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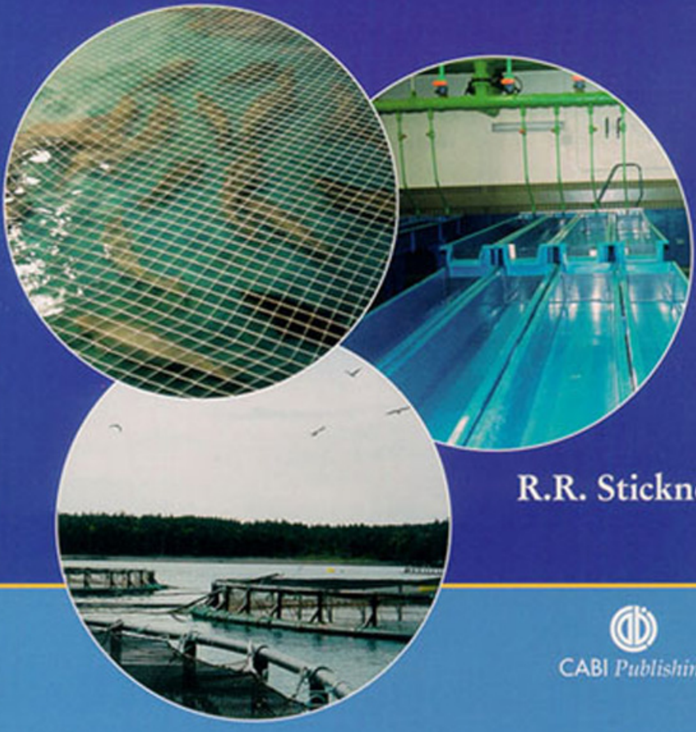
AN INTRODUCTORY TEXT



R.R. Stickney

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AN INTRODUCTORY TEXT

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Robert R. Stickney

Texas Sea Grant College Programme
Texas A & M University
USA

CABI Publishing

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This book is dedicated to four important young people, my grandchildren Amanda, Trey, Ryan and Hannah. I hope you find as much joy in the professions you will choose as I have in mine.

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Preface

A Chinese proverb says something like the following:

> *Give a man a fish and he will have food for a day,*
> *Teach a man how to fish and he will have food for a lifetime.*

To that we might add:

> *Teach a man how to grow fish and he can feed the world.*

As we shall see, the production of aquatic plants and animals – a subject we call aquaculture – takes a variety of forms, including items that enter the human food supply. That is the primary type of aquaculture discussed in this book, but it is far from the only type that is practised as you will see in Chapter 1.

The purpose of this book is to introduce you to the subject of aquaculture and to acquaint you with some of the techniques involved in aquatic organism – primarily aquatic animal – production. The emphasis is placed on shellfish – such things as oysters, scallops, mussels and shrimp – as well as on finfish. Both fresh- and saltwater culture are included.

Many books on aquaculture look at details on how to produce a particular type of animal: shrimp or salmon, for example. That approach is excellent for the student or practitioner who has decided on a particular species or species group upon which to concentrate. For the general reader who wants to gain some knowledge of the breadth of aquaculture, a different approach is required. Here, we discuss all aspects of aquaculture, from business planning through site and water system selection, to management of the system once it is in operation.

Aquaculture is a combination of natural science, business management and tradecraft. The successful aquaculturist needs to have many tools in his or her toolbox, or lacking those tools, needs to be a member of a team that brings all the proper tools to the enterprise. Increasingly, individuals who select aquaculture as a profession have received some formal education in the field. This is particularly true of practitioners from developed countries, whether they work in one of those countries or in a developing nation. Whereas there were very few aquaculture and related courses available at the college level 35 years ago, many colleges and universities now offer degrees in the subject. Increasingly, there are also aquaculture classes or at least some aquaculture activity available in high schools as well.

Over the past several years, strong opposition to certain types of aquaculture and to aquaculture in certain environments has developed due to concern about environmental degradation as a result of aquaculture practices. Aquaculturists, who once saw themselves as doing good by producing aquatic plants and animals to feed people (I like to think of them as the cowboys in the white hats), suddenly became villains in the eyes of critics (cowboys in the black hats). The perception that aquaculture is a bad thing, whether supported by the facts or not, became reality after being repeated over and over and after being picked up by the various forms of media: print and electronic. The response of the aquaculture community to the critics has received much less attention, though it has been significant. The topic has taken up an incredible amount of time over the past couple of decades and is discussed in some detail in this book. Tiersch and Hargreaves (2002) discussed how the aquaculture community can respond sensibly to the controversy that surrounds their profession.

Lists of additional sources of information can be found at the end of each chapter. Those of you who have caught or will catch the aquaculture fever and would like to delve more deeply into the complex and very interesting world of aquatic plant and animal production are encouraged to look at the wealth of additional, and often much more technical, material that exists. The sources listed under the Additional Reading sections at the end of the chapters are mostly books, since they are readily available in many libraries and from booksellers, particularly booksellers who have internet sites. The books contain thousands of additional references to the scientific literature.

Aquaculture is a risky business. Some who have been involved with the subject for a number of years have indicated that commercial aquaculturists should include, in their balance sheets, plans for a total crop failure once every six or seven years. In addition, the aquaculturist is, in most cases, at the mercy of the marketplace in terms of how much money will be obtained upon sale of the product.

While risky and requiring a lot of hard work, aquaculture can also be highly satisfying. It is often a family activity as well. Salmon fishermen in Norway are commonly also salmon farmers. While one spouse is off on a commercial fishing boat, the other spouse and children tend the fish cages.

Speaking of family involvement, when I was a graduate student conducting research on channel catfish, there were many nights when thunderstorms caused power failures. You would find my wife, Carolan, standing with me splashing water with paddles in fish tanks to help maintain the oxygen level until the power was restored: hard work lasting into the wee hours of the morning, yes. But we also have looked back on such experiences with fond memories, particularly since we were able to save the fish upon which my doctoral degree depended.

Fish farming may mean the occasional vehicle in a pond, tractor stuck in the mud, getting grabbed on the thumbs by an aggressive crab or getting spined by a fingerling catfish. Frustrating, and sometimes costly or painful when such things happen, at least some of them are looked back on as humorous incidents months or years later. My experience with aquaculture has involved teaching, research and providing advice. I have never had to raise a crop for a profit, but I fully understand the difficulties involved and also the pride when one sees the crop on the truck headed for the market. My hat is off to those who are commercial aquaculturists. To those who read this book, my intention is to provide you with some insight into the complexity of this discipline we call aquaculture.

Robert R. Stickney, PhD.
Hearne, Texas

1 The Who, What, When and Where of Aquaculture

Definitions

Many definitions of aquaculture have been proposed. The one I have used is as follows: *Aquaculture is the rearing of aquatic organisms under controlled or semi-controlled conditions*. This is a fairly simple definition, but it can be boiled down even more to simply *underwater agriculture*.

Let us break down the longer of the two definitions of aquaculture into its components. The term 'aquatic' refers to a variety of water environments, including freshwater, brackish water and marine.[1] 'Aquatic organisms' that are of interest with regard to human food include a wide variety of plants, invertebrates and vertebrates. Mariculture is a term reserved for the culture of organisms in saltwater (from brackish to full strength seawater).

While the above definitions are fairly simple, they embrace an extremely broad and complex topic that involves a broad array of scientific disciplines along with engineering, economics, business management and trade skills. The serious student of aquaculture should have experience (and preferably have taken formal courses) in mathematics, chemistry through at least organic chemistry, physics, biology, business management and economics, and if possible, some basic engineering. The practising aquaculturist also needs to be able to drive trucks, tractors and have skills in plumbing, electrical wiring, welding, painting and carpentry. Experience in pouring concrete will also come in handy. As you read on, the reasons for having knowledge and skills in the areas mentioned should become apparent.

One-person or one-family operations are becoming much less common as the field develops, so it is not always necessary for an individual to have all the background and skills mentioned. As long as all those components exist within the staff, the enterprise should be able to function effectively.

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[1] The amount of salt in the water is known as its salinity. Freshwater is nearly salt free, while full seawater contains about 3.5% (35 parts per thousand or 35 ppt) of salt. Brackish water has salinities intermediate between freshwater and full seawater.

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 the settlement of larval oysters is at one extreme, while operation of an indoor hatchery for fish that incorporates a water reuse system (see Chapter 2) is at the other. 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 environment for the animals. When operating a recirculation system, the aquaculturist exerts a high level of control and the system is called intensive. There are a number of other approaches that lie somewhere in between those two extremes, so 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 the very latest in 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 the level of technology employed increases, so does probability of system failure.

Aquaculture organisms tend to be classified as having a preference for warm, cool or cold water. While not absolute, warmwater species tend to grow optimally at or above 25°C (for example, catfish and tilapia), while coldwater species exhibit optimum growth at temperatures below 20°C (trout, salmon, halibut). Coolwater species grow best at temperatures between 20°C and 25°C (walleye, yellow perch). Most commercially cultured species are either of the warmwater or coldwater variety, while some sport fish, as mentioned in the examples, fall into the mid-range group.

Culture systems may involve the production of one species (monoculture) or they may contain two or more species (polyculture). The latter approach is perhaps best exemplified by Chinese carp culture in which several species of carp are produced in the same pond, with each species using a different food source. Grass carp would eat higher plants, silver carp and bighead carp would consume plankton,[2] with silver carp eating phytoplankton and bighead targeting zooplankton. Other carp could feed on organisms living in the mud or may be provided with feed by the farmer. Fertilization is used to promote the growth of the plankton and other communities that are used as food.

Many terrestrial plants can be grown by immersing their roots directly into water or planting them in soils through which water flows. That method of growing plants is called hydroponics. If the water is used for growing both plants and aquatic animals, the technique has been called aquaponics, which is a form of polyculture.

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[2] Planktonic organisms are those that are suspended in the water column and have limited ability to swim, so they are at the mercy of currents. The plant component of the plankton is the phytoplankton community, which is comprised of small, often microscopic, single-celled and multi-cellular algae. The animal component of the plankton is referred to as zooplankton.

Why Aquaculture?

You have undoubtedly seen stories on television or in magazines and newspapers or heard them on the radio about the fact that many of the world's capture fisheries are in decline. Some, like the New England cod fishery and the North Atlantic halibut fishery, have collapsed. It was estimated many years ago that the world's oceans can produce sufficient amounts of fish and shellfish to allow for about 100 million metric tonnes[3] to be harvested annually. In fact, that level of harvest was reached in the 1990s and has not increased since then. As fisheries have declined, new species have been targeted. Squid, popularly sold as calamari today, were not available in many western hemisphere markets until about the 1980s as there was no market for them, though historically, a market has existed, particularly in parts of Asia. Only by finding new target species was the annual harvest from the sea maintained.

Today, we are in a situation where the capture fisheries 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 rising *per capita* consumption of seafood. We have all heard about studies that seem to show certain health benefits from eating fish. One recent recommendation was that everyone should eat at least two fish meals a week. So, demand is increasing, while the supplies of fish are not increasing. How can we resolve this dilemma?

The answer that has been widely touted is aquaculture. The average consumer does not see any reduction in the availability of seafood in restaurants or supermarkets and the overall amount of seafood in the markets of the world continues to increase, despite the fact that capture fishery volumes are not increasing. This is because aquaculture has been able to fill the gap. Currently, at least 20% of the fish and shellfish marketed globally are produced by aquaculturists and that percentage can only be expected to grow.

While the demand for aquacultured products is increasing, opposition to aquaculture, or at least to many aquaculture practices, is also increasing and is so strong in at least a few countries that it has curtailed some forms of aquaculture development. That issue is explored in more detail later in this chapter.

History

Aquaculture has been practised for millennia. Its origins appear to be rooted in China, perhaps as long ago as 2000 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. The Japanese reportedly began farming oysters intertidally about 3000 years ago, and pictographs from the tombs of the Pharaohs of Egypt show people fishing for tilapia in what appear to be culture ponds.

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[3] A metric tonne is 1000 kg. Throughout this book use of the word 'tonne' implies metric tonne.

Oysters were cultured by the Romans nearly 2000 years ago (Beveridge and Little, 2002). Preceding that by a few hundred years was prototype aquaculture associated with the Etruscans who managed coastal ponds for fish production.

Native Hawaiians constructed hundreds of coastal ponds that were flooded as a means of stocking them with marine organisms, which were then allowed to grow to the desired size for harvest (Costa-Pierce, 2002). Pond construction preceded the discovery of the Hawaiian Islands by Captain Cook in 1778 by perhaps 500 years. Seaweed culture in Korea apparently dates back to the 15th century.

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 learned 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 a more scientific approach to the discipline. The first applications of science to aquaculture can be attributed to workers in Europe and North America.

In 1871, Spencer F. Baird, then Secretary of the Smithsonian Institution in Washington, DC, 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 US Fish and Fisheries Commission was established that year was to hire fish culturists to develop the technology required to mass produce, transport and stock various marine and freshwater fish and shellfish in the nation's waters. Several of the very few fish culturists of the time, including 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. As the 20th century dawned, fish and shellfish were being stocked by the hundreds of millions. I like to think that if those early fish culturists were alive today, they would be able to walk into a modern hatchery and recognize much of what is going on. Computer controls (Fig. 1.1) and modern materials would be baffling at first, but those men would quickly understand and relate to them.

In the early years, glass jars were used to incubate fish eggs, fry were being reared in raceways (see Chapter 2), devices had been developed to aerate water, and various species were being transported live, not only throughout the USA, but also across the world's oceans. Jars are still sometimes used to hatch fish eggs, though today they are likely to be made out of plastic or plexiglass (Fig. 1.2).

Brown trout were introduced to the USA from Europe and rainbow trout were sent to Europe and New Zealand from the USA. Chinook salmon from the Pacific Northwest of the USA were shipped to New Zealand, where they continue to thrive. European carp were established in the USA, largely with the strong support of Spencer F. Baird. Carp quickly became a nuisance species and its culture was discontinued. The species became established and appears to be with us to stay. Details of the development of aquaculture in the USA can be found

Fig. 1.1. Computers are often used to control water flow rates and collect data on water quality in modern aquaculture facilities.

Fig. 1.2. Plexiglass containers used to hatch marine fish eggs in a research laboratory.

in the book by Stickney (1996) which is on the additional reading list at the end of this chapter.

Interest in recreational fishing in both Europe and North America led to the establishment of hatcheries responsible for stocking fish of interest to anglers. Commercial aquaculture was a cottage industry during the first half of the 20th century and involved only a few trout farms. Most of the fish being raised – which included trout but also quite a number of other freshwater and marine species – were produced for stocking by government agencies at the state and federal levels. Parallel activities were underway in Europe. During the 1930s, tilapia were introduced from their native North Africa and the Middle East to tropical Asia where they quickly became established. The average Filipino, Malaysian or Indonesian undoubtedly thinks tilapia are native to their countries since they have been there for so long.

