 14°C, during which times dead fish may be much more effective than manufactured bait.

Crayfish producers began producing softshell crayfish in 1985 and there was a significant demand for the product during the first few years after it became available and commonplace. To produce softshell crayfish, immature animals are trapped and put in culture trays at high density where they are fed. The culturists were able to identify crayfish that were about to moult and would remove them from the population to avoid cannibalism. Once they moulted, the softshell crayfish were packaged and frozen for sale. Despite the premium price, the economics changed when a competing product started to flow into the USA from Asia in the 1990s. The result was the closure of most of the softshell production facilities that were once numerous in Louisiana, and only a few continued to operate. Imports also outcompeted frozen crayfish tails in the US market by selling for less than the domestic product. As a result, the market for processed crayfish, mostly in the form of frozen tail meat, is now dominated by imported product. The majority of the crayfish harvested in Louisiana are now sold live for the numerous crawfish boils that are held in the late summer and spring of the year, which have been discussed previously. Figure 9.15 should convince you that crawfish boils are popular. The crayfish are sold in various outlets, including grocery stores. I (R.R.S.) recently saw a sign (in late February) indicating that one of major grocery chains in my area had live crayfish available on Friday, Saturday and Sunday of each week.

Live Hauling

We have already seen that live hauling can involve carrying harvested aquaculture animals to market in tanks of water mounted on trucks. Such trucks need to be equipped with aeration equipment. Tanks on pickup trucks traditionally employed agitators that consist of small electric motors from which paddlewheels in a cage are suspended half in and half out of the water. The cage is made of

Fig. 9.15. Attendees of a crawfish boil enjoy peeling and eating the 'mud bugs'.

about 0.6 cm hardware cloth and protects the live fish from contacting the paddlewheels when the motor (which is powered by the truck battery) is running. The caged paddlewheel part of the agitator is dropped through a hole in the top of the hauling tank (usually four agitators will be used on a pickup truck hauling tank). The motor itself has a metal flange between it and the cage, so the motor can sit on top of the hauling tank with the cage going through the hole in the top of the tank. When activated the paddlewheels spin rapidly, causing agitation of the water, leading to aeration and the maintenance of DO in the hauling tank (Box 9.2). Another commonly used method of aeration is to carry bottles of compressed air, gaseous oxygen or liquid oxygen that will feed gas into the water through airlines and air stones.

Large trucks may use any of the methods mentioned for pickup trucks, in addition to perhaps carrying a liquid oxygen tank and/or a generator that runs an air blower, air compressor or agitators. In many cases, at least two aeration methods are available on large trucks so that there is a backup in case one of the methods of aeration should fail.

Box 9.2.

When I (R.R.S.) was a graduate student, I had the opportunity to spend a summer at a federal government laboratory in Arkansas, USA, where the focus was on catfish culture as I have previously related. A researcher from another government laboratory located in the neighbouring state of Missouri came to the Stuttgart facility to obtain a load of catfish fingerlings. We loaded the fish in the hauling tank on his pickup truck and connected the agitators to the truck battery. His plan was to drive through the night, which is what he did. A rubber wheel at the top of each agitator – one for each of the compartments of the hauling tank – could be observed spinning, so the driver could stop periodically and observe the agitator to ensure that the motor of the agitator was running. We found out later that all the fish in one compartment of the tank had died from lack of oxygen, even though the wheel on the agitator associated with that compartment was checked frequently and continued to spin as it was supposed to. What the researcher failed to check was if the paddle was functioning properly. In that one compartment, the paddle had come loose and had fallen to the bottom of its compartment. Thus, there was no aeration in that chamber.

Animals scheduled for hauling should not be fed for at least 24 h prior to being loaded so that they can purge their intestinal tracts. That will reduce fouling of the water during transportation. Ice can be added to hauling tanks, and it is also common to use insulated hauling tanks to help keep the water from becoming too warm (or too cold, if warmwater fish are being hauled during cold weather, when ice would obviously not be necessary). Anaesthetics may also be used in hauling tanks but should not be used when hauling fish to a processing plant if there is a possibility of leaving a chemical residue in the flesh. Carbon dioxide may be an acceptable anaesthetic for fish going to processors, because it is a natural by-product of respiration. More information on anaesthesia and sedation is provided Table 9.1.

Since the last edition of this book, several other chemicals or techniques have been evaluated as anaesthetics for their utility in aquaculture. Those we have found are:

- azaperone;
- electrosedation;
- *Eucalyptus* sp. oil;
- essential oils;
- geranium oil;
- isoflurane;
- Lippia alba oil;
- *Oranium* sp. oil;
- propofol;
- tea tree oil;
- temperature; and
- thymol.

It is highly recommended to access information available at the Aquatic Animal Drug Partnership (https://www.fws.gov/fisheries/aadap/aquaculture.html, accessed 21 December 2021) to be sure which products are approved by the FDA or are of low regulatory priority.

The density at which animals are hauled can have a major impact on water quality and, as density increases, so does fish-to-fish contact that may cause damage – all in addition to the handling stress that the fish have experienced. There does not appear to have been a great deal of research focused directly on the question of optimum density during live hauling of either fish or invertebrates.

Table 9.1. Many of the anaesthetics and sedatives that have been used on aquaculture species.

2-Phenoxyethanol	Alfaxalone
AQUI-S®	Benzocaine
Bushy matrass (*Lippia alba*)	Camphor (*Cinnamomum camphora*)
Carbonic acid	Carbon dioxide
Clove oil	Clove basil (*Ocimum gratissimum*)
Ethanol	Etomidate
Eugenol	FINQUEL®
Magnesium chloride	Menthal
Menthanol	Methyl salicylate oil
Metomidate	Mint (*Mentha arvensis*)
MS-222 (tricaine methanesulfonate)	Propiscine
Quinaldine	Sodium bicarbonate
Spearmint oil	Tricaine-S®

Some types of fish eggs and oyster spat can be shipped damp but not in water, so long as they reach their destination within several hours. Air freight costs can be reduced considerably by shipping such items without water or in a small amount of water, and they can be delivered anywhere in the world within 24 h, assuming there are not weather, equipment or other types of delays. Traditionally, shipments of trout eggs are packed in wet Spanish moss (*Tillandsia usneoides*). Baseball-sized packages of oyster spat (several million spat in each package) can be wrapped in wet gauze and shipped. In both cases, the animals should be shipped in insulated boxes to keep them at the proper temperature. Ice may be used as well, in some instances.

Fish fry can be shipped in plastic bags. Small fingerlings have also been shipped the same way. It is common practice to ship ornamental fish around the world in plastic bags. Several hundred or a few thousand fry (depending on fish size and the size of the bag) are placed in a plastic bag that is filled with about one-quarter to one-third of its capacity with water of the appropriate temperature. An air tube is placed in the bag, the top of the bag is wrapped around the tube and pure oxygen is pumped into the bag to saturate the water and displace the air in the bag above the water. The air tube is then extracted, and the bag is sealed with a rubber band. The bag is then placed in an insulated box that is also sealed. Boxes of fish fry or small fingerlings can be sent virtually anywhere in the world via air freight, though for shorter distances various forms of land or boat transportation can be used. The main concern is to have the boxes delivered within 24 h, if possible (Box 9.3).

Box 9.3.

I (R.R.S.) was once asked to send some tilapia fingerlings (3–4 cm in length on average) from Texas, USA, to Canada. We boxed up a few hundred fish in bags that each contained no more than about 50 fish. The flight schedule called for delivery at their destination within about 8 h after the boxes were first boarded on a plane. The route involved flying from College Station to Houston, both in Texas, and then on to Canada. Several weeks passed after the fish were shipped before I heard back from Canada. I was told that the fish were supposed to change planes in Chicago, Illinois, USA, but that they had been held there for nearly three days. When they finally arrived in Canada the water was yellow with fish metabolites (the fish had not been fed for 24 h prior to shipment to reduce faecal production) and the DO was virtually zero. Of about 400 fish in the shipment, fewer than ten failed to survive the trip. I do not recommend trying that with any other species. The tilapia probably would not have survived either, except that the shipment was made during the winter and the cold weather helped reduce their metabolism while they waited on the tarmac. Fortunately, it was not cold enough to kill them.

Anaesthesia and Sedation

A list of various anaesthetics and sedatives that have been effectively used on fish and shellfish is presented in Table 9.1. One commonly used anaesthetic is tricaine methanesulfonate (MS-222), which is commercially sold under the brand names FINQUEL®, Tricaine-S® and perhaps others.

MS-222 is effective but expensive and can cause a significant reduction in water pH. The concentrations of the chemicals needed for effective anaesthesia vary with the species involved, water temperature and other factors. Quinaldine has come into disfavour because of potential toxicity to humans. Clove oil has been shown to anaesthetize at least one species of penaeid shrimp, but is apparently not effective on freshwater shrimp, nor are MS-222 and 2-phenoxyethanol.