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 was expanding in the USA; research in Great Britain on plaice was underway; aquaculturists in the southern USA attempted to produce buffalo fish, but soon turned their attention to channel catfish; research on tilapia had begun in various nations; various tilapia species were introduced to the Americas; and interest among researchers to develop even more culture species blossomed.

This is not to say that aquaculture was not a prominent activity in other locations and with other species by the 1960s. In their landmark treatise on aquaculture, Bardach *et al.* (1972) chronicled the state of affairs around the world and presented detailed information on the methods used to produce a variety of seaweeds, fish 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 described techniques associated with the production of common carp, Chinese carp, Indian carp, catfish, tilapia, milkfish, eel, trout, salmon, striped bass, yellowtail, flatfish, shrimp, crayfish, crabs, oysters, clams, cockles, scallops, mussels, seaweeds and others, including species of primarily recreational fishing interest. Some species were of local interest (e.g. yellowtail in Japan), while others, such as common carp, 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 former USSR. In the USA, the channel catfish industry was growing rapidly but had only been in existence a little over a decade by 1972. Catfish quickly replaced buffalo fish as the warmwater species of choice by US aquaculturists.

There was some interest in developing economically viable culture techniques for such difficult-to-rear species as pompano and lobsters, but aquaculture of many species, particularly in the tropics, was largely a subsistence activity. That is, fish were being cultured by small farmers primarily for home or village consumption.

Compared with production levels in the early years of the 21st century, those of the 1960s tended to be very low. For example, channel catfish farmers in the USA produced from about 500 to 1000 kg/ha[4] in their ponds, compared with up to ten times those levels today. Feeds were primitive, diseases and their treatment were not well understood, and water quality requirements had not been well defined. Those problems were attacked with vigour during the 1970s and progress was rapid. There was a great deal of optimism surrounding the notion that aquaculture could fill the anticipated gap between supply and demand of 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. 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. Part of the explanation for the difference lies in the fact that techniques associated with the culture of the few species that were commercially reared prior to the 1960s had been developed in government hatcheries for the purpose of stocking the nation's waters. Only a few farmers had adopted the 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 the commercial industry for those new species became established.

Most species of interest to terrestrial farmers – both plants and animals – were already being grown in the USA prior to 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. 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.

Some desirable species have proved difficult to culture. Included are American and Florida lobsters, along with many species of crabs. Rearing of Florida lobsters is impeded by the fact that their larval stage is several months long. During those months the larvae are rather feathery in appearance and are very fragile. If two of them come into contact with one another, they will become intertwined and will die. American lobsters – the ones with the big claws or chelae – are highly cannibalistic. When one animal in a confined area such an aquaculture tank moults[5] it is vulnerable to attack by others that are present. Crabs typically exhibit the same behaviour as American lobsters. The result of stocking a large number of lobsters or crabs in a single container may

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[4] kg/ha = kilograms per hectare. A hectare is 10,000 square metres.

[5] Moulting, or ecdysis, is a process by which lobsters and other crustaceans shed their hard shell (exoskeleton) and are very soft and vulnerable to predation for a few hours until the new exoskeleton forms. It is during this time that a good deal of water is taken up, thereby increasing the lobster's size. Water is traded for tissue as the lobster grows into its new exoskeleton.

be that you end up with one large animal at the end of the growth cycle. 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.

During the 1960s and 1970s, a lot of attention 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). Because some species of Asian shrimp were much more amenable to culture than the shrimp that inhabit US waters, culture of native species in the USA was abandoned (though some interest in their culture for the bait industry has emerged in recent years).

Some species have almost defied commercialization even though considerable amounts of research have been conducted. Pompano is an example. That fish has recently received some new attention from researchers, but there are some problems to be overcome before it becomes commercialized. Tuna is another example. While it is now possible to spawn and rear some species of tuna, the limited amount of aquaculture being conducted in North America (primarily Mexico) and Europe involves capturing young fish, putting them in sea cages and rearing them to market size. The primary market is in Japan where sushi-grade tuna brings extremely high prices.

Culture Objectives

Under the definition of aquaculture used in this book, any one of a number of objectives may be the focus of the culturist. Production of fish for stocking, which began in the USA, Canada and elsewhere after hatchery programmes were put in place, was 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 targets organisms produced for other purposes. The majority of aquatic animals currently being cultured for human food are animals and most are members of one of only three phyla: Mollusca, Arthropoda or Chordata. There are also a few echinoderms, amphibians and reptiles that are cultured for food. Sea urchins are produced for their edible gonads, while frogs and alligators are reared for meat in both cases, and also for their hides in the case of alligators. Sea turtles, in particular green sea turtles, have also been cultured for food as well as for use of some body parts for jewellery and curios. Because of the threatened or endangered status of some sea turtle species, the possession of sea turtles or products produced from them is against the law in some countries, including the USA.

Pearl oysters are also produced by aquaculturists. As we will see, aquatic plants, in particular seaweeds, make up a significant amount of aquaculture production, some of which is used as human food.

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 are collected when they enter streams to spawn and are taken to a hatchery where the eggs and milt are obtained. The fish are reared to the smolt stage,[6] after which they are released. After they reach maturity at sea (the time required varies by species), they will return to the hatchery where they were born. The majority of returning adults are intercepted by the commercial fishery; however, escapement quotas are established to allow sufficient numbers of returning adults 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 fee from commercial fishermen which pays the operating costs of the hatchery.

Stock enhancement of marine fish is similar to sea ranching as it involves spawning and hatchery rearing of young fish for release. Basically, enhancement stocking had its beginnings with the US Fish and Fisheries Commission's activities that began in the 1870s. What has changed is that few species are being stocked in public waters to augment commercial fisheries today, though that may change, as it has in places like Japan. 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 replace existing brood fish.

In addition to something like 40 years of enhancement stocking with dozens of species, Japan has begun research programmes to determine why the results of their programme have been highly variable. Certainly, stocking the 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 out-compete other desirable species, are considerations that play a role in the success of any enhancement programme. Until recently, little attention was paid to those factors as the effort was all expended on putting animals into the environment, not on determining if there was a benefit that accrued from the activity. The focus has now shifted and a considerable amount of interest has developed in understanding how to use enhancement most effectively and wisely.

In Hawaii, Pacific threadfin, known locally as moi, show promise for enhancement, while in Texas tens of millions of young red drum (also known as redfish or channel bass in some places) are released into the Gulf of Mexico each year. That activity, which is meant to enhance recreational fishery, has been underway for over 20 years. China has been involved with an enhancement programme for Chinese sturgeon for a similar number of years.

The culture of ornamental fish and invertebrates is a growth industry. While significant production occurs in several countries, there has been little scientific research related to developing the technology for captive production of most species of interest until recently. Most of the technology was devel-

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[6] The smolt stage is the life stage at which fish become physiologically prepared to enter seawater. Depending on the species, that may occur from a few weeks to several months after the eggs hatch.

oped by hobbyists and commercial culturists, but increasingly over the last few years, academic researchers have become involved. The result has been that more and more species are being successfully cultured each year. The first international conference of collectors, culturists, conservationists and researchers was held in Hawaii in 1999. That was followed by a second conference in Orlando, Florida in 2001 and a third, once again in Hawaii in 2004. Additional biennial conferences are planned. It has been estimated that worldwide, the ornamental fish industry is valued at between US$4 billion and US$ 15 billion (Hoff, 2001).

Ornamental fish are marketed by various nations, and the sources are often a combination of animals collected from nature and those reared in culture facilities, though the majority of marine species in the marketplace are caught wild, since spawning and rearing techniques for the larvae and fry of most marine species are yet to be developed. Leading exporting nations include Singapore, the USA, Malaysia, the Czech Republic and Indonesia (Lem, 2001).

Historically, 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 has commonly been used to collect marine ornamental fish with lethal effects on non-target species and frequent latent mortality of the target fish as well) and improper handling of captured animals have been major problems facing the industry. Those problems can be largely overcome if the species are cultured rather than captured. Techniques for the culture of many freshwater species have been in place for many years and, increasingly, the ability to culture marine species is being developed. However, of the over 1500 species that have been classified as ornamental fish, the trade is dominated by no more than a few tens of freshwater and marine species.

Collection of corals for marine aquaria has been banned in some areas, and the industry has turned to the production of live rock: that is, natural rock (not coral) that has marine organisms growing on it. The collection of natural live rock has been banned in some places so an industry that revolves around placing terrestrial rocks in the marine environment, allowing them to be colonized by marine organisms, and then collecting and selling them has developed.

Aquatic plants, like their animal counterparts, have a variety of uses. Many types of seaweed are consumed as human food. For example, the red algae nori 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. 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* (Fig. 1.3) is used as the basis for a very expensive facial cream which is supposed to make the user look younger. Seaweeds are also sources of such chemicals as iodine and the red pigment, β-carotene, which can be used in fish feeds to develop pink flesh coloration in salmon and trout. The worldwide commercial harvest of seaweeds has been

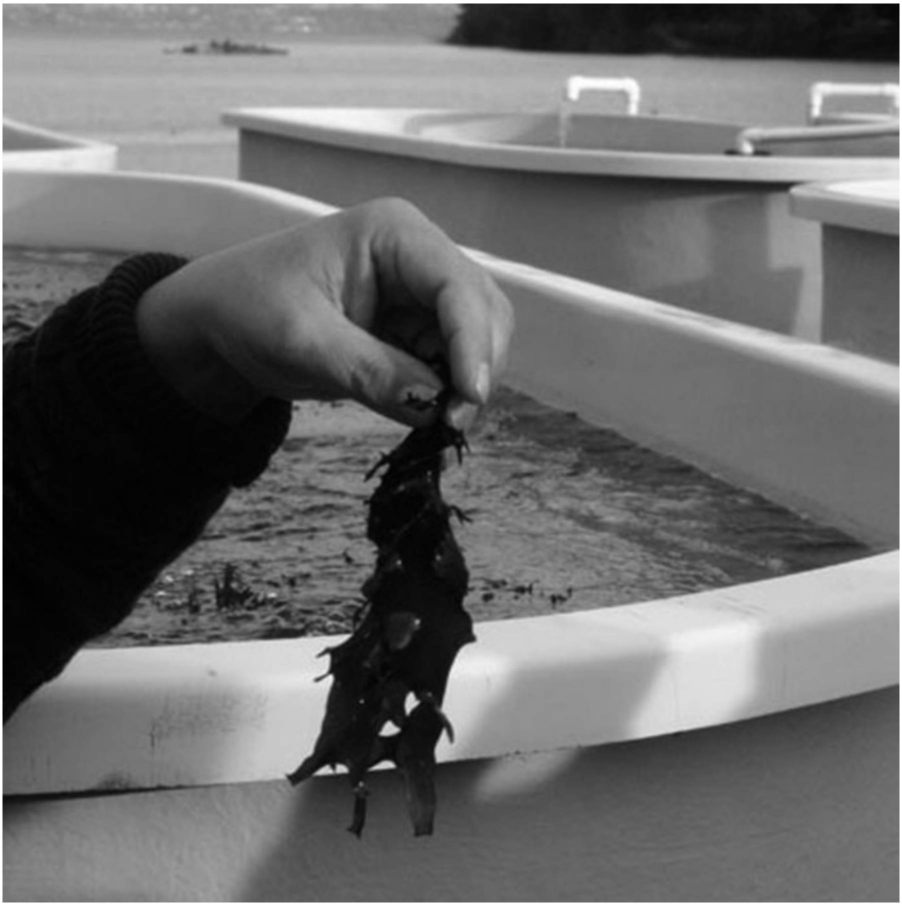

Fig. 1.3. A specimen of the red algae, *Chondrocanthus* sp.

estimated at nearly 8 million tonnes, over 85% of which is said to be cultivated. Other types of algae are found in nutritional supplements and find wide use as food for other cultured species. These are primarily microscopic and often single-celled, called phytoplanktonic algae.

Another objective of aquaculture is bait production. In nations where sportfishing is popular, the availability of live bait is very important. In terms of aquatic organisms, live bait includes minnows, polychaetes,[7] shrimp and a number of other organisms. Of those, minnows of various species – including a marine fish known as the mud minnow, which is actually not a member of the minnow family – are the basis of a large industry, which is dominated by

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[7] Polychaetes are segmented marine worms.

freshwater minnows. Technology for the production of bait shrimp is in the research stage in the USA, but may soon become a commercial reality. Cultured bait shrimp could be used to maintain the supply 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 futuristic use of genetically modified fish to produce pharmaceuticals useful in human medicine. Essentially, the fish would be used as bioreactors or incubators.

Common Aquaculture Species

Table 1.1 presents a list of representative species of plants and animals that are currently being cultured commercially around the world. Some of the species listed are new on the aquaculture scene and are currently available only in small amounts, while others support mature industries. Aquaculturists seem

Table 1.1. Representative species of aquatic plants and animals cultured or being developed for culture as human food. This list includes species cultured in various parts of the world, as well as some species that are currently under development.

Taxonomic Group	Common Name	Scientific Name
Algae	Eucheuma	*Eucheuma* spp.
	Gracilaria	*Gracilaria* spp.
	Kelp	*Laminaria* spp.
	Laver	*Porphyra yezoensis*
	Nori	*Porphyra* spp.
	Wakame	*Undaria pinnatifida*
Echinoderms	Sea urchin, green	*Strongylocentrotus droebachiensis*
	Japanese	*S. intermedius*
Molluscs	Abalone, black	*Haliotis iris*
	black lip	*H. rubra*
	donkey's ear	*H. asinina*
	green	*H. fulgens phiippi*
	red	*H. rufescens*
	South African	*H. midae*

	Taiwan	*H. diversicolor*
	Clam, geoduck	*Panope abrupta*
	Manila	*Tapes philippinarum*
	northern quahog	*Mercenaria mercenaria*
	southern quahog	*M. campechiensis*
	Mussel, bay	*Mytilus edulis*
	blue	*M. trossulus*
	brown	*Perna perna*
	green	*P. viridis*
	greenshell	*P. canaliculus*
	Mediterranean	*M. galloprovincialis*
	Oyster, American	*Crassostrea virginica*
	European flat	*Ostrea edulis*
	Indian back-water	*C. madrasensis*
	Pacific	*C. gigas*
	Scallop, bay	*Argopecten irradians*
	catarina	*A. circularis*
	Japanese	*Patinopecten yessoensis*
	king	*Pecten maximus*
	queen	*Chlamys opercularis*
Crustaceans	Crab, mud	*Scylla serrata*
	Crayfish, marron	*Cherax tenuimanus*
	red claw	*C. quadricarinatus*
	red swamp	*Procambarus clarkii*
	white river	*P. acutus*
	yabbie	*C. destructor*
	Lobster, American	*Homarus americanus*
	European	*H. grammarus*
	spiny	*Panulirus* spp.
	Shrimp, banana	*Penaeus merguiensis*
	black tiger	*P. monodon*[a]
	blue	*Litopenaeus stylirostris*

continued

Table 1.1. (*continued*)

Taxonomic Group	Common Name	Scientific Name
	Chinese	*Fenneropenaeus chinensis*
	Indian white	*F. indicus*
	Japanese freshwater	*Macrobrachium nipponense*
	Kuruma	*Marsupenaeus japonicus*
	Malaysian giant freshwater	*Macrobrachium rosenbergii*
	Pacific white	*L. vannamei*
	Pink	*P. paulensis*
Fish	Ayu	*Plecoglossus altivelus*
	Barramundi	*Lates calcarifer*
	Bass, black sea	*Centropristis striata*
	European sea	*Dicentrarchus labrax*
	palmetto	*Morone chrysops* x *M. saxatilis*
	striped	*M. saxatilis*
	sunshine	*M. saxatilis* x *M. chrysops*[b]
	Carp, bighead	*Aristichthys nobilis*
	catla	*Catla catla*
	common	*Cyprinus carpio*
	grass	*Ctenopharyngodon idella*
	mrigal	*Cirrhinus mrigala*
	mud	*Cirrhinus molitorella*
	rohu	*Labeo rohita*
	silver	*Hypophthalmichthys molitrix*
	Catfish, blue	*Ictalurus furcatus*
	channel	*I. punctatus*
	Indian	*Clarias batrachus*
	Pangasiid	*Pangasius* spp.
	sharptooth	*C. gariepinus*
	Charr, Arctic	*Salvelinus alpinus*
	Cobia	*Rachycentron canadum*

Cod, Atlantic	*Gadus morhua*
Dolphin	*Coryphaena hippurus*
Drum, red	*Sciaenops ocellatus*
Eel, American	*Anguilla rostrata*
European	*A. anguilla*
Japanese	*A. japonica*
Flounder, olive	*Paralichthys olivaceus*
southern	*P. lethostigma*
summer	*P. dentatus*
winter	*Pseudopleuronectes americanus*
yellowtail	*Pleuronectes ferrugineus*
Halibut, Atlantic	*Hippoglossus hippoglossus*
California	*Paralichthys californicus*
Pacific	*H. stenolepis*
Milkfish	*Chanos chanos*
Mullet, striped	*Mugil cephalus*
Pacific threadfin	*Polydactylus sexfilis*
Pacu	*Piaractus mesopotamicus*
Paddlefish	*Polyodon spathula*
Perch, yellow	*Perca flavescens*
Plaice	*Pleuronectes platessa*
Rabbitfish	*Siganus* spp.
Salmon, Atlantic	*Salmo salar*
chinook	*Oncorhynchus tshawytscha*
chum	*O. keta*
coho	*O. kisutch*
masu	*O. masou*
Sea bream, gilthead	*Sparus aurata*
red	*Pagrus major*
Snakehead	*Channa striatus*
Snapper, red	*Lutjanus campechanus*
Sole	*Solea solea*

continued

Table 1.1. (*continued*)

Taxonomic Group	Common Name	Scientific Name
	Tambaqui	*Colossoma macropomum*
	Tilapia, blue	*Oreochromis aureus*
	Mozambique	*O. mossambicus*
	Nile	*O. niloticus*
	red hybrid	Various crosses
	Trout, brown	*Salmo trutta*
	rainbow	*Oncorhynchus mykiss*
	Tuna	*Thunnus* spp.
	Turbot	*Scophthalmus maximus*
	Sturgeon, white	*Acipenser transmontanus*
	Yellowtail	*Seriola quinqueradiata*

[a] Virtually all cultured marine shrimp were classified as members of the genus *Penaeus* in the past, but in recent years taxonomists have been recommending changing the genus name for several commercially important species. The currently recommended taxonomy is used here.
[b] The first species listed for each hybrid is the male, the second the female.

to be always 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 species will continue to grow for some time. The list is not exhaustive by any means but does provide an indication of the diversity of species being cultured.

An introductory text such as this cannot hope to provide all the details associated with the culture of any single species, but there a number of books available with that type of focus. A few recent examples are presented in Table 1.2 and the full citations to each can be found in the additional reading list at the end of this chapter along with some other useful books.

Seaweeds are cultured in the marine waters adjacent to most continents, with the largest amount of activity occurring in Asia. Japan, Korea and the Philippines are among the nations of Asia that have large seaweed culture industries. In the Western Hemisphere, Canada produces a considerable amount of seaweed. Freshwater plants such as water chestnuts are also grown in many nations.

Oysters, mussels, clams, abalone and scallops are grown in marine waters around the world. Both warmwater and coldwater species of oysters and mussels are grown. Their culture sometimes involves merely planting young animals on the bottom in areas that will support their growth and waiting until the molluscs reach harvest size. More sophisticated culture of molluscs typically involves hanging the animals from rafts on so-called strings (actually ropes) suspended above the bottom or from long lines tethered to buoys at each end

Table 1.2. Books that focus on individual culture species or species groups.

Species or species group	Literature citations
Molluscs	Fallu (1991), Hardu (1991), Shumway and Sandifer (1991), Kraeuter and Castagna (2001), Matthiessen (2001), Spencer (2002), Gosling (2003)
Crustaceans	Sandifer (1991), Browdy and Hopkins (1995), New and Wagner (2000), Phillips and Kittaka (2000), New and Wagner (2002), Wickens and Lee (2002)
Fish	
Carp	Michaels (1989), Billard (1999)
Eels	Usui (1991)
Catfish	Lee (1991), Tucker (1995), Tucker and Hargreaves (2004)
Striped bass and hybrids	Harrell (1997)
Salmonids	Sedgwick (1989, 1995), Stickney (1991), Pennell and Barton (1996), Willoughby (1999), Johnston (2002)
Tilapia	Costa-Pierce and Rakocy (1997, 2000), Beveridge and McAndrew (2000).

from which strings are suspended. Squid and cuttlefish (which are also molluscs) are also cultured, but only for use in biomedical research. The giant optic nerves of these species are of particular interest.

Marine shrimp culture in Asia is dominated by Thailand and China, and there is significant production in the Philippines, Malaysia, Indonesia, India and several other nations. In the Western Hemisphere, Ecuador is the leading producing nation, but a number of other Latin American countries also produce shrimp. In the USA, the leading producing state is Texas. There is also some shrimp culture in coastal regions of Florida, Hawaii, South Carolina and the territory of Puerto Rico. Species tolerant of nearly fresh water can be cultured if the water is sufficiently hard.[8] For example, some marine shrimp culture is being conducted in Mississippi and Alabama ponds converted from catfish production. The salinity is quite low but sufficient for some shrimp species. Marine shrimp are also being produced far from the ocean in Arizona and Texas, though the largest amount of production in the USA is along the Texas coast. Freshwater shrimp culture was once a growing industry in many tropical

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[8] The hardness of the water relates to the amount of divalent cations (primarily calcium and magnesium) that are in the water. This factor is discussed in more detail in Chapter 3.

nations and also attracted some interest in temperate regions where a single crop a year is possible, but production has declined to relative insignificance as marine shrimp culture has expanded. Higher dressout percentage, consumer preference and better frozen storage life are among the reasons marine shrimp dominate in the marketplace. A cottage industry for freshwater shrimp has been reported from Illinois, where several producers grow sufficient numbers of animals to satisfy local communities at summer festivals. Because of the novelty of such events, the producer can make a good profit from relatively small production; however, if big producers enter the game, the price will undoubtedly fall.

Carp (members of the minnow family) 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 introductions into the USA in the 19th century and Israel during the last century were in response to the desires of European immigrants to have that fish available to them. As previously indicated, there is no commercial common carp production in the USA and carp has been replaced to a large extent by tilapia and sea bream culture in Israel. Grass carp are produced in the USA primarily for weed control in ponds. There is also a modest amount of silver and bighead carp production in the USA.

During a visit to China in 1999, I was told by government biologists that there is no governmental programme underway to expand carp culture in that country. The reason given was that while carp are suitable for farmers, city dwellers are more interested in fish of higher quality. That statement was reinforced during visits to several restaurants in Guangzhou and Beijing which featured a wide variety of excellent seafoods, but carp were not available, either in the display aquariums that seemed to be a fixture at each restaurant or, apparently, on the menu.

Salmon are grown to market size in captivity in North America, Europe and Chile. The Atlantic salmon is by far the most widely commercially cultured species. Production grew by some 50,000 tonnes a year during the 1990s and probably exceeds one million tonnes annually today (Sylvia *et al.*, 2000). Enormous numbers of other species of salmon are produced for stocking and by sea ranchers. Pacific salmon species such as chinook and coho are reared in North America, Chile, Japan and Russia. There is also some chinook salmon production in New Zealand for recreational fishery, and Japan has a large sea ranching programme underway with chum salmon. China has initiated plans to re-establish depleted runs of salmon in some of that nation's northern rivers.

The rainbow trout is the most important trout species being cultured. That species, native to cold waters in the western USA, is popular with aquaculturists across much of the USA, as well as in Chile and northern Europe. Rainbow trout are also produced for sportfishing in New Zealand. Arctic charr appears to be a good culture candidate and there is growing interest in it by the commercial sector.

US fish culture production is dominated by the channel catfish. The commercial industry began to take off in the 1960s, with early fish farms centred in the state of Arkansas. Mississippi quickly surpassed Arkansas because water tables were falling in Arkansas while the amount of water of excellent quality in Mississippi that was available to the industry appeared to be inexhaustible.[9] Large amounts of channel catfish are also produced in Louisiana and Arkansas with lesser amounts in many other states, including places as far away from 'catfish country' as Idaho where catfish, as well as the much less cold-tolerant tilapia, can be produced in outdoor systems supplied with geothermal water, even during subfreezing winter temperatures.

A Vietnamese catfish, the basa, has been imported to the USA in recent years and competes in the marketplace with channel catfish. That competition has resulted in a reduction of prices paid to domestic catfish farmers and created economic hardship within the channel catfish industry. With country of origin labelling being adopted in the USA, the industry believes that consumers will select the domestic product over the import. In the meantime, prices paid to domestic producers have recovered to some extent.

Walking catfish 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 sometimes equipped with vertical walls or fencing. Once reared on Florida fish farms, possession of walking catfish was outlawed many years ago after escapees began to appear throughout the state. Rumours that the fish were eating small dogs and even babies were totally baseless, but created good stories for the tabloids and for telling around the campfire.

Tilapia are among the primary fish species being cultured 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 fish is limited in temperate regions except under special circumstances, such as when warm or hot geothermal water is available or when water is heated sufficiently above ambient temperature to ensure good fish growth. Some tilapia species and particularly hybrid tilapia are tolerant of high levels of salinity and can be grown in the ocean. Marine culture of tilapia has been underway for several years in the Bahamas and elsewhere in the Caribbean, for example.

Atlantic halibut, plaice and sole are the flatfish species being cultured in Europe, while flounders are produced in large numbers in Japan and are beginning to be commercially cultured in the USA. Atlantic halibut culture is underway in Canada and there has been some interest in both Atlantic and Pacific halibut culture in the USA, though commercialization is yet to be developed.

Milkfish are being cultured in the Philippines, Thailand and Indonesia. The typical approach, and apparently the most economical one, is to capture juveniles

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[9] Of course, no water source is inexhaustible and by the late 1990s the water table was dropping rapidly and it became clear that futher expansion of the Mississippi industry could not go on indefinitely.

and rear them in ponds, though milkfish have been spawned and reared in captivity.

Some sturgeon culture is occurring in North America. Sturgeon are also being cultured in China and Russia. Cobia culture has become established in Taiwan and research preliminary to the establishment of commercial cobia culture is being undertaken in the USA. There has been some interest in the culture of dolphin (the fish, not the marine mammal). Dolphin are known as mahimahi in Hawaii and that name has been adopted, at least on restaurant menus, throughout the USA.

Most sportfish have been excluded from the discussion above and the list in Table 1.1, though sportfish culture for stocking programmes in the USA, Europe, Japan, Australia, New Zealand and elsewhere is well developed and significant. Also, the list does not include bait or ornamental species.

World Aquaculture Production

Statistics on aquaculture production are compiled each year by a number of nations and by the Food and Agriculture Organization (FAO) of the United Nations. In many instances, landing reports include data from both commercial capture fisheries and aquaculture and it is often difficult to distinguish between the two. In addition, a considerable amount of fish and shellfish undoubtedly reaches the market without passing through a point where statistical information is being collected. Thus, obtaining reliable estimates of aquacultural production is not a simple matter. However, the FAO data are the best available with respect to global production, so the numbers used here come from that source. Unless otherwise noted, the information presented here was obtained from the FAO website report *The State of World Fisheries and Aquaculture 2002* (http://www.fao.org).

Total production from capture fisheries and aquaculture in the late 1990s was in the neighbourhood of 120 million tonnes. There were 210 species of plants and animals being cultured. It has been suggested that the future may see greater integration of marine fisheries and aquaculture. Examples of that already exist in a few nations. The example of Norway, where many salmon fishermen are also salmon culturists, has previously been mentioned. The other extreme is the state of Alaska where for-profit finfish aquaculture has been outlawed and commercial fishermen, while supportive of mollusc culture, have been vehemently opposed to any type of finfish culture and are not interested in combining the two activities of capture and culture. That attitude may be changing in at least some circles, and shellfish aquaculture is being actively promoted. In Maine, where the cod fishery collapsed, many fishermen were retrained as salmon aquaculturists only to have aquaculture opponents attempt to curtail expansion of the industry. Some opponents want salmon culture in Maine to cease entirely.

The contribution of aquaculture to the total amount of fishery production has been steadily increasing. From 1950 to 1969, aquaculture production grew at an annual rate of about 5%. During the 1970s that increased to

8%, and it increased again during the 1990s to 10% annually. The trend from 1994 to 1999 is shown in Table 1.3. It is clear that freshwater culture species dominate, largely because of the enormous amount of fish grown in China. Figures for 1998 were 18.1 million tonnes from freshwater culture (58.7%), 10.8 million tonnes from marine culture (35.0%) and 1.9 million tonnes from brackish water culture (6.3%).

The breakdown of species produced during 2000 in the three environments mentioned above is presented in Table 1.4. Finfish dominated in freshwater, while crustaceans represented the majority of the production in brackish water. The main crustaceans being cultured in brackish water are various species of marine shrimp. Molluscs and aquatic plants (seaweeds for the most part) dominated in the marine environment. Production totals for various species groups and the value in US dollars are presented in Table 1.5. Freshwater finfish dominated in both categories, again with the bulk of the production being in China.

Eight of the top 10 nations in terms of annual production in 2000 were in Asia. China continued to lead the world in aquaculture production by a very wide margin. While carp continued to dominate, China had also become one of the leading nations with respect to the production of marine shrimp by about 1997. The primary species being employed during the development of

Table 1.3. Annual aquaculture production (millions of tonnes, excluding plants) from 1994 to 2000 from freshwater and marine sources.