MS-222 is a powder that is added to the water. Effective doses are from 15 to 330 mg/l, with the level depending upon water temperature and hardness, stage of development of the fish and their size, species and the desired depth of anaesthesia. Fish anaesthetized by MS-222 products require a 21-day withdrawal period in the USA before being harvested and processed. AQUI-S® has been approved for aquaculture use in Australia, Chile, the Faroe Islands and New Zealand. Many anaesthetics used in conjunction with live hauling require a considerable amount of time to allow the fish to recover and may, as is the case with MS-222, require a withdrawal period. AQUI-S® has a couple of advantages here: the fish quickly recover and there is no withdrawal period.

CO_2 anaesthesia can be produced by adding CO_2 gas or carbonic acid to water. Anaesthesia can also be induced by hypothermia and electric currents. For invertebrates, 5–10% ethanol is effective for molluscs, as are CO_2 and $MgCl_2$.

Sedation involves creating a condition of calmness in the animal, not loss of consciousness, as is the case with anaesthesia. Sedation is particularly useful when used in association with hauling live animals. Reducing the temperature of the water works as a means of sedating both finfish and shellfish (Box 9.4). Using reduced levels of anaesthetics can also have a sedation effect. Much more detail on the topic of anaesthesia and sedation is presented in the book by Ross and Ross that is listed in the 'Additional Reading' section of this chapter.

Box 9.4.

Early in my (R.R.S.) first stint at Texas A&M University (I was there from 1975 to 1984, returned in 1996 and retired in 2011), a colleague asked me to bring him some catfish fry for use in his research. They had been produced by a team of graduate students doing research in the cooling lake of an inland power plant about 150 km from my research facility near the Texas A&M University campus. The students at the power plant had been provided with a small wet laboratory where they had spawned several catfish, hatched their eggs and had grown the fry to the swim-up stage. Once I arrived at the power plant the A&M students helped me distribute the fry into several plastic bags; aerate the water in the bags to saturate the oxygen level; seal the bags; and place them in a large ice chest, to which we added ice to keep the water cool. The trip back to my lab took less than 2 h, so I didn't see any need to check on the fry – they should have been in good shape, or so I thought. When I arrived to meet my colleague at the lab so he could stock the fry into his experimental units, we found all the tiny fish floating at the water surface in the bags. The water temperature had fallen dramatically, demonstrating that cooling the water will lead to sedation and anaesthesia – something I was not aware of at the time. I thought all the fry were dead. My colleague tried to soothe my feelings by saying: 'I think they'll recover when we get the water warmed up.' He was partially correct. Many of the fish did recover – in fact, enough of them to allow him to conduct his experiment. But many were lost, and I learned a couple of good lessons: (i) don't use a lot of ice when a little ice will do the job; and (ii) frequently check the water temperature and status of the fish being hauled.

Fee Fishing

Fee-fishing operations may be independent of other aquaculture activities, or they may be integrated into the activities of an aquaculture venture that also produces food fish for sale to the public or to a processor. Fee fishing provides recreational anglers with the opportunity to catch fish with the assurance of a reasonable degree of success. In the USA, fee-fishing operations for channel catfish (*I. punctatus*), rainbow trout (*Oncorhynchus mykiss*) and sometimes both can be found in many regions, with the species available being dependent primarily on climate. In Brazil, various local fishes such as pacu (*Piaractus mesopotamicus*), as well as exotics such as tilapia (*Oreochromis* spp.), are found in fee-fishing operations (Fig. 9.16).

Some commercial fish farms set aside one or more ponds for fee fishing, while other facilities are strictly used for fee fishing. In the first instance, the fee-fishing lakes are restocked from production ponds that may also produce fish that are sent to a processing plant (which may or may not be on site), while in the

Fig. 9.16. A sign at a fee-fishing operation in Brazil showing the species that are available and the cost of each to the angler who catches them.

latter, catchable-sized fish of sizes desired by anglers are purchased from a grower. An intermediate activity would involve production ponds used strictly for growing fish to be stocked in fee-fishing lakes (on the same facility where the fish are produced) and possibly for sale to other fee-fishing facilities.

Fee-fishing lakes are often more natural in appearance than production ponds. They may be irregular in shape and can be landscaped to provide an aesthetically pleasing experience for the anglers (Fig. 9.17). Picnic tables, playgrounds for the children and other amenities may also be provided. On facilities that feature a range of species, signs on individual ponds tell anglers what they can expect to catch (Fig. 9.18). Of course, not every fee-fishing pond is well maintained, though that does not necessarily dissuade recreational fishermen from using the facility (Fig. 9.19). Anglers are expected to keep all the fish they catch (Fig. 9.20) and pay on the basis of the weight or number of fish they remove from the ponds. In some cases, an entry fee may also be required.

It is interesting to talk to fee-fishing facility operators. While the prices asked by the operators are usually very reasonable – an additional fee for processing may be imposed but can often be avoided if the fisherman is willing to dress the fish either on site or at home – fishermen sometimes try to avoid paying for some or all the fish they catch. They will try to smuggle fish out in the wheel wells of their cars, hidden in the trunk or secreted somewhere else on the vehicle. If they catch a fish and do not want to keep it, they will try to be sneaky about releasing it without being seen. Most people are honest, but the staff at a fee-fishing operation will need to be always vigilant so they can spot those who do not play by the rules, which, incidentally, should be clearly displayed by signage and/or on handouts that are given to each fisherman.

The operator of a fee-fishing operation will stock the ponds with catchable fish and replace the ones caught with new ones at frequent intervals to maintain a high density and give the anglers a high probability of catching fish. A few very large fish may also be stocked, and there have even been cash awards or prizes offered to the angler who catches a particular tagged fish (see the 'Tagging' section of this chapter for more information on procedures).

Because fee-fishing operations profit from the capture and removal of fish, it makes sense to keep the ponds well stocked and to limit the amount of feed that is offered to them so the fish will be hungry when the gates are open to anglers. A good fishing experience by the anglers is not only good for profits; it also helps ensure customers will return for additional enjoyment in the future.

Fee-fishing operations tend to work well in the vicinity of large cities and in other areas where public fishing opportunities are limited, overcrowded by anglers, not well maintained, polluted and have been overfished, or just because the operations provide a convenient place for a quick fishing opportunity (Figs 9.21 and 9.22). The fee-fishing operations R.R.S. visited in Brazil were far removed from any population centre but were apparently economically successful. People living in urban environments may find it difficult to mount major fishing expeditions, but they can often be tempted to fish with some regularity if a well-maintained fee-fishing operation is located within easy commuting distance.

Fig. 9.17. These fee-fishing ponds in Brazil are provided with benches for anglers to sit on, covered picnic areas, well-kept grassy areas and other amenities.

Fig. 9.18. A sign on the pond levee of this Brazilian fee-fishing operation tells the angler the species that have been stocked in that pond.

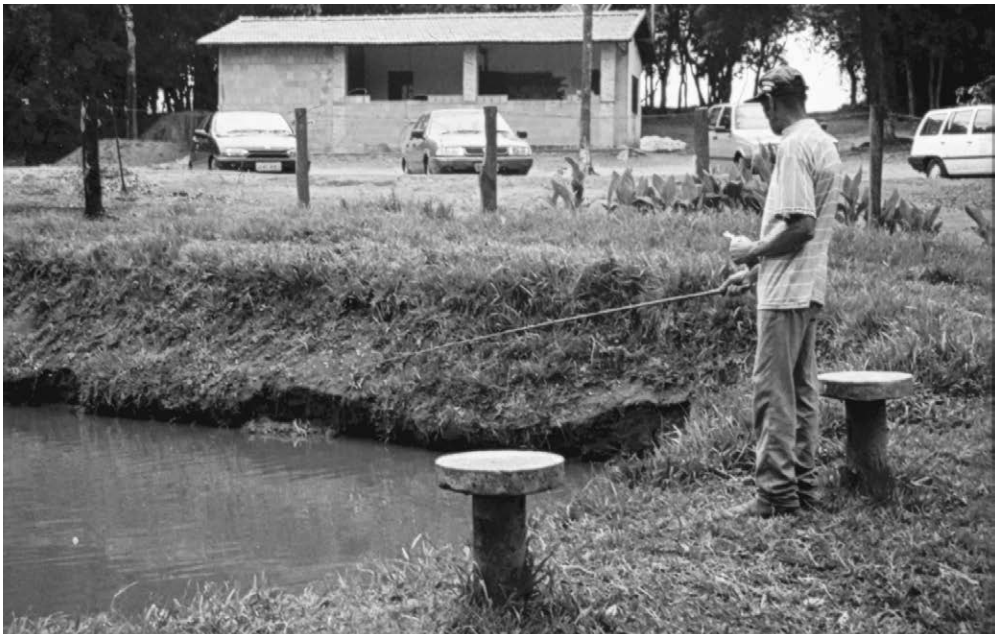

Fig. 9.19. This angler does not seem to be concerned about the poorly maintained fee-fishing pond on a facility in Brazil.