Year	1994	1995	1996	1997	1998	1999	2000
Production							
Inland	12.1	14.1	23.4	25.1	26.7	28.0	~22
Marine	8.7	10.5	10.9	11.2	12.1	13.1	~14
Total	20.8	24.6	34.3	36.3	38.8	41.1	~36

Table 1.4. Global aquaculture production (percentage of total) in freshwater, brackish water and the marine environment during 2000.

Environment	Aquatic plants	Molluscs	Crustaceans	Finfish
Freshwater culture	0	0	2	98
Brackish water culture	1	6	50	43
Marine culture	44	47	1	8

Table 1.5. Global aquaculture production and value for various species groups in 2000.

Species group	Production (millions of tonnes)	Value (US$ billions)
Aquatic plants	10.1	5.6
Molluscs	10.7	9.5
Crustaceans	1.6	9.4
Freshwater fish	19.8	20.8
Diadromous fish[a]	2.3	6.7
Marine fish	1.0	4.1

[a] Diadromous species may spawn in freshwater and migrate to the ocean to mature (anadromous species such as salmon) or spawn in the ocean and migrate to freshwater to mature (catadromous species such as freshwater eels).

shrimp culture in China was a coldwater shrimp, but disease problems plagued the industry and production shifted to warmwater species, leading the Chinese industry to move to the warmer waters of the southern coastal region. Table 1.6 presents a list of the top ten aquaculture-producing nations in various regions of the world.

Table 1.6. Top aquaculture-producing countries (by quantity of product) in various regions of the world.

Asia	Europe	Latin America	Africa	Oceania
China	Norway	Chile	Egypt	New Zealand
India	Spain	Ecuador	Nigeria	Australia
Japan	France	Brazil	Madagascar	Fiji Islands
Philippines	Italy	Colombia	South Africa	Kiribati
Indonesia	United Kingdom	Mexico, Zamia	New Caledonia	Guam
South Korea	Netherlands	Cuba	Tanzania	
Bangladesh	Germany	Venezuela	Morocco	French Polynesia
Thailand	Russian Fed.	Panama	Tunisia	Papua New Guinea
Vietnam	Greece	Costa Rica	Sudan	Solomon Islands
North Korea	Denmark	Honduras	Congo, Dem. Rep.	Cook Islands

A Question of Sustainability

During the last decade of the 20th century, a considerable amount of attention began to focus on agriculture and aquaculture with regard to the sustainability of those activities. Among the many definitions that have been proposed are the following:

- Sustainable: exploiting natural resources without destroying ecological balance.
- Sustainable development: economic development maintained with acceptable levels of global resource depletion and environmental pollution.

While those definitions seem reasonable, they are somewhat open-ended. 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? What is an acceptable level of global resource depletion? What is an acceptable level of environmental pollution? Those questions are central to the debate that continues to swirl around aquaculture and a number of other human activities that impact aquatic ecosystems.

What everyone involved in the debate can probably agree upon is that most types of aquaculture require some level of exploitation and the utilization of 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 natural productivity as the food source for the aquaculture species probably have little impact on natural resources, assuming the construction of the ponds does not result in the destruction of valuable habitat. Intensive systems such as raceways, high-density ponds, recirculating systems and net pen operations (see Chapter 2 for descriptions of those systems) require energy supplied from, for the most part, fossil fuels.[10] Such systems also utilize living resources or their products, including fish meal 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 employed, all of which require exploitation of natural resources and/or fossil fuel energy. Further, development of large pond systems may disrupt wetlands, mangroves or other types of environments that have significant ecological value.

At the extremes of the debate are individuals and groups that have the goal of eliminating aquaculture in most, or all its forms, to those who refuse to acknowledge that aquaculture has any negative environmental consequences. In between are a growing number of people – including researchers and a

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[10] Once in place, there is not a great deal of fossil fuel energy consumed directly to operate the system. However, fossil fuel is expended to make feed, power the boats that are used to service the facility and so forth.

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 of making aquaculture more sustainable in instances where there are problems.

Again, there is no doubt that aquacultural practices result in the utilization of at least some natural resources. The question is whether the degree to which that utilization occurs represents environmental insult and is, thus, an irresponsible activity. The facts are that some aquacultural practices have been destructive, while others have had little or no negative impact. A better term, and one that has been used to some extent in place of sustainable aquaculture, is responsible aquaculture.

Aquaculture, particularly in areas where it competes with other users, such as in lakes, reservoirs and the coastal and offshore marine environment, needs to find ways of being compatible with 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, and in their minds, have priority. More details on various controversies and how they are being dealt with are presented in the next section of this chapter. For additional information on the sustainability challenge in the marine environment, see DeVoe and Hodges (2002).

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 the culture organisms. Thus, it is in the interest of the aquaculturist to focus on sustainability and on maintaining a healthy environment.

Developed nations quickly recognized the fact that some aquaculture practices do have environmental consequences and have promulgated regulations aimed at sustainable and responsible development of the industry. The same is increasingly true of developing nations (Pullin *et al.*, 1993), though there is still a long way to go.

While the potential negative impacts of aquaculture have been widely discussed, the role of aquaculture in the amelioration of environmental problems is only now emerging as a topic of interest. Properly sited and stocked with the right species or combination of species, an aquaculture facility can actually maintain the levels of nutrients in the water. This can be accomplished by stocking filter-feeding animals that consume plankton to keep the plankton populations from exploding or blooming in the presence of high nutrient levels (generally in the forms of nitrogen and phosphorus). 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[11] serve as fish-aggregating devices. This is particularly true in open-ocean situations

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[11] See Chapter 2 for descriptions of these types of facilities.

where there are not many surfaces available in the water column upon which food organisms which attract fish and other species can grow. Fish and other types of organisms may reach densities outside the culture chambers that are as great or greater than within. Thus, aquaculture facilities can actually provide habitat in some instances. For a discussion of how marine facilities may act as habitats, see Costa-Pierce and Bridger (2002).

Opposition and Response

There appears to have been little opposition to aquaculture until some time in the 1980s when fish farms – salmon net pens and shrimp farms, in particular – began to appear in coastal waters (Fig. 1.4) and coastal shrimp ponds were

Fig. 1.4. A commercial net pen in Maine, USA.

proliferating at an exponential rate. Aquaculture, which had largely been practised, at least in the Western Hemisphere, on private property inland from the coasts, began to infiltrate the commons. There had been a small amount of cage culture in public waters, but that was insignificant by comparison with what was happening around the world in the marine environment. Net pen salmon culture and cage culture of yellowtail and sea bream became popular in Japan, with many bays eventually becoming overcrowded with such structures to the point that sensitive species, including the cultured fish, were sometimes heavily stressed or killed. Japan promulgated regulations through fish cooperatives which reduced the density of aquaculture facilities and led to a more healthy environment.

In the state of Washington, USA, cries of *visual pollution* from upland property owners were heard. These cries of protest were soon followed by outcries from a variety of individuals and groups with vested interests in the bays, sounds and estuaries[12] where aquaculture was a newcomer. While aquaculture in coastal marine areas is seen as an eyesore by some, in Japan, aquaculture facilities are almost considered to be an amenity and can often be seen in the shadow of resort hotels, as shown in Fig. 1.5.

Fig. 1.5. A bay in northern Japan where aquaculture net pens and mollusc long-line culture are practised in front of a resort hotel in the absence of opposition.

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[12] An estuary is a semi-enclosed coastal water body in which saltwater mixes with incoming freshwater.

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. 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 had also been discussed, as were a virtual laundry list of other objections to salmon net pen culture beginning in the 1980s, 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 later to Maine and the Maritime Provinces of Canada.

Shrimp culture was also under attack for constructing ponds in coastal wetlands and, in particular, in mangrove areas. Nutrient and sediment loading of waters that received the effluent from shrimp ponds were also in for criticism (Treece, 2002).

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 has no responsibility to prove that those practices are harmful. 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.

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

Issue 1:

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

Industry Sector: This criticism has been lodged against the cage and net pen industry with respect to salmon and other species.

Reality: The problem can be very real and significant, leading to virtually sterile zones immediately under net pens or cages and extending 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 as sufficient flow will disperse the solids broadly.

Solution: Proper siting of the facility accompanied by frequent monitoring to detect any changes before they become significant are means of solving the problem.

Issue 2:

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

Industry Sector: Again, this complaint largely targets net pen and cage fish culture.

Reality: Unlike the accumulation of waste feed and faeces under cages and net pens, this concern relates to dissolved nutrients in the water column.

Nitrogen and phosphorus releases to the water can be significant in areas where large numbers of cages or net pens are located, as has been the case in Japan.

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 is not a problem. Information from places like Puget Sound, Washington and Hawaii, among others, shows that nutrient increases do not occur in either protected or open ocean waters if there is sufficient current through the culture chambers. Frequent monitoring is recommended as well.

Issue 3:

Issue: Water released from culture ponds can cause algal blooms and silting up of waterways.

Industry Sector: This is an issue with fish and shrimp pond culture.

Reality: When water is released from culture ponds, 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 silt up public waterways.

Solution: Employing feed ingredients that contain forms of phosphorus and highly digestible proteins (the major source of nitrogen) that are more fully utilized by the culture animals can help resolve the nutrient issue. 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.

Issue 4:

Issue: 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 in the latter instance. It has also been raised with respect to exotic finfish and shellfish as it is thought that exotic species[13] may bring in new diseases as well as pass them to wild populations.

Reality: The potential exists, but there is probably a higher probability that wild fish or invertebrates will pass a disease to the cultured species since the high density of animals in a pond, cage, net pen or other facility exposed to surface freshwater or marine water can distribute pathogens within the community very rapidly compared with transmission among more widely dispersed animals in the wild. The use of exotic species in marine aquaculture was discussed by Stickney (2002).

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[13] Exotic species are those that do not occur in the location but have been introduced in some manner. In the case of aquaculture, those introductions are intentional. Unintentional introductions through ballast water exchange in ships is a major issue. Exotic species are also called non-native and non-indigenous species.

Solution: Quarantine of exotic species before stocking to ensure, to the maximum extent possible, that they do not carry pathogens; careful monitoring of all cultured animals in the hatchery prior to release; certification of health from a certified 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:

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

Industry Sector: This concern has been focused on finfish and shrimp. It has been raised with respect to cultured exotic species as well as native species. (Also see Issue 6 below, which is related.)

Reality: Escapement has been a problem, and is never going to be 100% preventable, though aquaculturists do everything they can to curtail escapes from occurring since lost animals represent lost revenues as well. A major concern in the state of Washington has been that Atlantic salmon escapees would become established as reproducing populations (recall that the US government stocked Atlantic salmon along the Pacific coast for many years in the late 19th century without success). There seems to be little evidence to indicate that Atlantic salmon escapees are successfully competing with wild Pacific salmon. In Norway, the issue revolves around cultured Atlantic salmon – that have been selected for fast growth and adaptability to culture conditions – that could escape and potentially displace wild Atlantic salmon. Studies have shown that the cultured fish do not adapt well to the wild and displacement of wild populations does not seem to be a severe problem. In Texas, 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 no cultured shrimp have been observed in the commercial trawl fishery.

Solution: Improved biosecurity has reduced the escapement problem, though catastrophic failures of net pens can still occur and there is always the chance that screens preventing shrimp from leaving ponds could fail as well, or that shrimp could be lost during harvesting.

Issue 6:

Issue: When cultured species are reared in waters where wild animals of the same species live, escapees from aquaculture could breed with their wild counterparts, resulting in changing the genetic diversity of the wild population. For more information, see Hershberger (2002) and Lester (2002).

Industry Sector: This is primarily an issue associated with Atlantic salmon farming in Norway and along the North Atlantic region of North America at the present time, but it has been mentioned in relation to various other species as well.

Reality: This issue has been a major one in Maine where native 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 reducing the populations of wild fish in the state. 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.

Solution: Prevention of escapement is the most important step that the aquaculturists can take. In Maine, the state has placed traps in some rivers so as to capture salmon returning to the spawning grounds. Biologists say they can visually discriminate wild from cultured fish that are trapped. They release the fish identified as being wild upstream and sacrifice those fish they determine to be from fish farms. The state is now requiring that fish stocked in the net pens be derived only from Maine stock.

Issue 7:

Issue: The use of antibiotics in salmon feeds leads to the development of disease-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 since there have not been many studies of the situation, it is not known whether this is a concern that has merit. It should be noted that the amount of antibiotics that enter the water through sewage outfalls (antibiotics entering the water with human waste) and from pastures and feedlots (antibiotics used to treat livestock) pose a more serious threat because the amount of chemical entering the water is much higher than that associated with fish farms. Another more serious problem is the presence of traces of antibiotics found in shrimp grown in Asia that are imported into 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 a minimum can play a major role in reducing the incidence of disease epizootics,[14] though treatment is necessary when a disease is detected. In the USA, only approved antibiotics can be used and there are regulations on which species can be treated, the amount of the drug that can be utilized and the number of days the antibiotics can be used. Withdrawal periods between cessation of offering the antibiotics and the time the fish can be marketed are also specified. Fish farmers only use antibiotics when a disease problem has been identified. Some nations have banned importation of shrimp containing residues of unapproved antibiotics, while others screen incoming shipments of shrimp to ensure that minimum acceptable limits are not exceeded.

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[14] Human disease outbreaks are referred to as epidemics. When a disease outbreak occurs in other animals, the proper term is epizootic.

Issue 8:

Issue: Destruction of mangrove areas has a number of significant ecological impacts.

Industry Sector: This issue has focused primarily on the shrimp farming industry in Asia and Latin America. Mangroves have also been cleared for fish pond construction in parts of Africa, but not to the same extent as in other parts of the world – at least, not yet.

Reality: Shrimp farms in tropical Asia and Latin America have been blamed for wholesale destruction of mangrove areas, which are known to provide protection from storms and serve as nursery areas for many marine species. The problem is exacerbated because shrimp ponds constructed in mangrove areas are only productive for a few years, so the practice has been to construct new ponds to replace those that are no longer productive, which often means the clearing of more mangroves. Soil acidity in ponds constructed in mangrove areas is a primary reason for eventual abandonment. Many human activities other than aquaculture have had enormous impacts on mangrove swamps, though the impacts of pond construction for aquaculture should not be ignored. This issue has been discussed in detail by Boyd (2002).

Solution: The governments of many affected nations have come to recognize the importance of the 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:

Issue: Using fish meal in aquaculture feeds is unsustainable and improper.

Industry Sector: Salmon and shrimp culture have been the primary targets of the opposition.