Fig. 9.20. A sign indicating that if you catch a fish, you are charged with keeping it – so you will have to pay for it.

Well-operated fee-fishing facilities offer an array of services to anglers. Bait is commonly sold, and the facility may rent or sell tackle. Sales of tackle can be lucrative as well. Many fee-fishing operators will clean the catch and ice it down for an additional fee. Cleaning stations where anglers can clean their catch before leaving the facility may also be available (Fig. 9.22). Public restrooms (often in the form

Fig. 9.21. A trout fee-fishing operation in Redmond, Washington, USA. This town is a few kilometres from Seattle, adjacent to Lake Washington and not far from Puget Sound, both of which offer other fishing opportunities.

Fig. 9.22. Anglers entering the trout fee-fishing facility in Redmond, Washington, USA. Fee-fishing facilities often have an area where the fish can be cleaned, either by the angler or an employee of the facility – for a fee, of course.

of portable toilets) are a must, and refreshments should be made available through vending machines or at a food stand or small cafe.

Tagging

Fish tagging is conducted routinely in many government hatcheries that produce fish for stocking recreational fishing waters and enhancement of commercial fisheries. Tagging is not a common activity on aquaculture facilities that produce food fish commercially. An exception was mentioned in the 'Fee Fishing' section above, in conjunction with providing cash or a prize to the angler who catches a tagged fish. Other reasons a commercial aquaculturist might wish to tag fish would be to identify broodfish for selective breeding purposes or to be able to identify the sex of broodfish when they are not in breeding condition. In some jurisdictions, fish are required to be tagged so they can be identified in the event they escape and mingle with wild conspecifics. The most common instance of that would be in conjunction with Atlantic salmon (*S. salar*) cage or net pen culture. In that case, there may be a requirement that all cultured fish have their adipose fin removed – a form of tagging.

Various other ways of tagging aquatic animals beyond fin clipping have been developed, and there are also methods available for tagging many types of invertebrates. Included are coded wire tags, which are 1–2 mm pieces of very-small-diameter wire with notches in them that carry a code allowing for identification of groups of fish, but not usually individuals. These tags have been widely used by salmon hatcheries, for example to identify the hatchery that released the fish. The tags are injected into the nasal cavity of smolts. When the fish return, tagged fish can be identified with a device that can detect the tiny tag, which can then be recovered and read.

Among the external tags that have been widely used are spaghetti tags (coloured plastic strips that can contain an individual identification number and other information) that are partially embedded in the flesh of a finfish or even a shrimp. Plastic discs with identification numbers can also be attached to a fish or invertebrate. One of the problems with external tags is that they can become detached and lost. The area where a portion of the tag enters the animal's muscle or where a disc is attached can also become a site for infection. When invertebrates moult, they typically shed their tags.

In the past few years an eye tag for fish has become popular. Each tag contains an individual alphanumeric code and is a small piece of material that is injected into the cornea. Liquid plastic tags can also be injected into aquatic animals, with a particular group being identified by the colour of the tag material.

Branding is another form of tagging that has found some use, particularly with catfish that do not have scales and can easily be branded, though it can be used with other fishes as well. The branding device is merely an electrode and source of electricity, such as a battery. The electrode may have a particular shape and be used similar to a branding iron, or each individual fish can have a unique brand drawn on it (Box 9.5).

The high-tech way of tagging aquatic animals is with passively integrated transponder (PIT) tags, which are in the form of a tiny electronic circuit embedded in glass. PIT tags are about the size of a grain of rice and can be injected by syringe through a large-gauge needle into the abdominal cavity or musculature of fish as small as a few grams. The circuit has a small antenna associated with it. When the circuit is interrogated with a device that sends out an electronic signal, the tiny chip sends back a unique alphanumeric code. Billions of combinations are possible, so individual animals can be identified. The major issue is cost, because each PIT tag has a price tag of up to a few dollars (the price varying depending upon how many are purchased – the higher the quantity of tags in an order, the

Box 9.5.

Years ago, a visiting scientist was working on sabbatical at my (R.R.S.) laboratory and mentioned that he had a branding device that he thought we might find useful for identifying individual brood catfish. During his sabbatical, he returned to his home country for a vacation and returned with the branding device. At the airport where his return was to begin, he passed through the screening area and was pulled aside and asked to open his briefcase. Inside was the branding tool, from which wires for attachment to a battery were present, along with an alarm clock. On the X-ray machine it looked like the makings of a bomb! Airport security thought he might be a terrorist. He ultimately convinced him that the tool was not a threat and managed to get the device to our lab where we used it to tag brood catfish.

lower the price per tag). Some hatcheries have modified their intake water plumbing to require returning salmon to pass through an area where PIT tags are automatically read as the fish swim through the detector. The unique alphanumeric code is then fed to a computer that can bring up the information on that particular fish, which might include hatchery of origin, date and size at release, and any other type of information that was recorded at the time the fish was tagged.

Processing and Marketing

If processed products are to be marketed, the aquaculturist basically has two choices after the crop is harvested. It can be processed on the farm, or it can be shipped to a processing plant. If the aquaculture operation is located near a traditional commercial fishing port or where commercial aquaculture is well developed, chances are there will be one or more processing plants in the vicinity. In other locations, the nearest processing plant may be quite distant from the aquaculture operation. The availability of local processing plants can be a determining factor about whether to process on-farm or ship the product to a processor. Very small and very large operations may process their own fish. In the case of the small operator, that would just require a small building or section of a larger building area where the fish or shellfish are processed by hand. For a large operation it may be a processing plant that employs a cadre of people and may be designed with sufficient capacity to process fish for several aquaculturists in the region, or even the fish and/or invertebrates from capture fisheries.

If the crop is processed on the farm, having a well-developed market for that product is essential. That may be anything from shipping frozen product to the market (wholesale or retail) in trucks owned by or leased by the culturist; being hauled by a commercial live or frozen product trucking firm; or selling the product fresh and/or frozen from a market established on the farm.

In 1997, a new regulation was implemented in the USA requiring seafood processors to implement Hazard Analysis Critical Control Point (HACCP) safety and quality systems in processing plants. Monitoring programmes and mandatory record keeping are part of HACCP. Seafood safety inspections have also been implemented at processing plants in some other countries. It may be difficult for individual farmers to meet the standards adopted by governments and could force some farmers, particularly those with small operations, out of the processing end of the business.

While some commercial processing plants handle a variety of species, most limit their activities to one or a small number of species. Typically, a crayfish-processing plant would not, for example, also process catfish or oysters. In fact, crayfish are often put into the marketplace live, not processed. Specialized equipment and techniques are required for each species being processed, so personnel require different types of training in the various plants.

The products may be processed by hand or using automated equipment, though efficient automated equipment has yet to be developed for some species. Imagine coming up with a machine to clean crabs, for example. Surprisingly, perhaps, such machines have been developed, though they do not tend to be very efficient, at least the ones I (R.R.S) have seen, which I admit has been limited to a very few. In any case, crab processing, in common with that of oysters and some other species, involves a considerable amount of hand labour.

Socio-economic conditions in the nation or region where the processing plant is located will dictate, in part, how much automation is adopted. Many plants use a combination of hand labour and machinery. For example, heading of channel catfish is usually done with a band saw, and skinning and evisceration can be accomplished with machines, but filleting is typically a hand operation. Skinning machines are similar to electric wood planes, while evisceration is done with devices similar to vacuum cleaners. The belly is opened, and the entrails are suctioned out of the carcass. At each stage of processing a person holds the fish and applies it to the machine.

Machines are available for use with some fish species that will sort the fish by size and shunt the different sizes into bins from which they may be hand-processed, put through a filleting machine or cut into steaks. Machines are also available to reduce the hand labour associated with shrimp processing, though not to eliminate manual handling of the product completely.

In the Chilean salmon operation described in the ‘Harvesting intensive systems’ subsection, the harvested fish are pumped into a chilling tank where they are cold-shocked. When the fish leave the chilling tank, they are immediately bled. The fish are then hand-filleted, any bones that remain in the fillets are removed, and the fillets are then flash frozen with a glaze of water over them to prevent oxidation. The frozen fillets are packaged in plastic, boxed and placed in a freezer until they can be air-freighted to virtually anywhere in the world. The product is of superior quality and can demand a premium price.

Some processors have developed value-added products; that is, some type of speciality product that will add to the price it can fetch. Examples are crab- or shrimp-stuffed flounder and trout. Also, some forms of processed fish are more valuable than others. Consumers often prefer boneless fillets over processed forms that contain bones. The size of the fish is also important and varies from one market to another. Restaurant customers from some cultures prefer to select their seafood live. The items they pick out are then processed, cooked and served. Smoking can add significant value to such products as salmon. The type of smoking can affect not only the flavour, but also the texture of the final product.

Marketing of seafood, including aquaculture products, requires year-round availability of the product in most cases. Seasonal availability of a product often makes it difficult for chain restaurants to maintain a consistent menu. Exceptions are fresh crayfish, which are available seasonally; and oysters, which are not usually available on the half shell during months with no 'R' in them. If you order oysters in May through August in the USA, for example, you can be confident that they have been in the freezer for a few months. The reason for not harvesting and marketing oysters in months without an 'R' is that the oysters will have spawned, and their quality is reduced. While they are edible, consumer acceptance is a problem because the oysters lose their 'sweet' taste.

Grocery stores may accept certain seafoods on a seasonal basis (live crayfish being one example), but they too would rather have the same types of products available on a year-round basis. Also, the processor or fish farmer who delivers directly to the marketplace needs to meet any contractual arrangements that have been made. Typically, a supermarket will require that a certain number of kilograms (or hundreds of kilograms) of product be delivered each week. The same is true of restaurants. High-end or white-tablecloth restaurants that feature seafood in some cases develop and print their menu daily and can adjust their menu according to what products are available. However, when there is a contract between a producer, processor or wholesaler with a retailer, failure to meet that commitment will lead to loss of a retail customer. The same holds true for restaurants. Chain restaurants are adamant about having a menu that is consistent in each one of what are in some cases hundreds of outlets. Imagine being the buyer for a large seafood restaurant chain and trying to keep the supply of cultured and wild-caught fish and shellfish flowing to meet the demand in 400 or 500 restaurants located across one or more nations.

Some aquaculturists have their own restaurants on (or adjacent to) their farms, where they feature the products that they grow. In cases where the product or products are only available seasonally, the restaurant may be closed for part or most of the year.

There is a considerable live market for fisheries products around the world. A wide variety of seafood species can be seen on display in association with restaurants in many countries. People in and from certain Asian nations like to select their dinner at a restaurant from among the live specimens on exhibit. In 1999, on a trip to China, I (R.R.S.) visited several restaurants in two major cities. In all cases, aquaria with a wide variety of seafood species were on display. Moreover, I once visited a tilapia farmer in Idaho, USA, who was shipping a few thousand kilograms of tilapia live each week to Vancouver, Canada. These were for live display for selection and consumption by patrons in restaurants that catered to Asian customers.

Presentation is also important for some cultures, not only in restaurants, but also in retail markets and at receptions and other gatherings. That is certainly true in Japan where the appearance of the food, including seafood, is extremely important. A primary objective of the farmer, producer, wholesaler (if any), grocery outlet and restaurant is to provide a high-quality product so that the consumer will have a positive experience when he or she eats the fish or shellfish. Certainly, there is a profit motive as well, but none of those entities can afford to lose sight of the importance of product quality. It is the responsibility of all those who grow or handle seafood products to ensure that product quality is maintained once the animals leave the farm, although control over the product devolves to someone else who takes on the responsibility for maintenance of its quality.

Typically, frozen fish and shellfish can retain their quality for up to a few weeks after freezing, but rancidity will eventually occur. Antioxidants in the feed during the growing season or supplemented prior to harvest may help increase the time before degradation occurs in frozen fish. Sell-by dates on frozen products are useful both to the retailer and the buyer.

Fresh fish and shellfish that are not sold before the next batch arrives at the marketplace need to be sold first or discarded if there is any indication they are beginning to spoil. Degradation of fish flesh post-mortem may be rapid or slow. A lot depends on the temperature at which the products are stored. Fresh fish on ice degrade more slowly than those displayed at room temperature. Proteolytic enzymes are responsible for much of the degradation process, though lipids can become rancid and, of course, bacteria can colonize the tissues, though at that point the fish should be well beyond the stage that they are suitable for sale.

Any remaining live animals from a previous shipment (e.g. of lobsters) should be sold before the display tanks are restocked. Retail outlets are concerned about having too much product on hand or too little, particularly when dealing with live or processed – but not frozen – fish and shellfish. Knowing their clientele and keeping good records of sales will provide an indication of how much of a given product to order from one period to another (often week to week or once every two weeks). No retailer likes to dump products because they have not been sold before going bad. That's a major problem with produce (fruits and vegetables), which you may think is another story, but not in the case where the products (almost exclusively vegetables) are grown in hydroponic systems.

Hygiene during processing is also important. For example, workers in facilities where shellfish such as shrimp are processed and sorted by size are typically required to wear coveralls, a head covering and gloves (Fig. 9.23). The shrimp are then packed into boxes and frozen prior to shipping (Fig. 9.24).

The final point of sale for fish and aquatic invertebrates, whether fish markets, grocery stores, restaurants, food trucks, or even pickup trucks selling from a parking lot or parked along a road, is a critical location where quality maintenance is important. In all those retail outlets, stock rotation is critical. Stock rotation is a simple concept. Sell the product in the order that it is received; that is, sell the oldest stock first, because the longer the product stays in the display case, refrigerator, freezer or out in the heat on a table in a rural market, the more likely it will be that the quality of that product will deteriorate.

Fig. 9.23. Workers sorting shrimp prior to packaging.

The one area where the production chain loses control is when the product is purchased for home use. The homemaker may make the mistake of mishandling a fishery product by keeping it on ice, in the refrigerator or even in the freezer too long; or, worse, leaving it out at room temperature for extended time. An increase in bacteria levels, including those that can cause medical problems, and rancidity can be the result. The consumer will often blame the retailer for causing the problem, but in many (most?) cases such problems result from mishandling of the product in the home.

Potential Aquaculture Moneymakers

My (R.R.S.) professional career has involved, in part, conducting aquaculture research and teaching both undergraduate and graduate students about aquaculture at the university level. I admit to never having had to depend on producing an aquaculture crop for my livelihood. I have had enough problems arise in conjunction with producing fish for research and have lost tens of thousands of animals at a time due to various unforeseen circumstances (Box 9.6). I used to tell my students: 'Until you have been responsible for killing a hundred thousand aquaculture animals, don't whine to me about your failures. I'm way ahead of you.'

Fig. 9.24. Boxes of frozen shrimp ready for shipping to marketing outlets.

If we were to go into the business – based on the experience of having observed commercial aquaculture for over many years – we would lean towards producing ornamentals (fish or invertebrates). The amount of space involved for their production is relatively limited because the animals are small when harvested and marketed, and the price per unit in the marketplace can be quite high, which means the remuneration to the producer is also an incentive for the choice. Most of the species that can be carried through their life cycle in captivity can go from egg to marketable size within several weeks at most, so several crops a year are possible.

The high prices that can be obtained from the sale of ornamentals are particularly true for marine fishes and invertebrates. The problem with marine ornamental species is that successful culture has only been achieved for a few of them compared with freshwater species. That will change with time, so if we were involved in producing marine

Box 9.6.

Another embarrassing experience I (R.R.S) had when transporting channel catfish fry occurred many years ago when I was charged with picking up several thousand fish from a commercial producer for use in research. A small airplane had been chartered to take me to the point of pickup and return me home. I took two polypropylene carboys to carry the fry. I had a small battery-operated pump to provide aeration in the carboys through air stones. Everything went well for about half the flight. Periodically I checked on the fish. After an hour or so, I saw the fish fighting for space at the water surface, where they appeared to be experiencing oxygen depletion. It occurred to me that the oxygen-holding capacity of the water was diminished because of the altitude at which we were flying, and asked the pilot to find a lower altitude, which helped the situation. Regardless, I still managed to lose a high percentage of the fish.

aquaculture species, we would develop a research programme as an add-on to our production facility so we could develop culture techniques for new species. Being the first to market a species new to the ornamental trade would mean having control of the market at least for a while until others learned how to spawn and rear them, at which time competition would undoubtedly drive the price down, which would be a good thing to the industry overall. One of the nice things about ornamentals (to the producer, not to the purchaser) is the fact that they are rather short-lived. If the hobbyist likes a particular species, that person is likely to be back within a year or two to replace those that have died.

Koi carp are also attractive as an alternative to food fish. Koi can bring extremely high prices if fish with the most sought-after colour patterns are produced. The problem is in getting high-quality broodstock from producers in Asia who do not want to give up their advantage in having control of the best genetic lines. Even relatively common coloured koi bring fairly good prices, though, so production of them is an option to be considered.