Reality: Fish meal is a widely used ingredient in livestock and aquaculture feeds. It is obtained from species such as anchoveta, herring and menhaden. 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 fish meal as an ingredient in aquaculture feeds often use the argument that it takes two or more kilograms of fish meal to produce a kilogram of edible fish which, following their logic, shows that aquaculture is not a sustainable practice. There is also a perception that aquaculture is the primary user of fish meal in the world. The fact is that the amount of fish meal used in feeding terrestrial livestock far exceeds that used in aquaculture, though the percentage going to aquaculture is increasing with industry expansion. Aquaculture utilized about 10% of the world's fish meal supply in 1990 and may be using more like 20% today. The fact remains that the world's fish meal will be used in animal feeds whether or not aquaculture animals are involved. In addition, fish meals are made from species that are not usually acceptable as human food. See Hardy and Tacon (2002) for a discussion of this topic.

Solution: Aquaculture nutritionists are attempting to reduce the percentage of fish meal used in aquaculture feeds. That ingredient has been reduced to nearly zero in channel catfish feeds and has been reduced to some extent through the use of alternative protein sources in feeds manufactured for various other aquatic species.

Issue 10:

Issue: The use of genetically modified organisms (GMO) 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 would be incorporation of a growth hormone gene from one fish species into another to enhance the growth of the latter. Stories have circulated in the press that so-called GMO 'Frankenfish' (in reference to the monster created by Dr Frankenstein in the novel by Mary Shelley) have been developed that grow many times faster than non-GMO fish of the same species. The prediction has been that these dreaded superfish could wreak havoc on the aquatic environment and inhabitants therein. No actual examples of such spectacular increases in growth have been confirmed in the scientific literature. Improved growth rates have been realized, but they are more in the order of 10% than several hundred per cent. 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 favourite authors, Clive Cussler, wrote in *White Death* about an unscrupulous aquaculture firm that produced voracious GMO salmon that were depleting the oceans of other species. Another fear is that eating GMO fish will somehow affect the consumer.

Solution: In the USA, the Department of Agriculture (USDA) developed the National Biological Impact Assessment Program 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, though no aquacultured GMO are currently being produced commercially. 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. Controls such as those imposed on transgenic fish releases in the USA may not apply in other nations. In fact, regulations on GMO utilization appear to be lacking in many developed nations. The European Union does not allow the production or import of GMO. One area where GMO may see a great deal of use is in feed ingredients used in aquaculture. GMO plants that have enhanced protein levels are more digestible, or have other positive attributes, could play a major role in aquaculture feeds in the future as replacements for fish meal and other expensive ingredients.

Issue 11:

Issue: Aquacultured organisms are inferior to those that are wild caught.

Industry Sector: Fish and shrimp are the primary targets. The issue does not seem to involve molluscs.

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. Aquacultured animals have also been indicted for having high levels of biocides and heavy metals – particularly mercury – compared with their wild counterparts. In blind sensory evaluations by taste panels, aquaculture products often are judged as superior to wild ones, though that is not universally true. Chemical tests have not shown that chemicals and heavy metals in cultured fish pose an added threat to humans.[15] It has been suggested by some critics that cultured fish and shrimp that are 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 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 at 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 six 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 the misconceptions lies in conducting valid research to investigate the claims and widely disseminate the results through aggressive public education programmes. All such studies need to be pursued with all due diligence to scientific integrity. There is too much ‘junk science’ in the media, and regrettably, in the scientific literature.

Issue 12:

Issue: Diseases of aquaculture species can be passed to humans.

Industry Sector: Fish and shellfish are both considered to be reservoirs of human pathogens.

Reality: There seems to be little or no scientific basis for this objection in conjunction with fish. Diseases that affect the fish cannot be transmitted to humans. Human pathogens that may be on the surface of fish or that have been consumed by filter-feeding shellfish can affect humans. Some pathogenic bacteria have been known to infect people who clean fish that are contaminated (such as those exposed to sewage effluent or reared in ponds fertilized with manure or night soil). Bacteria from the fish integument can enter through an open wound or if the individual’s skin is cut or pierced while cleaning the fish.

Solution: Individuals who clean fish should take care to avoid being cut by spines or knives. Consuming raw fish or shellfish that have been reared or captured from the wild in contaminated water should be avoided, particularly by

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[15] Exceptions do occur. Salmon from the Great Lakes of the USA do contain high levels of certain chemicals and public health warnings about consumption of those fish have been issued. That is an exception and applies to all the salmon in the Great Lakes, where there is some natural reproduction and also some hatchery production. Salmon are not native to the Great Lakes; they were introduced in the early 1980s and a multibillion dollar industry has developed.

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 until the shellfish 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:

Issue: 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.

Reality: Concerns expressed by critics include the contention that cage and net pen culture interferes with navigation and access to traditional commercial fishing and recreational fishing grounds. That is true to some extent, but facilities are generally small in total area and when properly regulated are sited in locations where the least possible negative impacts on other users will occur. For more on this topic, see Harvey and McKinney (2002) and Barnaby and Adams (2002).

Solution: Proper siting will help resolve the issue, but some will not be satisfied until all aquaculture in public waters is banned.

Issue 14:

Issue: 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 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 in the nets and drowning. Incidents of mammals being negatively impacted through entanglement appear to be rare. 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. The issue has been discussed by Würsig and Gailey (2002).

Solution: Marine mammal predator nets placed outside of 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.

Issue 15:

Issue: 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, lobsters, young milkfish or immature tuna from nature for stocking aquaculture facilities is taking place. This practice apparently has had an 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 as those industries expand. This issue has been discussed by Hair *et al.* (2002).

Solution: Researchers have developed techniques to culture each of the organisms mentioned, so it is now possible to close their life cycles. That does not mean that collection of wild stocks will cease, but moving increasingly to hatchery stocks will be helpful. Economics and government regulations are considerations that will influence the course of action taken by culturists.

Issue 16:

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

Industry Sector: This is another complaint aimed primarily at net pen culture.

Reality: Very little noise is associated with net pen operations, at least those I have visited in the USA, Norway and Japan. Odours would only become a problem if mortalities were allowed to accumulate and decompose.

Solution: Noise appears not to be a real issue. Best management practices call for picking up mortalities and properly disposing of them daily.

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, in the USA the killing of predatory birds by fish farmers is strictly regulated through a permit system. In some nations, there is no regulation and birds, including songbirds, may be killed indiscriminately.

Coastal aquaculturists who have pond systems, whether for the rearing of vertebrates or invertebrates, have come into conflict with residential, condominium and shopping centre developers; with industries interested in expansion; and with wetland protection and preservation laws. The demands on land adjacent to the sea coast in many parts of the world – particularly in developed nations – are great, and the amount of suitable and available land area for aquaculture, assuming the land could be economically purchased for that use, is shrinking. At the same time, there is competition for space in coastal waters. Many believe that the future of aquaculture development in the USA, and in other developed nations, will be associated with recirculating systems and offshore facilities (see Chapter 2).

Worldwide, the aquaculture community has been reactive rather than proactive when addressing the real problems that have been identified as bringing the sustainability and potential negative impacts of aquaculture into question. In recent years, various groups, including the FAO and the Global Aquaculture Alliance (GAA) have developed Codes of Conduct for aquaculture. The current GAA Code of Conduct is for shrimp culture but the organization plans to expand their activities to other sectors of aquaculture. Several individual nations also have Codes of Conduct with respect to aquaculture. Included are 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. GAA developed a series of best management practices that shrimp producers can adopt to reduce the environmental impacts associated with their operations.

Regulation of Aquaculture

Discussing aquaculture regulations in a general fashion is difficult because the regulatory situation both within and among many nations 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.

Permits to operate facilities may or may not be required. Depending on where the aquaculturist is and what the aquaculturist plans to do, filling out a form and paying a small fee may be all that is required in order to obtain a permit. In other cases, the prospective aquaculturist may have to visit several different agency offices at various levels of government, fill out complicated forms, collect environmental data in support of the application, develop an environmental impact statement, wait for public comment, put on a legal defence in court or appear before a hearing board, pay a significant amount of money for the permit itself and possibly pay a lease payment to utilize the proposed site if it involves the use of public waters. There is also the possibility that after the expenditure of large amounts of time and money, the permit application will ultimately be denied.

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 is a commonly lax regulatory environment. In some instances where regulations have been promulgated, enforcement has been weak. Some nations provide tax advantages to aquaculturists, and there has also been the lure of cheap land and labour. 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.

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2 Getting Started

Deciding What to Produce and Where to Do it

An aquaculture facility needs a sufficient quantity of good-quality water in order to produce a high-quality crop in enough quantity to make a profit. Depending on the level of technology that is 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, about the only places where there is no aquaculture are in the Arctic and Antarctic regions.

Just because a functioning aquaculture facility can be established in a particular place does not mean that the venture will, or even can be, profitable. Requirements for water treatment, or simply the costs of obtaining the necessary water, can exceed the profit potential. One firm established an indoor facility to grow warmwater marine shrimp in Chicago, Illinois several hundred kilometres from the nearest ocean, about 25 years ago. The costs of purchasing a salt mixture that mimics seawater when mixed with freshwater, coupled with the requirement to heat the water during much of the year so it would support acceptable shrimp growth, were among the reasons why the venture failed. The hiring of numerous highly skilled engineers and biologists to design and operate the facility was also costly, particularly since the nation was going through an economic recession at the time the operation was beginning to produce a very small amount of marketable product.

In many cases the aquaculturist will select 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 very compatible. A culturist may have training and experience with a particular species and concentrate on that species because of being most comfortable with it.

On the other hand, a prospective aquaculturist may already own a piece of land and desire to establish an aquaculture facility thereon. In that case, or in the case where the culturist purchases an existing aquaculture facility, the best course of action is to select a culture species that is appropriate for the site.

Soil properties are an important consideration when a pond culture system is to be developed. Inferior soil characteristics can lead to extensive seepage from ponds, thereby increasing operation costs because of having to provide replacement water. Pond liners are available but expensive. Thus, dedication to a poor site can lead to significant problems, which may include financial disaster.

The Business of Aquaculture

Many aquaculturists have established their aquatic farming activities as one part of a larger agrobusiness enterprise. This has been true for portions of the catfish industry in the USA, salmon culture in Chile, and shrimp culture in many nations. For example, in the USA, Mississippi cotton growers turned to channel catfish farming as an additional crop as did rice producers in Arkansas and farmers in Alabama. 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.

When a new aquaculture species reaches the market, it will often demand 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 there is little or no competition in the marketplace. Subsequently, as other culturists begin producing the same species, the price to the producer will begin to drop.[1] 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 got into the business early and were able to pay off their costs of facility development before the market became saturated may survive, but those who arrived late and have heavy debt loads may end up bankrupt.

The Atlantic salmon farming industry in the state of Washington is an example. At one time in the mid-1980s, net profits – that is, the amount of money left over after all the bills were paid – were often over US$2/kg of fish produced. Within a few years, as the amount of cultured salmon reaching the marketplace expanded, profits fell to only one-tenth of that amount or even less.

Since prices for channel catfish paid to producers have increased only marginally in the last few decades (something like US$1.10/kg in 1960 to about US$1.65 to US$1.75 in 2004), and have actually fallen considerably when the value of the dollar in 1960 and today is factored in, producers who borrowed large amounts of money to purchase land and construct facilities often faced financial difficulty. Those who entered the business in the early years of production and were able to pay off their debts years ago in many instances continue to operate at a profit. In the channel catfish industry, the

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[1] Prices to consumers rarely drop, though they may remain constant when prices paid to producers fall.

producers are also often members of cooperatives that produce the feed and process the fish grown on the farms. For each kilogram of feed purchased or kilogram of fish taken to the processor, the members of the cooperative get shares in the profits of the company, so there are additional revenue streams to the farmers.

Aquaculture is a particularly high-risk type of farming. The aquaculturist is rarely certain as to the exact number of animals that are in the 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 consumed by other animals in the system or they may decay without floating to the surface where they can be observed and retrieved for disposal. 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.

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.

The Business Plan

Having a good business plan is a necessity for the prospective aquaculturist who needs, as do most, to borrow money in order to establish 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 chance that their loan or investment would be sound. That situation has changed to some extent as aquaculture has expanded, but investors and bankers recognize that aquaculture is risky. Also, shady individuals – the ones I like to call bioshysters – have come up with grandiose plans that predict windfall profits for investors: plans which are reality only in the minds of those who are talked into supporting them. As a result, large amounts of money have been lost by investors who backed projects that had little chance of survival or which were merely schemes to line the pockets of the individuals who shopped their proposals around.

For the honest aquaculturist – which is by far the majority – the job of convincing bankers and investors is still a primary activity during the early stages of a project: that is, unless the prospective aquaculturist is independently wealthy. Selling the concept of a new facility is still required even in places where aquaculture is commonplace. Just because others are successful in the area does not mean that the newcomer has what it takes to operate profitably.

By having considered all the costs of startup 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. Once again, many have fallen prey to supporting schemes that had little or no chance of success, so they now have done their homework in many cases and know what the realities are with respect to the costs of development and operation and the profit potential.

The budget that is developed with respect to the business plan needs to identify the fixed or ownership costs – the once-only expenses, such as for purchase and modification of land and for the purchase of durable equipment – things that have life expectancies measured in terms of years – and 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 animals to stock, labour, chemicals and utility expenses.

While the specific items required for inclusion in the budget will vary to some extent in relation to the type of facility that is proposed (culture system options are discussed later in this chapter), many items will appear on nearly every aquaculture budget. Table 2.1 provides a list of the major budget items that would be associated with development of a pond culture facility. Similar lists should be developed for other types of facilities.

Table 2.1. A list of expenses (fixed and variable costs) associated with development of a typical pond culture facility.

Fixed Costs

Land (cost of purchase, amount of lien in place, or value if already owned)

Facility Construction

- Earthwork to build ponds or renovate existing ponds
- Material and installation of drainage system
- Landscaping and sod or seeds to vegetate pond levees
- Gravel for roads
- Well drilling
- Plumbing from water source to ponds
- Pumps to deliver water to ponds
- Support building(s) such as office, laboratory, storage, shop and hatchery

Equipment

- Feeding system (automatic feeders, if used; feed storage building or bins)
- Spraying equipment for dispersal of chemicals such as herbicides
- Boat, motor and trailer
- Tractor(s) and implements (mower attachments, disc, front end loader, box blade)
- Trucks (pickup truck, fish-hauling truck)

continued

Table 2.1. (*continued*)

	Laboratory equipment (microscope, water quality analysis equipment, computer for data acquisition, storage and analysis)
	Office equipment (computer, furniture, fax machine, copy machine)
	Shop equipment (welder, drill press, mechanics' tools, carpenters' tools, cutting torch)
	Hatchery tanks and associated plumbing
	Supplemental aeration equipment for use in hatchery, ponds and live hauling (one or more among blowers, paddlewheel aerators, compressed air tanks and liquid oxygen tanks)
	Live hauling tank (pickup truck bed size for small loads, large tanks for long hauls)
	Emergency equipment (back-up generator)
Variable Costs	
	Feed
	Miscellaneous supplies (dip nets, seines, brooms, buckets, nails and screws, plumbing supplies, paint, spare parts and many more)
	Salaries and wages (including the owner's salary)
	Fringe benefits
	Animals for stocking (juvenile fish or postlarval shrimp, for example); the costs may be associated with purchase or production if a hatchery is incorporated into the facility
	Repairs and maintenance of facilities and equipment
	Energy (electricity, natural gas, petrol, diesel fuel)
	Chemicals (fertilizer, disease treatment drugs, supplies associated with water quality determinations)
	Harvesting and hauling (may be contracted to custom harvesting and live-hauling firm)
	Interest paid
	Depreciation
	Taxes
	Insurance

The business plan should include a marketing component if the aquaculturist plans to sell directly to the public or to a retail outlet. In many nations there are aquaculture associations or cooperatives that do the marketing for a group of culturists. To pay for those marketing activities, there may be a fee added to each tonne of feed purchased or fish processed. The revenue can go to support such activities as consumer surveys, advertising and the development of new markets.