Those who are interested in aquarium species and would like to make a living working with them might consider the aquarium maintenance business. Those considering that career (or side activity to another profession) would probably have to live and work in a large city to be successful. The business involves maintaining display aquariums in businesses, medical offices and other locations that would pay for the service. An aquarium service could sell the entire set-up or just maintain the aquarium(s) that the business has already purchased. Maintenance involves routine cleaning of the tank(s), periodic replacement of the finfish (and invertebrates, if any) when mortalities occur and may even involve routine feeding. In fact, some people who are in the aquarium maintenance business ask their customers not to feed their fish, because there is a tendency to overfeed. If the maintenance person is the only one who feeds them, there will be better control on the feeding schedule and amount of feed offered. Of course, that takes a lot of time if there are many clients, in which case you might want to impart a bit of training to the people who own the aquariums or hire assistants who are tasked with routine feeding and maintenance of the aquariums.

A few people are making a living by being 'fish doctors'. Those people provide veterinary services (Box 9.7) to clients who maintain high-priced fish such as koi. Those who are successful in the fish doctoring business are usually located in big cities where sufficient affluent clients are available who may need the services that the fish doctor can provide. Combining aquarium maintenance with veterinary services is an option that could be lucrative if you happen to have customers who are displaying valuable species. In large aquaculture corporations and areas where many aquaculture facilities are located (e.g. in the USA: Idaho for trout and Mississippi for catfish), there may be opportunities for what can be dubbed 'aquavets' to make a decent living. This has become increasingly important now that a VFD must be issued by a licensed veterinarian for antibiotics or other types of medications to be included in feeds for use in commercial aquaculture. Additional information about a VFD can be found on the following FDA website: https://www.fda.gov/animal-veterinary/development-approval-process/veterinary-feed-directive-requirements-veterinarians-veterinary-students (accessed 21 December 2021).

Box 9.7.

We are not implying that the person providing those services must be a veterinarian, as you do not have to be licensed to treat aquaculture animal diseases. Being a Doctor of Veterinary Medicine (DVM) would undoubtedly be useful, however, as it would help you establish your credentials. Aquaculturists who have advanced degrees that include courses in fish diseases (and who have perhaps conducted research on fish diseases in graduate school) are fully capable of diagnosing and treating diseased aquaculture species.

If you find a way to produce a pharmaceutical or nutraceutical product from an aquatic plant or animal species, you could potentially make a fortune. Be advised that we have been told that it takes a screening of 5000 or more chemicals from aquatic species to find one that has any commercial value. The costs of finding some chemical that will have some potential in treating a disease can be huge, and far beyond what an individual can provide, unless that person has won the lottery or has made enormous amounts of money in some other way. Getting a new drug cleared for use can take years and require large-scale, expensive clinical trials. That is the purview of drug companies, not individuals. There is an extremely high probability that the search for novel compounds from aquatic creatures that might have biomedical uses will continue to be conducted in university and drug company research laboratories, rather than in somebody's kitchen.

As the commercial marine aquaculture industry moves offshore, it will be necessary to rear species that demand a premium in the marketplace, and there are not many of those. You can pay US$15–20 (often more) for a salmon or shrimp dinner, but the producer is selling the commodity for a fraction of that. Once you add processing costs and go through wholesalers and perhaps other middlemen before the product gets to the restaurant, there are significant increases in the cost at every step along the way, after which the restaurant or retail outlet needs to figure in its profit. So, what might sell on the pond bank or out of the net pen for US$4–5/kg, for example, may end up selling for several times that amount when it reaches the consumer. Considering what is currently being produced, the best opportunity to make a profit in the open ocean waters far from land would be in rearing tuna (*Thunnus* spp.) and, in particular, sushi-grade tuna that can bring truly remarkable prices (sometimes in excess of US$100/kg). However, as we have seen, today's tuna aquaculture largely depends on capturing young tuna at sea and growing them out in net pens. Ultimately, the entire life cycle of tuna will have to be controlled by the aquaculturist. As has been said, some species of tuna have been spawned and the offspring captively reared, in at least small numbers, but the technology needs to be much better developed and the cost of producing tuna for stocking will have to be greatly reduced to make it economical in comparison with capturing and growing out wild tuna. There are hurdles to overcome, but that is nothing new in aquaculture, and many roadblocks that were once thought insurmountable have long since been removed for many species. The same may be said for tuna one day. Many who go into commercial aquaculture do so because they want to provide nutritious high-quality food for people. That has been what the bulk of this book is all about and we applaud those who embark on that form of aquaculture.

A Few Additional Topics

As stated early on in this book, the emphasis has been on aquaculture species produced for human consumption. Periodically, culture for enhancement to recover wild stocks, bait production, stocking recreational species, ornamentals, jewellery, development of pharmaceuticals, and conservation of threatened and endangered species has been mentioned, and in some cases various details have been presented. Hydroponics and aquaponics have also been mentioned, but not discussed to any extent. In this section, we want to expand upon a few of these topics. In some cases, species being cultured for food are also of interest to culturists with other objectives. For example, channel catfish, striped bass, trout and various other species are cultured directly for the human food market and are also produced for stocking into recreational fisheries.

Jewellery and curios

The primary sources of jewellery and curios associated with aquaculture are pearl oysters, pearl mussels and colourful abalone shells (Table 9.2).

The primary pearl oyster under culture is the Akoya oyster (*Pinctada fucata*, also known as *Pinctada imbricata fucata*). The major global producer is the Mikimoto company in Japan. Pearls develop when a foreign object, such as a grain of sand, is present in the mantle of a pearl oyster. The oyster lays down nacre (mother-of-pearl) around the foreign particle, which creates the pearl. Mikimoto Kokichi, who may not have been the first person to understand the process, was the first to mass-produce cultured pearls by inserting small pieces of mother-of-pearl beads into the mantle of pearl oysters. The result was the eventual development of the global pearl oyster trade, dominated by production of pearl jewellery on Mikimoto Pearl Island in Japan (Figs 9.25 and 9.26). Visiting the island is an interesting experience. Demonstrations are given for visitors several times daily by female pearl divers who 'free dive' (i.e. they do not use scuba gear) to recover oysters from the bay where the island is located. There are also tours through the facilities where visitors get a look at the technology associated with producing pearls (in nature, very few pearl oysters produce pearls). Implantation ensures most oysters produce pearls. The objective is to sell pearl earrings, necklaces, rings and so forth, and the beauty of the jewellery, featuring pearls of several colours and hues, is a definite selling point.

The freshwater mussel, *Margaritifera margaritifera*, was a major source of clothing buttons beginning in the early 19th century. The buttons were so popular that the mussel became threatened

Table 9.2. Common and scientific names of several pearl oyster and pearl mussel species for which culture has potential, has been attempted and/or has been successful.

Type	Common name	Scientific name
Pearl oysters	Akoya	*Pinctada fucata* (*Pinctada imbricata fucata*)
	Atlantic	*Pinctada imbricata*
	Black-lip	*Pinctada margiaritifera*
	Gold-lipped or silver-lipped	*Pinctada maxima*
	Gulf	*Pinctada radiata*
	Shark Bay	*Pinctada albina*
	White-lip	*Pinctada mazatlantica*
Pearl mussels	Biwa	*Hyriopsis schlegeli*
	Freshwater	*Margaritifera margaritifera*
	Paddy field	*Lamellidens corrianus*
	Pond	*Lamellidens marginalis*
	Riverine	*Parreysia corrugata*
	Threeridge	*Amblema plicata*
	Triangle shell	*Hyriopsis cumingli*
	Washboard	*Megalonaias nervosa*

Fig. 9.25. Sorting pearls by size and quality at the Mikimoto Pearl Island in Japan.

throughout its native range in Europe, Canada and the USA. China is the primary source of cultured freshwater pearls in the world today and annually produces hundreds of tonnes of the triangle shell mussel (*Hyriopsis cumingli*) and hybrids with other species, which is some 95% of total global production. The USA and Japan have small levels of production. Traditional Chinese medicine has long employed both pearls from pearl oysters and pearl mussels to treat a variety of ailments. Pearl powder is often prescribed for a variety of ailments and may be the primary use of freshwater pearls, though jewellery made from freshwater pearls is also attractive and popular. The technology to create freshwater pearls in mussels is basically the same as that used by the pearl oyster industry. It also should be noted that the captive propagation of several different freshwater mussel species has

Fig. 9.26. Strings of pearls at the Mikimoto Pearl Island in Japan.

been implemented for conservation purposes in some US states such as Texas.

Abalone can produce beautiful layers of mother-of-pearl in both the internal and external surfaces of their shells (Figs 9.27 and 9.28). The paua abalone of New Zealand was a highly valued food by the native Māori. Three species of paua are recognized in New Zealand (see Table 1.1). The external shell is not attractive in nature but can be cleaned to reveal the nacre below what is assumed to be the calcium carbonate that hides the beauty beneath. Jewellery from paua shells includes pendants, necklaces, rings and earrings. Employing methods similar to those used with oysters and mussels, pearls can also be produced in paua. The shells are beautiful and are available as curios in New Zealand.

Fig. 9.27. Internal view of a paua shell.

Hydroponics and aquaponics

Hydroponics is the growing of terrestrial plants suspended over fertilized water with their roots submerged. When R.R.S. first heard the term, it was generally accepted that the fertilizer could be from a commercial source added to the water, or that one or more aquatic species could be reared in the culture system and would provide fertilizer for the plants through their waste products and dissolution of any feed the aquatic animals did not consume. In most cases hydroponic systems that include aquatic animals involve fish. In the past several years, such aquaculture types (that may include plants and fish, or both) have been called aquaponic systems. The latter has been touted as being truly organic production, which is probably a better way to discriminate between hydroponic and aquaponic systems whether aquatic species are a part of the system or not. Rather than quibble over the definitions, the term hydroponics is used in this subsection with respect to water systems that include either or both terrestrial plants and fish.

Hydroponics is conducted in recirculating water systems. The plants are often grown over raceways, while the fish are maintained separately in tanks or raceways. Hydroponic systems are of necessity freshwater systems because the plants grown are those that are typically grown in soil outdoors or in greenhouses: primarily vegetables, but also fruits, herbs and flowers. Vegetables that have been grown in hydroponic systems include asparagus, beans, broccoli, cabbage, cucumbers, leaf lettuce, peas, radishes and squash, among others. A popular fruit for hydroponic production is the tomato. Fishes associated with hydroponic systems include barramundi, carp, catfish, pacu, tilapia and various species of sportfish. Small-scale hydroponic systems (with or without fish) have been developed for home-grown vegetables and herbs. Examples of hydroponic systems in greenhouses are shown in Figs 9.29 and 9.30. Leaf lettuce ready for harvest in a small indoor system is shown in Fig. 9.31.

Fig. 9.28. External view of a paua shell.

Enhancement and conservation

If you look at the 'History of Aquaculture' section in Chapter 1, you will see that a large number of both freshwater and marine species began being produced in hatcheries in the USA (and Europe) in the mid-19th century. Early production was of trout to provide recreational fishing, and of salmon to increase the numbers of fish entering the commercial fisheries and – in some cases – also the recreational fishery. Common carp (*Cyprinus carpio*) were introduced in the 1800s but became considered

Fig. 9.29. A greenhouse hydroponic system with plants growing in bathtubs (right) and fish in circular tanks (left).

Fig. 9.30. A greenhouse hydroponic system with producing tomato plants (background) and newly introduced unidentified plants (foreground).

more of a problem than a benefit over the years. With the development of thousands of reservoirs in the USA, interest and activity in recreational fishing increased, and expanded the stocking of such species as sunfish, largemouth bass, channel catfish and walleye. Much of that activity was to establish populations in new water bodies, though supplemental stocking has often been necessary.

Millions, perhaps trillions, of marine fish were produced in government hatcheries in the USA and released as fry into the environment for several decades during the late 19th and early 20th centuries, probably with little or no survival of those fish as a result. Most culture of marine species is now focused on aquaculture for growout and introduction into the seafood market, not enhancement, though there are exceptions.

Conservation involves attempts to produce enough threatened or endangered species to keep them from going extinct. In the USA, the US Fish and Wildlife Service is the primary agency that has developed conservation hatcheries. As human developments continue to intrude on the habitat of species that are now threatened or endangered, the pressure on those involved with trying to conserve those species continues to increase. Conservation of some species involves producing and maintaining them in captivity until such times as suitable environments that

Fig. 9.31. Leaf lettuce ready for harvest in an indoor small-scale hydroponic system.

will support them can be found. That approach is only used when there is an immediate threat to the extinction of the species involved.

Bait

The recreational fisheries of the world are multi-billion-dollar industries. It has been estimated that in the Great Lakes of the USA, salmon fishing provides some US$4 billion annually to the economy of the region. In addition to artificial lures, the availability of live bait is often important. Live bait may involve marine worms, shrimp and various species of small fish from different sources. Bait species may be cultured or collected from the environment. An example is bait shrimp. Bait shops often sell shrimp by the dozen to anglers. The shrimp are usually sub-marketable and have been collected by small boats that trawl with the objective to specifically collect bait (Box 9.8). Aquaculture comes in when the shrimp are landed. They need to be kept alive before sale and some retailers have developed recirculating systems to ensure the shrimp are in good condition when sold. A list of some bait species being produced or of interest for aquaculture is provided in Table 9.3. Each of the species listed in Table 9.3 is aquatic, though a large amount of bait produced commercially involves terrestrial species (earthworms and crickets, for example).

Ornamental species

As mentioned in Chapter 1, there are hundreds of freshwater and marine species of ornamental fishes and invertebrates available in the ornamental fish trade. The wild capture of ornamental fishes by

Box 9.8.

There is interest along the Gulf of Mexico coast of the USA in culturing native shrimp species for bait (Table 9.3). To date, however, it does not appear that commercial production has been established to any extent. Bait shrimp are netted by trawling in Gulf of Mexico bays, and are hauled live to ports that have retail outlets. It is important to get the shrimp to the dock within a few hours of capture. An issue is that bait shrimp are in demand by anglers year-round, but there are periods during the year when bait shrimp are either not available or when demand far exceeds supply. Some dealers have put in recirculating systems to maintain the shrimp alive for extended periods, which can extend their period of availability.

Table 9.3. Examples of bait species of interest or in production.

Organism	Common name	Scientific name
Polychaete worms	Lugworm	*Arenicola marina*
	Ragworm	*Nereis virens*
Shrimp	Atlantic white	*Litopenaeus setiferus*
	Gulf brown	*Farfantepenaeus aztecus*
	Gulf pink	*Farfantepenaeus duorarum*
Finfish (freshwater)	Chub suckers	*Erimyzon* spp.
	Fathead minnow	*Pimephales promelas*
	Golden shiner	*Notemigonus crysoleucas*
	Goldfish	*Carassius auratus*
	Green sunfish	*Lepomis cyanellus*
	Stone rollers	*Campostoma* spp.
	Tilapia	*Oreochromis* spp.
	Top minnows	*Poecilia* spp.
	Shiners	*Notropis* spp.
Finfish (marine, estuarine)	Croaker	*Micropogonias undulatus*
	Gulf killifish (mudminnow)	*Fundulus grandis*
	Mummichog	*Fundulus heteroclitus*
	Pigfish	*Orthopristis chrysoptera*
	Pinfish	*Lagodon rhomboides*
	Spot	*Leiostomus xanthurus*
	Striped mullet	*Mugil cephalus*

those who used (and in some cases continue to use) sodium cyanide to stun fish, and make them easy to capture, has been a major issue. The fish appear to recover and are sold into the aquarium trade; however, in many cases those fish die either before or not long after sale to the public. The use of cyanide is illegal in most places where ornamentals are captured but as indicated, there are still those who ignore the law and continue to collect using cyanide. In addition, wild capture has put pressure on many populations of ornamentals. As a result, interest in aquaculture of both freshwater and marine ornamentals became a topic of interest to researchers in recent years.

Aquarists (primarily hobbyists) have developed techniques for the reproduction and production of many freshwater fish species over the decades and those procedures are readily available from the Internet (formerly largely through aquarium trade magazines). Many marine finfish and most invertebrates remained difficult to produce in captivity. Aquaculture scientists became more interested several years ago, as indicated, and began developing technology to produce marine species in captivity; partly as a way of reducing the pressure on wild populations and partly to help develop an industry to meet the demand by hobbyists and seafood restaurants that often have large saltwater display tanks. A series of scientific meetings has been held that focused on the subject and progress is being made as a result. There is still a great deal of research needed and the challenges are real, but the payoffs could be significant in terms of lessening the pressure on threatened and endangered species and possibly reducing the cost of ornamentals to hobbyists.

We would be remiss in not mentioning the progress that has been and is being made in closing the life cycle of various species on display in public aquariums. The use of aquaculture to produce aquatic animals for display in public aquariums visited by the public makes a great deal of sense, as collection of species from the wild can be expensive. Aquaculture can produce information that can be used to enhance the development of new commercial aquaculture species (for human consumption or for the home aquarium trade). In addition, development of culture techniques for threatened and endangered species could lead to production of those species for enhancement. Conservation is another potential contribution of public aquariums. Species that have been overfished can perhaps be conserved if technology is developed for captive production and then passed along to government agencies involved with building stocks of threatened and endangered species.