Investors and banks will also 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).

Water: the Common Factor

Over 70% of the surface of the Earth is covered by water (the vast majority of which is saltwater). In addition, there is an abundant supply of groundwater in some areas. At the same time, there are parts of our planet where surface water is not to be found, groundwater may be absent, or the quality of either makes it useless for aquaculture or for much of anything else. Aquaculturists have taken advantage of water sources that include surface water, groundwater and rainwater or snowmelt runoff. Municipal drinking water may come from any of those sources. In this section we look at the different sources of water and some of their advantages and disadvantages. Water quality issues are discussed in Chapter 3.

Municipal water

Those of us who live in places where there are abundant supplies of clear, clean tap water are fortunate indeed. At first glance it might seem highly fitting to use that water in aquaculture; however, there are major drawbacks. First, municipal water is expensive. For the average home, the monthly water bill is acceptable since it typically involves only a few to several thousand litres a month per person. To use that water in an aquaculture facility would be prohibitive unless it could be reused over and over again – as is the case with recirculating water systems as discussed below. The cost of water to supply the needs of a pond or flow-through raceway system would be prohibitive. The other major drawback is that municipal water contains chlorine or chloramines that are added to kill bacteria and make the water safe for drinking. Those chemicals are also lethal to aquatic animals and would have to be removed prior to exposing such organisms to the water. Removal of the chemicals is not difficult, but it is an added expense, except for chlorine which can be eliminated by letting the water stand for 24 h or by aerating it for a shorter period of time. Chloramines are not removed using those methods. Both chemicals can be removed by passing the water through a column containing activated charcoal or by adding sodium thiosulphate.

The use of municipal water for aquaculture is relatively rare. It has been tried in some large cities where other water sources were not available. The success rates have been variable, with fewer successful ventures than failures seemingly being the rule to date. 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 and snowmelt water that flows across the land ultimately enters the ocean, lakes, streams and other water sources. Rainfall also falls directly into surface waters as well as being a major portion of the runoff water supply. I separate out runoff as a distinct source of water since some aquaculturists use it as their only supply. This is true, for example, of many fish farmers in Arkansas. It is also true in other areas around the world, particularly those 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 to fill them 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 portion of the year makes a good deal of sense in such locations.

Surface water

Surface saltwater occurs in the oceans, bays, sounds, estuaries, fjords and some 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 some facilities sited in exposed ocean waters. Many of those locations are well away from the protection of land. Open ocean aquaculture is beginning to expand and is at least being talked about much more extensively today than it was only a few years ago. Some aquaculturists envision establishing facilities well offshore in the Exclusive Economic Zone (EEZ) of their nation or beyond. 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 fish culture.

The surface 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. 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. Upstream users of stream water may deplete the supply by taking it first, thereby leaving the aquaculturist without a reliable source. The prospective aquaculturist should make sure that his or her water rights are protected from acquisition by upstream users.

One government fish production facility with which I was involved in the Philippines depended upon water from an irrigation canal for filling the ponds. The irrigation canal was reliable much of the time, but should it be breached (which was not an infrequent occurrence) it could be shut down without notice, leaving no water available to the facility for an indefinite period of time. To ameliorate the problem, the facility design included a holding reservoir that would provide additional water if the irrigation canal was taken out of operation.

Lakes and reservoirs can be good sources of water. The water from them can be flowed into ponds or through raceways. Lakes and reservoirs can also be used as sites for cage culture. The effluent water may be flowed back into the lake or reservoir where, if the water body is sufficiently large, it will undergo natural treatment and could be suitable for reuse.

All water sources should be checked for such contaminants as trace metals, herbicides and pesticides, if there is any possibility that toxic levels of any of those substances might be present. Contamination with biocides may be seasonal, as in the case of agricultural regions where nearby fields may be sprayed during the growing season, either from the ground or through aerial application. Trace metals may come from prior industrial users of the land or they may occur as natural levels in the water. Another common source of contamination is waste runoff from pastures into surface waters used for aquaculture.

Groundwater

Groundwater is often the preferred source for aquaculture, particularly if an abundant supply of good-quality water can be obtained without having to drill a deep well. Artesian wells are best as they flow under pressure, thus possibly eliminating or greatly reducing the need for pumping. Prospective aquaculturists can talk to the appropriate government agency, well drillers or their neighbours to get an indication as to the depth of various water tables, the amount of water that can be removed, the water quality and whether permits for well drilling and water removal are required. The latter point can be very important. I was speaking with landowners in eastern Washington state several years ago, who wanted to look at alternatives to growing wheat as they were not making the profit from wheat that they had in earlier times. They thought fish culture might be an option and the more we discussed it, the more interested the farmers became. They had wells to irrigate their wheat and thought the water could just as easily be put toward fish production. The whole idea was quickly abandoned, however, when a state agency official said that under existing regulations water could only be pumped so many days a year – I think it was less than 200 days – during the normal crop growing season but at no other time. That made trout farming impractical since it depends on a consistent supply of flowing water in virtually every case.

For ponds, I have been told that it is desirable to have at least 150 l/min available for each hectare of water under culture. Other types of water systems may be less demanding (recirculating systems) or much more demanding (open raceway systems) of water. Raceways may require complete changes of water a few times a day, once an hour or more frequently depending upon the species being reared. Once the volume requirement for water is known, the well driller, working in conjunction with the aquaculturist, can recommend which water stratum to utilize, determine the number of wells that will be needed and indicate 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.

As more and more wells are drilled and the volume of withdrawal increases, such as can happen when a facility is expanded or neighbours construct their own aquaculture facilities (or turn to crop irrigation), drawdown of the water table may occur. That happened in Arkansas, when rice land that was flooded to a depth of only several centimetres when used for that crop was converted to fish ponds that require 1.5 to 2 m of water for the same surface area as that used for rice. The continued growth of catfish farms in Mississippi over a 30-year period finally led to drawdown of the water table in the catfish farming region of that state as well. Many other examples could be cited. In some cases, the farmer can obtain suitable water by drilling a deeper well into the same water table, but that may only provide temporary relief if other users adopt the same approach. Searching for even deeper water tables is also sometimes an option, but for each increase in depth increment required to hit suitable water the cost increases, not only for drilling, but also for pumping.

In general, the temperature of well water increases with increasing well depth. In some geologically active regions, hot water of good quality can be obtained from geothermal wells. An example is shown in Fig. 2.1.

Saline wells can be drilled in some regions, including some areas far from where the oceans are today, but in areas that were once inundated by the sea. Saltwater wells can also be drilled below or adjacent to marine waters. Recharge of such wells from the overlying or adjacent estuarine or marine

Fig. 2.1. A tilapia culture operation in Idaho, USA, that was able to operate all year round due to the availability of high-quality geothermal water in an area noted for bitterly cold winters.

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.

Well water can come to the surface depleted in oxygen and may contain relatively high levels of such things as hydrogen sulphide, iron or carbon dioxide. I have even seen well water that was high in ammonia. Aeration will solve most of the problems. Bubbling air through the water or splashing it over rocks, for example, causes iron to precipitate to form ferric hydroxide ($FeOH_3$). That precipitate can be removed through the use of filters. If not removed, it will stain pipes and other surfaces and if present at high enough levels it can clog gills. Aeration will drive off hydrogen sulphide 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 be used for fish rearing.

If the water contains high levels of dissolved nitrogen it can cause gas bubble disease 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 are at depth for long periods. As they surface, the gas comes out as bubbles in the bloodstream. 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.

Culture System Options

There are a variety of culture system options available. Some can be used for purposes of rearing a variety of species, though a few have been developed specifically for one or a few related organisms. Once you have seen an example of any particular type of water system you will immediately recognize others of the same type. However, you will virtually never see two that are identical. There are always readily apparent differences in design. Some culturists are so dedicated to their particular design that they are protective about showing outsiders what they have. They may be afraid that their 'secrets' will be stolen. Having visited a large number of aquaculture facilities and been told in some instances not to take photos or reveal what I have seen, I can only say that I have yet to have a 'secret' revealed to me that I had not seen before. In many, perhaps most, instances, aquaculturists are happy to share their techniques and designs for equipment with their peers.

We begin with the most popular type of water system, the open pond. After that we look at flow-through raceways (circular and linear), followed by semi-closed and closed (or recirculating) water systems. Specialty systems like poles, long lines, rafts, cages and net pens complete this section. For a more detailed discussion of culture systems, see Lawson (1995).

Ponds

The majority of aquaculture is conducted in ponds with sloping earthen levees and earthen bottoms, though in some places rigid sides are employed. In

China, for example, one can find many ponds with mortar-clad brick vertical walls and earthen bottoms (Fig. 2.2). In most cases, once a pond is filled, additional water is only added to replace that which is lost through seepage and evaporation. One exception that I have seen involved ponds used for trout culture – at least a few of those can be found in Idaho – through which water is continuously flowed, though not at a high rate of exchange. Most trout culturists use raceways (discussed below) instead of earthen ponds.

Location, location, location

Where ponds are constructed depends to a considerable degree on water source and topography. To avoid excessive seepage loss of water, the soil should contain a minimum of 25% clay. Since soil composition can change significantly over short distances, particularly in river valley sites where historical meanders of the river may leave deposits of sand or gravel in one area and heavy clay deposits only a short distance away. Thus, unless you know 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 concentration is present. The cores need to be sufficiently long to reach what will be the bottoms of the ponds that are to be constructed. A thin clay layer over sand would not be detected if the cores are not long enough. Ponds constructed in the ground in such an area would be a source of constant frustration (and cost) due to seepage. Pond liners can be effective at controlling seepage, but they can also be very expensive. Clay blankets at the bottoms of leaky ponds will also help and bentonite (a clay mineral that expands when wet) has apparently been successfully used to help seal leaky ponds. My experience with bentonite has

Fig. 2.2. A pond with vertical walls of brick covered with mortar in China.

been almost entirely negative, though others claim to have had 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.

Sites near saltwater are sometimes characterized by very sandy soils, in which case liners of some kind are a necessity unless water is to be constantly flowing into the ponds. A rather unique situation exists at an ornamental fish-growing facility in Hawaii where ponds have been constructed on a lava flow. The substrate is rock hard, porous, and has lava formations with very sharp edges associated with them. 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 prevents seepage losses. A second layer of carpet over the plastic helps protect the liner from the activities conducted by the culturists. The two layers of carpet protect both the liner and the feet of employees.

Watershed ponds are those that are filled with runoff water. They are often constructed in gulleys with a levee at the downstream end or by excavation in an area that receives a high volume of rainfall runoff. In the latter case, the earth removed during excavation is used to construct the levee (Fig. 2.3). Similar pond construction can, of course, be used if water is obtained from a well, or a surface water source, but more typically ponds that depend upon some water source other than runoff are laid out on land that is level or gently sloping. When collection of rainwater runoff is not a consideration, it is pos-

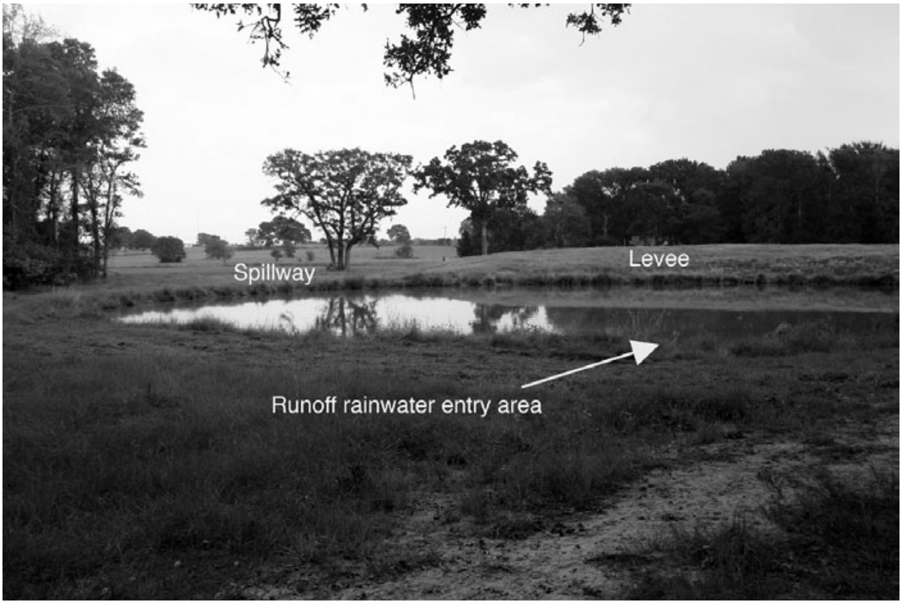
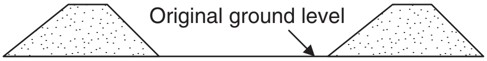


Fig. 2.3. An excavated watershed pond looking from the end into which runoff water flows.

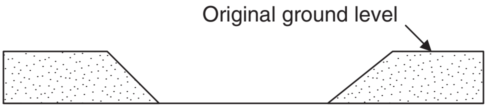
sible to have as many ponds at a site as can be filled and kept full with the available water supply.

Ponds can be constructed above ground level, in the ground, or partially in the ground. Levees are typically earthen and sloped, though vertical concrete walls have been used in some places as previously mentioned (Fig. 2.2). Above-ground ponds are those in which the initial ground level becomes the pond bottom. The levees are constructed from soil that is brought in. The source of that soil is often from in-ground ponds where the levee top is at the initial ground level and soil is removed to build the pond. A partially in-ground pond will be one in which soil that is removed is used to construct a levee around the pond. Typically, about half of the pond depth in a completed partially in-ground pond will be below original ground level and half above (Fig. 2.4). On a sloping site one would end up with in-ground ponds at the upper elevation, partially in-ground ponds at the middle elevation and above ground ponds at the lower elevation, resulting in all the levee tops being at approximately the same elevation when the site slopes gently. 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 construction.