Colour is an important feature for many ornamental species, as well as in fish such as salmon. Colour is expressed in the external appearance and/or flesh from the diets of the fish. Carotenoids are important as they can impart red, orange and other colours in fish. Salmon obtain their pink colour from carotenoids in their natural food (which often includes shrimp and krill). Interestingly, salmon must contain a certain enzyme to deposit the colour in their flesh. Some chinook salmon (*Oncorhynchus tshawytscha*) – and please don't ask us to pronounce the species name, there doesn't seem to be any agreement on proper pronunciation of that word among those we've asked – don't harbour the enzyme. They have white flesh even though they consume food items that contain carotenoids. The largest chinook salmon that R.R.S. ever caught (which was one among a few) had white flesh. Most chinooks have pink flesh.

The bright colours on the surface of ornamental species are associated with chromatophores (pigment-bearing cells); these express the various colours that are expressed in their food. Colour in cultured ornamentals can be imparted by feeding carotenoids, xanthophylls and/or melanin, each of which provides one or more particular colours. Adding shrimp meal to the feed formulation can result in enhancement of colour, as can adding a small amount (around 1%) of *Spirulina* algae to the formula. *Spirulina* is expensive, but in ornamental fish feeds it can be incorporated without appreciably adding to the cost of the final product. Other things that can add colour to ornamental feed include marigold leaves, beetroot meal and a variety of other plant meals. Melanin provides black colour to such fishes as zebrafish and angelfish.

Attractants can also be important in ornamental feeds, particularly those in conjunction with species that are carnivorous. If the carnivores will accept prepared feed, making sure that there is sufficient feed offered to satiate them daily can reduce their preying on other species in the aquarium. Again, there is a balance between feeding enough to ensure the fish have plenty without overfeeding and producing an impact on water quality. In many cases, carnivorous species have little or no interest in prepared feeds, so hobbyists typically provide small live fish (which also can be produced in aquaculture as bait) of the appropriate size, frozen krill, brine shrimp, tubificid worms or other organisms as food. Krill meal and shrimp meal may be used as attractants, as can mixtures of certain amino acids. Carnivores that prefer live food may still need to be maintained separately from potential prey species or the hobbyist may wind up with an aquarium housing only one species.

Fish markets in Japan

Appearance and presentation are very important to seafood purchasers in Japan. Quality and freshness are also important but are a major consideration in conjunction with the first two items. Taking for example, the Tokyo fish market, new products come in very early in the morning, are processed, put on display and sold quickly. Most arrive at the market on ice, while tuna arrive frozen. Experts examine the frozen tuna and place a price per kilogram on individual fish, some of which may be valued at over US$100/kg. Photos from fish markets in a few cities in Japan are presented in Appendix B.

Fish species for biomedical research

Fish have been used in biomedical research for decades. Fish that are of small size at maturity are primary candidates for such research as they develop rapidly from birth to maturity so many generations can be produced rapidly. The most mentioned species in the literature are medaka (*Ozyzias latipes*) and zebrafish (*Danio rerio*). Both are of interest to geneticists. For example, zebrafish research has focused on producing genetic mutations which can model various human diseases associated with most organ systems such as the nervous, endocrine and skeletal systems. These fish go through their various developmental stages from hatching to maturity within only a few months such that the various phases of a disease can be characterized within a relatively short period of time. Platyfish and swordtails (*Xiphophorus* spp.), two popular home aquarium fishes, have been studied as sources of cancer detection for decades. Research on cuttlefish (*Sepia* spp.), which are related to octopus and squid, has been focused on their large optic nerves. Fish such as fathead minnows (*Pimephales promelas*), which are also commonly used as bait by anglers, also have been routinely used for toxicological research.

Enhancement stocking

Enhancement has been mentioned previously with respect to the billions of fish being released in the 19th and early 20th centuries which probably perished, for the most part, having been stocked as eggs or fry; the several-year stocking programme of red drum in Texas waters that are being reared in hatcheries; and the recovery of sea turtle eggs for hatching and early rearing by NOAA. A major programme to enhance sea turtles has been underway for several years. However, a major challenge to the Gulf of Mexico sea turtle population occurred during the winter of 2021. Unusually cold weather during February resulted in the need for recovery of sea turtles by the thousands as they came ashore. Volunteer groups and government employees collected turtles and took them to facilities where the hope was to recover them from the cold. Many volunteers along the Texas coast helped collect turtles and carried them to places where they could be properly warmed; such facilities as the Texas State Aquarium in Corpus Christi, the marine fish hatcheries operated by TPWD and the NOAA lab in Galveston where people with the requisite experience were located. Large numbers of estuarine fishes were also killed by the bitter cold weather.

The Future

It seems that we have come full circle. In this book you have seen the basis upon which aquaculture was developed; the opportunities for, and opposition to, aquaculture; and have been provided with many of the concepts, techniques and approaches used by aquaculturists, including what happens to the final product. The concentration has been on the production of food fish (which, if you recall, we defined as being inclusive of finfish and invertebrates that are cultured as human food). Aside from the preceding subsections and a few mentions of plant culture in this book, food fish and invertebrates have been the focus, and are the focus of the comments that follow.

There is no doubt in our minds that aquaculture will continue to grow globally. The increasing human population and the concomitant increasing demand for seafood in the face of the level or declining capture fisheries require increases in aquaculture production and the data from FAO and other sources support that conclusion. The question is:

from where will the products emanate? It was said in the first edition of this book that the growth areas are primarily in Asia and in parts of Latin America. That remains to be true, though we see increased production in many other parts of the world as well. If offshore aquaculture regulations and a reasonable leasing programme can be developed for the USA, and if it can be shown – a big if – that open ocean aquaculture can be conducted economically and sustainably, the potential for expansion in that approach is enormous. Open ocean aquaculture is growing in a few parts of the world and can be expected to grow significantly in the future as the technological problems are solved and environmentalists' objections can be satisfactorily addressed.

One interesting aspect about aquaculture growth will be achieving a balance between hatchery production capacity and growout facility demand. It is a bit like which came first, the chicken or the egg? You cannot grow fingerlings to market size unless you have a source of fingerlings (the hatchery and early fingerling production phase) but, at the same time, a hatchery is not very useful unless there is an outlet facility where the fish produced can be reared to market size (the open ocean growout facility). Some of that problem could be resolved by having marine fish hatcheries initially operated as enhancement facilities. The cost could then be borne by government or the private sector. Government hatcheries have been operated by various states and the federal government in the USA for well over 100 years. Their goal has been to produce fish for enhancing both commercial and recreational fisheries. In the state of California, the state is paying a private entity to produce marine fish for enhancement while, at the same time, that entity is interested in developing growout facilities for the same species. The hatchery could also be used to supply fish to companies that want to get into open ocean culture, thereby resolving the problem the private facility would face with respect to obtaining fingerlings in the absence of its own hatchery.

Many believe the future lies in on-land recirculating aquaculture systems. Yet, after many years now of development – at least since the early 1970s – many attempts at commercial production in such systems have not resulted in many success stories. The vision of warehouses by the hundreds in large cities being turned into aquaculture facilities has not materialized to date. Someday perhaps we will see an explosion in such facilities, but there will need to be additional breakthroughs in technology that lead to reduced production costs, so we are not going to predict when, or indeed if, that is going to happen. Recirculating systems are often suitable for research – limited production of species for use in biomedical research, hydroponics and perhaps other uses – but production of food fish at high levels of production for the human food market has so far typically been uneconomical in recirculating systems.

We follow what might be called the aquaculture wars closely, by reading news releases that range from deriding aquaculture products as being sources of dangerous foods to products that are very desirable as they provide unique health benefits. Consumers are obviously confused and their responses to stories in the media help shape aquaculture development. In the USA and various other nations, environmental regulations have been responsible, in part, for reducing the rate of aquaculture growth. Yet, one can argue that is not a bad thing. While the pace of development is slowed, and sometimes unreasonably so because of a frivolous charge made by an opponent of aquaculture, it does mean that when a permit is granted, there is a very high probability that the entity for which the permit is granted will operate in an environmentally responsible manner. And that is a good thing.

We, like most people who are interested in aquaculture, are opposed to environmental degradation, but believe that aquaculture can be developed in a manner that will not cause unacceptable environmental impact. We would reiterate that all human activities have some measurable impact. What we would not like to see is pressure from the increasing human population being so great that environmental concerns are ignored. Frankly, we cannot see that happening. We would reiterate another point made earlier in this book. The aquaculturist is also an environmentalist because he/she will be the first to suffer if the environment is degraded and the species that are being raised are adversely affected as a result. And you can rest assured, the aquaculture species would be right up there near the front of the line among species that are negatively impacted by environmental degradation.

Currently, the demand for fishery products is being filled, in large part, for some species (such as salmon and shrimp) and in some nations (such as the USA), through imports. Recent estimates are that the trade deficit in US seafood is of the order of several billion dollars annually. That is, the USA expends much more on imported seafood than it gains from seafood exports. The USA imports both high- and low-cost fishery products. As developing nations become more affluent, the amount of domestic demand for aquaculture species will likely increase.