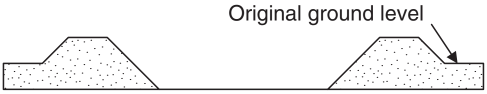
If the culturist has a level site, the most economical approach would be to build partially in-ground ponds. The removed soil would all go into levee construction



Above-ground pond



Below-ground pond



Partially in-ground pond

Fig. 2.4. Cutaway view of above-ground, below-ground, and partially in-ground pond configurations showing the elevation of ground level prior to 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 were constructed on a level site, involves significant expense and often the use of trucks. Similarly, constructing below-ground ponds on a site might require trucks to haul away the soil to an appropriate fill site – again leading to additional expense.

A matter of size and shape

The size of aquaculture ponds is highly variable. The range of commonly seen ponds is from about 0.05 to 10 ha, but the typical fish farm might have ponds in the 0.20 to less than 4.0 ha range (Fig. 2.5). Small ponds are easier to manage and easier to feed than large ones. If one wishes to distribute feed evenly across the pond, a boat may be required for large ponds, while a feed blower pulled by a truck or tractor can be used if the feed is distributed fairly near the edges of the pond (Fig. 2.6). Small ponds can be fed by hand or with feed blowers. Large ponds are also difficult and expensive to treat with chemicals if there is a weed or disease problem that requires the application of a chemical to the pond. Also, should there be a fish kill that involves a high percentage of the fish in a pond, the financial loss will be greater in a large pond stocked at the same density per unit area than a smaller pond. Finally, the larger the pond, the more difficult it is to harvest. People can pull seines through small ponds by hand, whereas it is necessary to use trucks or tractors to pull seines through large ponds.

Fig. 2.5. A typical aquaculture pond.

Fig. 2.6. A tractor-drawn feed blower parked under feed storage bins.

One advantage that large ponds have over small ones is the fact that more water area is available in the same amount of space. The reason is that levees reduce the available water space, as is shown diagrammatically in Fig. 2.7. The wider the levee, the more space it takes, of course. And, since at least one side of each levee needs to be wide enough for a vehicle to drive along in order for workers to have access, at least one part of the levee needs to be several feet wide. Many aquaculturists prefer to be able to drive completely around every pond and construct their levees appropriately wide, though often only certain levee areas are gravelled so that they can provide all-weather access. The other sides can be grass covered and can be driven on when dry.

You will note in Fig. 2.7 that the diagram shows rectangular ponds. That shape provides for the economical use of available space but as one travels around from one aquaculture site to another, it is possible to observe ponds of various shapes, including circular, oval, triangular, trapezoidal and so forth. Sometimes pond shapes follow natural ground contours and the shape takes advantage of those contours to reduce the amount of earthwork involved in construction. Old facilities, in particular, were constructed before heavy mechanized equipment was available and used available land contours as far as possible to save on the amount of hand- or horse-drawn labour involved in moving dirt.

Prior to construction the land should be cleared of all vegetation, including tree roots. Any woody debris that ends up in a levee will eventually rot and the void space created can provide a channel for water to penetrate the levee and ultimately cause levee failure. The topsoil removed during construction can be stockpiled and later used to top-dress levees after construction is complete. It is much easier in most cases to establish grass on topsoil than underlying soil that might be used as the top layer of a levee.

In cases where above-ground ponds are constructed, a ditch should be dug a metre or so deep around the pond perimeter, or at a minimum in the location of the outermost areas under what will be the location of levees. In Fig. 2.7A, the core trench would be required under all levees, while in Figs 2.7 B, C and D, the core trench could be under each of the levees or only under the outer levees. This ditch is called a core trench. The core trench should be filled with the same material as that used to construct the levees. The core trench and levee itself should be compacted periodically during construction. When the pond is filled with water, it will try to flow under the levee where the soil is different in compaction from the levee. However, when the 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 stop. Lacking a core trench, the water may undermine the levee and lead to leakage and potential levee failure.

Levees should be built with side slopes that are from 1:1 to 1:3; that is, for every unit of elevation, there should be one to three units of width (Fig. 2.8). The 1:1 configuration is the steepest (unless vertical walls), with the levees being at a 45° angle to the pond bottom. This is desirable from the standpoint of limiting the amount of levee area where invasive rooted plants can take hold and grow, but it is an angle that bulldozer operators find dangerously steep and it is difficult for workers to enter or leave the pond once it is put into production. Shallower angles, such as 1:2 or 1:3, provide easier access but more shallow water area for aquatic weeds to become established.

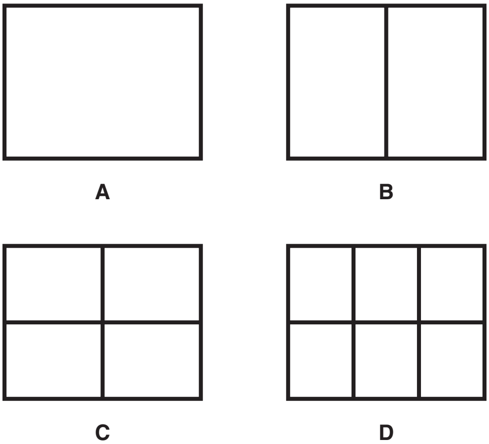


Fig. 2.7. Relative amount of a one-hectare site taken up by levees when there is one 1 ha pond (A) as compared with two (B), four or six ponds (C, D).

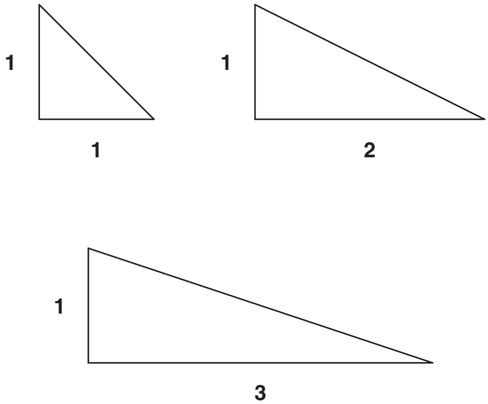


Fig. 2.8. Diagram of cross-sections of pond levees with slopes of 1:1, 1:2 and 1:3.

Pond construction is commonly accomplished with bulldozers, but draglines and scraper pans pulled behind tractors are among a variety of other types of machinery that can be used. Once construction is complete, road levees should be topped with gravel to provide all weather access. Again, the other levees should be planted with grass which will help reduce erosion.

'My pond is small, but it is deep.' I have heard that expression on many occasions. The implication is that because of the excessive depth, the farmer can stock more fish than could be stocked in a pond of standard depth. In reality, that is not the case.

The typical aquaculture pond is constructed to hold water to a depth of approximately 1.5 to 1.75 m. Levee height should be at least a few centimetres to a half metre higher than the intended water level. During summer in temperate climates and throughout most or all the year in the tropics, there is a noticeable decrease in water temperature with depth in the water column. This is due to a process called stratification of the water. 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 is called the thermocline. In aquaculture ponds the thermocline, when present, will extend to the bottom of the water column. In deeper ponds, 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 is also commonly oxygen depleted due to 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 with the same surface area as a standard depth pond has about the same carrying capacity; that is, they can each support about the same amount of fish.

Getting the water in and out

Each pond needs to be plumbed with one or more inflow lines and with a drain line. Inflow can be through open sluiceways (open channels that have side channels that can carry water to the individual ponds), but pipelines are more common. Polyvinyl chloride (PVC) plastic pipes and fittings are the most common type in use today. They have largely replaced metal pipes, which are subject to corrosion and can be a source of heavy metals at toxic levels. Connecting PVC pipes to fittings is a simple matter of gluing them together, while metal pipes need to be threaded, or soldered together in the case of copper. PVC is much less expensive than metal, is easy to cut, is non-toxic, and is very durable. PVC Schedule 40 pipe should be used since it can handle a wide range of temperatures and can 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. Drain PVC is available but should not be used in pressurized water systems. A disadvantage of drain PVC is that it will shatter if exposed to freezing temperatures. The pipes that carry water from the main water line to the individual ponds should each have a valve at the end so water can be turned on and off as needed.

Pipes should be sized with respect to diameter so that sufficient water can be carried to fill each pond within 72 to 96 h. Not all the ponds on a facility need to be filled simultaneously, but the culturist needs to carefully consider what the maximum amount of flow might be and design accordingly. It would certainly make sense to have sufficient flow through the system to fill it completely within a total of a few weeks. Thereafter, water would be used to maintain the water level as there will be loss to evaporation and possibly seepage. Larger pipe diameters will be needed for gravity flow systems (such as obtaining inflow water from a holding reservoir) than when the pipes are under pressure (as when the water is pumped from or flows under pressure from an artesian well). Some culturists put inflow lines at each end of the ponds, while others have a single inflow line. In the latter case, the inflow line is usually associated with the drain end of the pond, so new water can be added to maintain water quality during the last stages of pond harvesting that involves pond draining.

Note that two pipes of the same diameter will not carry the same amount of water as one pipe which is twice the diameter of either of the two. For example, two 5-cm pipes will not carry as much water as one 10-cm pipe. Recall that the area of a circle (the cross section of a pipe) 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 $2.5^2 \times 3.14 \times 2 = 39.25$ cm^2, while that of a single 10-cm diameter pipe is $5^2 \times 3.14 = 78.5$ cm^2, or twice as large. The reason I provide this example is that on one project I was involved with, the contractor wanted to substitute two small pipes for one larger pipe (again the two smaller ones had the same total diameter as the large one as in our example). Since the water flow requirement was based on the single larger pipe diameter, the contractors plan was rejected in favour of the one large pipe.

Water can be removed from ponds with pumps; however, that approach increases the expense because of the need to provide, petrol or diesel fuel to run the pump. The more desirable approach is to put in a drain system (a once-only expense) that allows water to be removed by gravity. Drains may be very simple (Fig. 2.9) or associated with some type of structure which controls water level, houses the drain controls and also is fitted with an inflow line (Figs 2.10 to 2.12). A standpipe may be fitted with a valve, or it may simply be fitted on an elbow and rotated (laid over) to allow the water to flow out. In either case, the height of the standpipe above the pond bottom when it is vertical should be lower than the height of the levee, so excess water that is added over and above the desired amount will be able to drain away. That excess water may be purposely added by the culturist who is trying to improve water quality, or by heavy rains. Figs 2.10 to 2.12 show examples of the many varieties of drain structures (sometimes called kettles or monks) that are seen around the

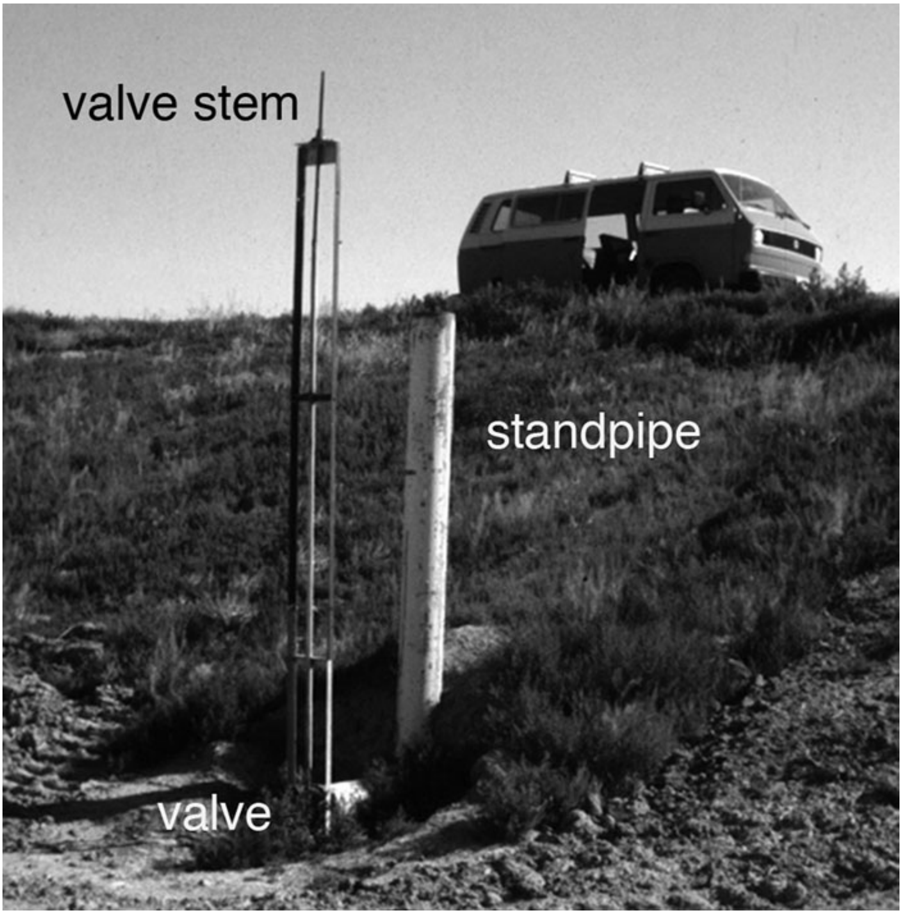


Fig. 2.9. Standpipe drain in an empty pond. Note that vertical standpipe will control water level in the pond while a valve at the base of the standpipe can be opened to drain the pond. The valve stem (structure in front of standpipe) protrudes above the water level when the pond is full.

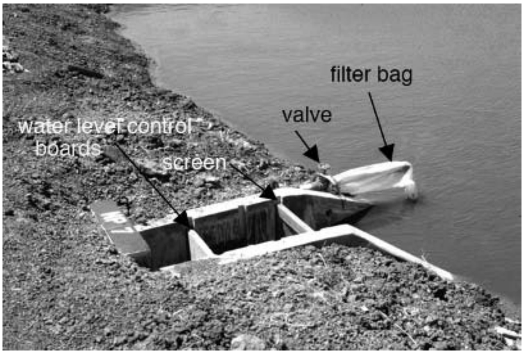


Fig. 2.10. A concrete kettle in the Philippines. Note the screen at the front (right) and dam boards at the back (left) of the kettle. Also note the nylon sock over the inflow line that protrudes over the pond. The sock helps keep unwanted wild fish and invertebrates from entering the pond during filling.

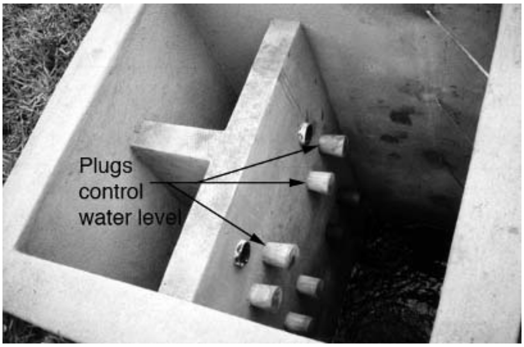


Fig. 2.11. A concrete kettle in Brazil in which water level is controlled with wooden plugs in the drain end of the kettle.

world. Rather than valves, as are common in North America and elsewhere, the one in the Philippines (Fig. 2.10) uses baffle boards to control water level. A series of boards fitted in grooves are stacked up to the desired height. When the pond level is to be lowered, one or more boards is removed and the water flows into a drain pipe at the bottom of the kettle. The structure, as are most, is fitted with a screen at the front to prevent fish escapement during draining. There is also a mesh sock over the inflow line to prevent unwanted organisms from entering with the incoming water, which in this case was from a reservoir fed by an irrigation canal. In the Brazilian kettle (Fig. 2.11), wooden plugs placed at various levels in the kettle can be removed or added to control water level. The inflow line cannot be seen in the photograph. The most elaborate type of kettle is one constructed of concrete that features inflow and drain valves, a stairway for access by personnel and a catch basin where the last of the fish are concentrated for easy capture by dip net during the final stages of harvest (Fig. 2.12).