It is our view that when imports to developed nations decline, those nations will take up the challenge and will produce more aquaculture products for local consumption. The public will demand it, and the opposition may not be able to continue its assault on aquaculture effectively, particularly as each of the issues raised by the opposition is addressed effectively. The important point is that when aquaculture expands to help meet growing local demand, domestic production should be accomplished without causing unacceptable environmental impact. We believe that can be accomplished. Researchers have been actively working on developing the techniques and technologies to ensure that aquaculture can be conducted in an environmentally responsible manner. More research is needed, but we are optimistic that aquaculture species can be produced with little environmental damage – but again, everything humans do has an impact at some level. The future will tell, and our crystal ball is still cloudy. In any case, the facts cannot be denied:

- The human population continues to grow.
- The demand for quality seafood continues to grow.
- Capture fisheries are stable or declining.

It is unlikely that any of these facts will change. People are just unwilling to even consider dealing with the first statement. The situation is not going to change with respect to the second statement, and efforts to recover fisheries that have collapsed or declined have not been very successful so far, though efforts to resolve that issue continue. Even if there is some recovery, the maximum sustainable yields from the capture fisheries may not be increased substantially.

At some point the public in nations where aquaculture is under fire are going to have to decide. What they decide will have a significant influence on the future of aquaculture in many nations. Our trust in human nature convinces us that the public will make the right decision which is, in our view, to support aquaculture development with appropriate regulations to ensure that the environment, and thus the quality of life of all of us, is protected.

Summary

This chapter covered some topics that were in some cases mentioned in previous chapters, but not discussed in detail, along with a few topics that did not fit well in other chapters. We began by considering harvesting of aquaculture crops, with the focus being on capturing motile species from extensive and intensive culture systems. Seines are commonly used to capture fish and shrimp in ponds, with partial harvest being conducted in some instances, though in most cases total harvesting is practised, and the ponds are drained and then made ready for the next growout period.

Capturing animals from tanks and linear raceways is relatively easy. Cages and net pens can provide challenges, particularly when the units are quite large. Fish pumps come in very handy and are also used with various types of culture systems. Such pumps can pick up the animals and transport them to hauling tanks or even directly into processing facilities without damaging them. A few specialized harvesting techniques, such as trapping crayfish and gathering molluscs, were also discussed briefly.

Hauling fish and shellfish to processing plants or directly to the market often involves trucking them. Examples of how hauling trucks are loaded and how they are equipped to keep cultured animals alive during transport were provided. Aeration is important and often the animals are sedated or anaesthetized during live hauling.

Development of a fee-fishing operation is an alternative activity that may be attractive to some aquaculturists. Fee-fishing operations usually involve ponds that are stocked with catchable fish and are open to the public. Users may pay an entry fee but are expected to keep what they catch and pay by the number or weight of fish caught when they leave the facility. The owner may grow the fish that are stocked or purchase them from a commercial producer. Various amenities such as picnic tables, refreshments, bait, tackle (for rent and/or sale) and playgrounds are often available to make the outing more pleasurable for families.

The next topic was a brief discussion of processing and marketing. Aquaculturists may process and market their own products but, for most part, the harvest is taken to a processing plant that then sells the processed products to wholesalers or retail outlets, including restaurants.

Next, we added information on some of the aspects of aquaculture whose focus is not always production for human food. Some of these provide opportunities for enhancing, recovering or conserving aquatic species; providing fish for recreational fisheries; production of bait; culture of ornamental species; culture of pearl oysters and mussels; and so forth. Not all these topics are covered in detail, and most have been covered to a limited extent elsewhere in this book.

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Appendix A: Aquatic Plants

Photos of ponds with various kinds of aquatic vegetation are shown in Figs A.1 to A.11.

Fig. A.1. Algae mats.

Fig. A.2. Algae problem.

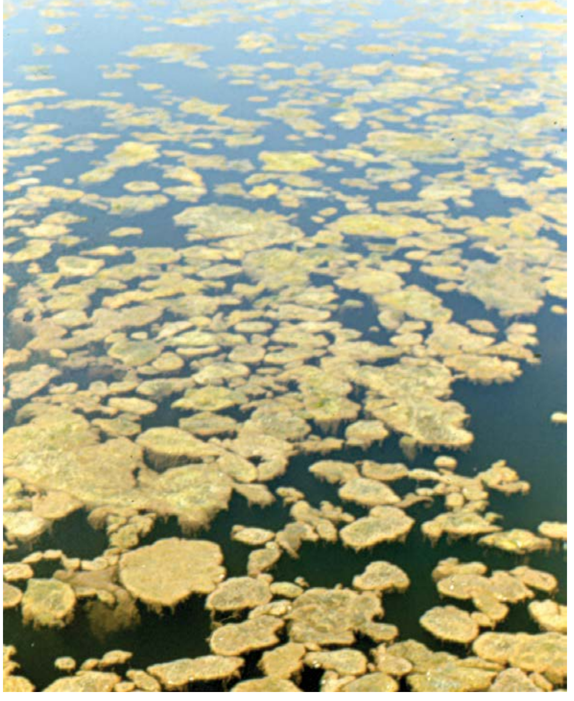

Fig. A.3. Clumps of algae.

Fig. A.4. Dense population of duckweed.

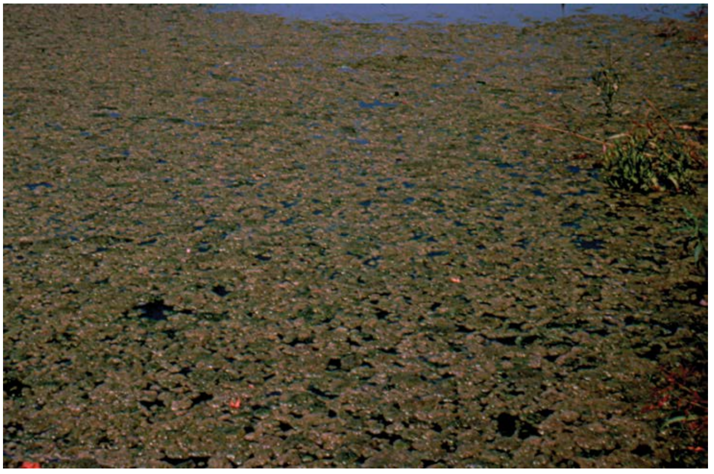

Fig. A.5. Dense surface algae growth.

Fig. A.6. Duckweed.

Fig. A.7. Filamentous algae.

Fig. A.8. Heavy growth of pond weeds.

Fig. A.9. Water hyacinths on Laguna de Bay.

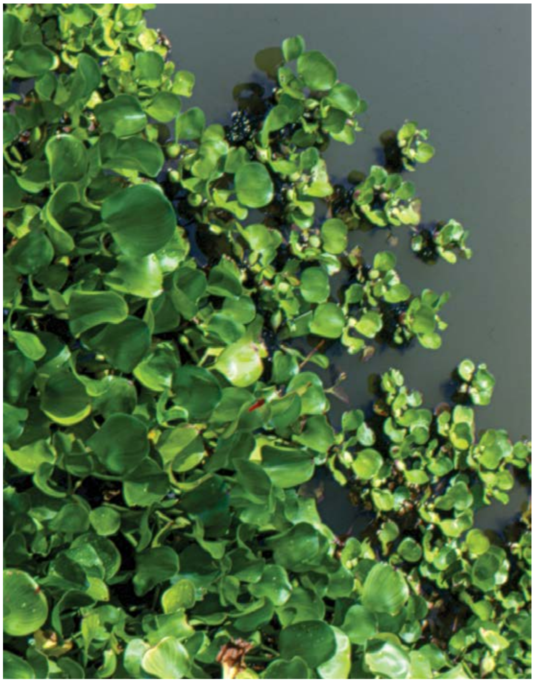

Fig. A.10. Water hyacinths.

Fig. A.11. Weedy pond.

Appendix B: Fish Markets

Photos from fish markets in Japanese cities are shown in Figs B.1 to B.10.

Fig. B.1. Crabs in Kushiro fish market.

Fig. B.2. Fish market in Kushiro.

Fig. B.3. Kushiro fish market.

Fig. B.4. Kushiro fish market.

Fig. B.5. Kushiro fish market.

Fig. B.6. Tokyo fish market.

Fig. B.7. Frozen tuna that have been graded and priced before being put on sale in the market in Tokyo.

Fig. B.8. Tokyo fish market.

Fig. B.9. Typical Japanese seafood market scene.

B.10. Grading tuna at a typical Japanese market.

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Note: The page references in italics and bold represents figures and tables respectively.

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