Shallow ponds

Rice–fish farming and crawfish farming are accomplished in shallow ponds. Rice–fish farming is practised, at least to some extent, in many rice-growing nations, including Egypt and various countries in Southeast Asia. Tilapia and carp are commonly used in conjunction with rice–fish culture. In the case of

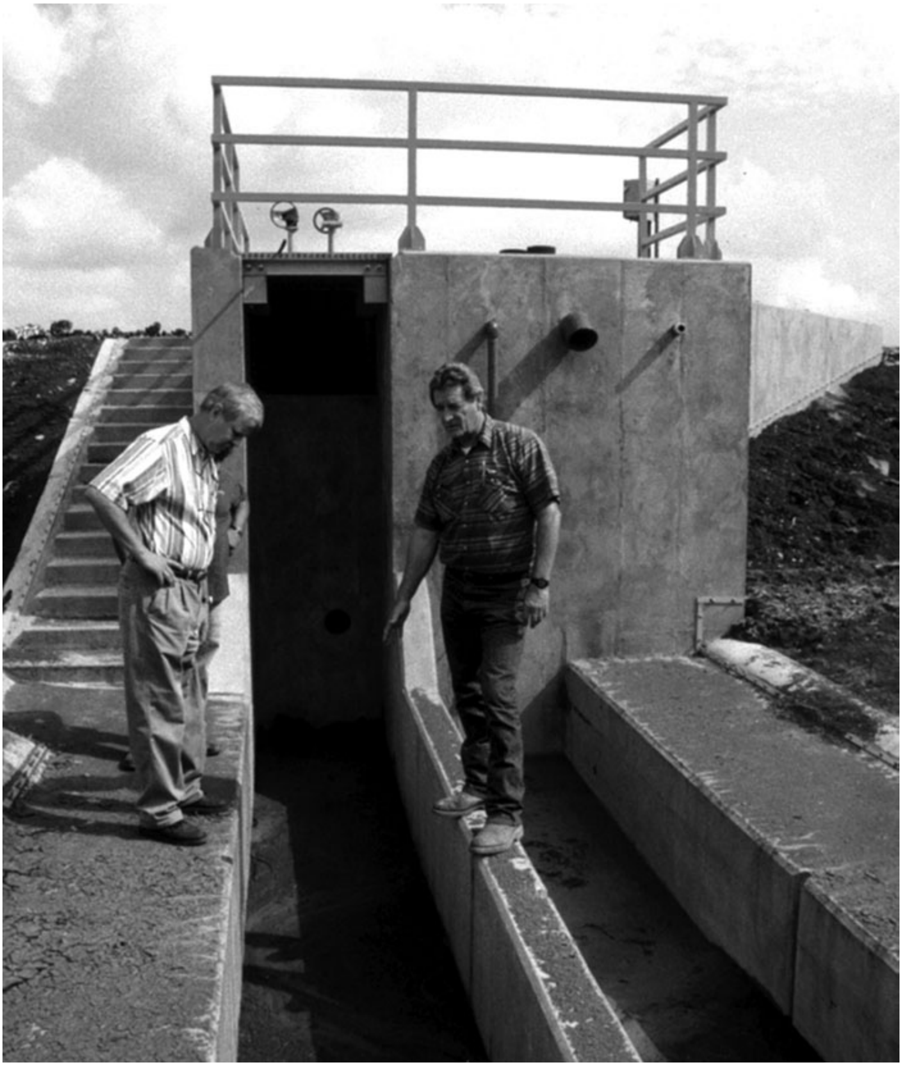


Fig. 2.12. A concrete kettle with access stairway and catch basin in Texas, USA.

crawfish culture in the USA, the industry began in Louisiana where farmers were looking for an alternative use for rice ponds. The rice farmers found that they could obtain a better profit from crawfish than from rice, though they sometimes rotated their crops between the two species. The coastal region of east Texas, which was also a rice-growing area, began raising crawfish in the 1980s. The US crawfish industry has declined in recent years with an influx of crawfish from Asia that has resulted in reduced prices paid to domestic farmers.

Rice ponds have low levees of about 15 cm. When used for crawfish production, the ponds are modified by increasing the levee height from 30 to 75 cm. Double cropping of rice and crawfish is possible, though if the farmer does not intend to harvest the rice, millet, alligator weed, wild rice or some other type of plant may be used as forage. In both rice–fish and crawfish farming, the animals forage on animals that grow on the rice (insect larvae, for example). Tilapia will also graze on algae (periphyton) that attach to the rice plants.

In the Philippines, rice pond levees are not modified when rice–fish culture is practised. Instead, a trench about 1 m deep and 0.5 to 1 m wide is dug down the middle of the pond. When the pond is flooded, the fish can swim about foraging as described in the previous paragraph. When the field is drained, there will be sufficient water in the trench to accommodate the fish. Draining of the rice field might be in conjunction with spraying for pests or for harvest. 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.

Raceways

Raceways are culture units in which water continuously flows. The most common shapes are circular (Figs 2.1 and 2.13) and rectangular (Figs 2.14 and 2.15). Rectangular units are called linear raceways. They were the first type to be developed and are commonly seen throughout the world. They have been most widely used in conjunction with the early rearing of salmon and for rearing trout from fingerling to market size. Early raceways were constructed of wood. Modern raceways are usually composed of concrete, aluminum or fibreglass. In a linear raceway, water enters one end and exits the other. Linear raceways may be grouped side by side or in series, whereby the effluent from one raceway enters the next in line (Fig. 2.16). To maintain dissolved oxygen, the effluent from each unit in the series will typically be passed over splashboards to aerate the water. The typical length:width:depth ratios in linear raceways are 30:3:1 (Piper *et al.*, 1982).

Circular raceways, or tanks, vary greatly in size. Small units are used for research and in hatcheries, while large ones can be used for growout. The largest practical size seems to be about 10 m diameter. Fibreglass and various types of plastic, such as polypropylene, are used in circular tank construction, with fibreglass being the material of choice for tanks larger than a metre or so in diameter. Typically, large circular raceways contain water to a depth of

Fig. 2.13. Small circular tanks used for replicated laboratory studies.

about 1 m, though tanks up to a few metres 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 as to create a current in the tank. The most common location for the drain is in the centre of the tank. A well-designed tank will have a bottom that slopes toward the drain. Suspended solids, which would primarily be faeces and unconsumed feed particles, will move to the drain and exit the tank, thereby helping maintain water quality. 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. The venturi drain can be placed 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. A diagram showing how such a drain will look inside a tank is presented in Fig. 2.17.

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 as it is located at one end of the raceway, while some material tends 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. Daily siphoning, at a minimum, is required until flow rates can be sufficiently increased to have the venturi drains function effectively.

As indicated by Piper *et al.* (1982), factors affecting the carrying capacity of a raceway are water flow rate (l/min), raceway volume, water temperature, dissolved oxygen content, pH, size of the culture animals and the species under culture. Formulae for calculating carrying capacity given knowledge of the other factors have been developed for some species (Westers, 2001),

Fig. 2.14. Small indoor raceways used to rear trout to fingerling size and subsequent stocking in larger raceways.

Fig. 2.15. Outdoor raceways for growout of rainbow trout.

Fig. 2.16. A portion of a series of raceways showing water being aerated as it passes from one to the next. The water entering at the top of the series is aerated at the inflow tower seen in the background.

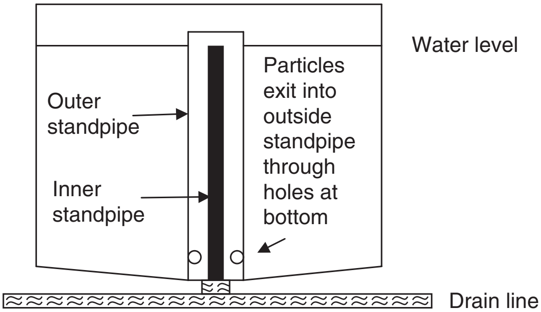


Fig. 2.17. Diagram of circular tank showing configuration of the venturi drain. Water flows through the holes at the bottom of the outer standpipe and up over the top of the inner standpipe, then down the drain. Solids accumulate at the bottom of the tank inside the outer standpipe. Pulling the inner standpipe periodically for a few seconds flushes the accumulated solids down the drain.

though experience gained through trial and error is undoubtedly still used by many culturists. The typical aquaculturist, in his or her determination to maximize profits, will push the water system to its very limits, and many times beyond those limits, thereby stressing the animals and be required to deal with disease epizootics or direct mortality as a result.

High flow rates and the currents that result can be used with juvenile fish that are adapted to them in nature. Salmon and trout are examples. Juveniles of other species and the early life stages of most may be able to tolerate only modest flows and, in some instances, will tolerate virtually no currents. Extremely low flow rates or static (no flow) conditions are sometimes maintained during the hatching of eggs, particularly the very small and often very fragile eggs of most marine animals, and may also be required during larval rearing. By cutting out holes in a large percentage of the outer standpipe of the drain and covering the openings with fine mesh nylon screen material or making a mesh sock out of what would have been the outer standpipe (Fig. 2.18), it may be possible to maintain a very slow exchange rate with new water, 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 keep as much of the mesh open as possible.

Mass algal culture is usually conducted in aerated static water, with the last phase occurring in large tanks. Typically, a sterile stock culture of each algal species is maintained in test tubes or small flasks containing a nutrient solution. The stock cultures are kept in a lighted incubator. When the cell density is high – hundreds of thousands to millions of cells/ml – a portion of the contents of each test tube or flask is used to inoculate a new container and the remainder is used to inoculate a larger container, such as a glass carboy or plastic bag that contains the nutrient medium.[2] 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 (Fig. 2.19). Carbon dioxide, which provides the carbon source for phytoplankton growth, may be supplemented as its concentration in the atmosphere

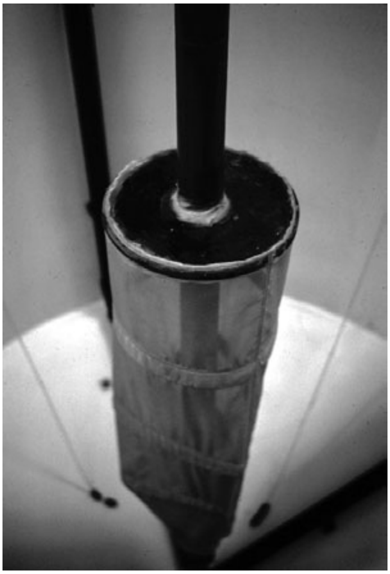


Fig. 2.18. Standpipe system constructed in part with fine mesh netting to retain larval fish or invertebrates.

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[2] Some standard nutrient broth formulae have been developed, but different species require slightly to significantly different proportions of nutrients. Diatoms, for example, require silicon whereas green algae do not.

Fig. 2.19. Algal culture carboys. The carboy on the left has a dense concentration of cells and is nearly ready for harvest, while those to the right contain cultures in the early stages of growth.

is low (about 0.5%). After a few days, cell density will be maximized and the algae can either be used as food for filter feeding aquaculture animals, or when large volumes of algae are required, such as in a commercial facility, the cells in the containers may be used to inoculate tanks with capacities of up to several thousand litres. If the algae are not immediately to be used as food, they can be concentrated into a paste in a continuous centrifuge, frozen or freeze-dried and stored for later use. While some mass algal culture is conducted outdoors in raceways or tanks, most culturists prefer to culture algae within a building or greenhouse to limit the possibility of contamination with unwanted algal species that could out-compete the species of choice.

Open raceway systems

When water is continuously flowed through a linear raceway or tank system it is classified as an open system. Once the water exits the system it is commonly flowed into a receiving water body, though it might also be used to irrigate pastures or row crops, and in some cases, may be picked up by a downstream aquaculturist. Another option is to dispose of water into a municipal sewage system, but that, like using municipal water, will be very expensive in open systems that use high flow rates and no reuse of the water. Open systems are commonly used for rearing trout, particularly in locations where there are abundant supplies of freshwater of the proper quality. Some 95% of US trout culture occurs in the Hagerman Valley (also known as the Magic Valley) area of Idaho in a section called the Thousand Springs Area of the Snake River Canyon (Fig. 2.20). Several large springs flow out of the northern wall of the canyon.

Recirculating systems

Water systems in which a portion or all of the water is processed to restore water quality and then recycled back to the culture chambers are called recirculating or

Fig. 2.20. Spring water of excellent quality and huge volumes flows from the Snake River Canyon in Idaho, USA and supports several trout farms.

reuse systems. A recirculating system may recycle as little as a few per cent of the water a day, but if virtually all the water is reused over and over again, the system is referred to as a closed system. The home aquarium with an undergravel or outside filter that treats the water is an example of a closed system with which most people will probably be familiar. In reality, no system is 100% closed. As we will see, some components associated with closed systems need to be partially drained periodically to eliminate settled solids. Replacement water then needs to be added and new water will also be required to replace losses due to evaporation and splashout.

Most recirculating systems are housed in buildings such as pole barns or greenhouses. Some have been established in warehouses as well. Usually, the amount of natural sunlight that the systems are exposed to is minimized to keep algae from growing in the tanks. However, at least a few systems have been established in which the culture protocol calls for establishment and maintenance of an algal bloom which can function as a component of the water treatment system, food for the culture animals or as the final product. Polyculture systems that combine plant and animal culture in the same system require light for the plants. That may be either artificial or natural light.

Designs for recirculating water systems vary widely. Most are designed by the culturists themselves, though there are engineering firms that will 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. In any case, there are some features of recirculating systems that are consistent from one system to another. They include the culture chambers (tanks or raceways in most cases), a biological filter and commonly, one or more settling basins, mechanical filters and one or more pumps to move the water from one component to another. In recent years, filters have been developed which both treat the water and capture suspended solids for removal from the system. Examples of these are described below.

The culture chambers used in recirculating water systems are as described in the raceway section above, with the exception that instead of effluent water being disposed of after one use, some or all of it is treated and recycled back to the culture tanks or raceways. Circular raceways are more commonly seen as elements in recirculating systems than are linear raceways.

Water exiting the culture chambers may flow into a settling chamber or be mechanically filtered to remove suspended solids. Settling chambers are basically tanks where the water flow rate is slow enough to allow the solids to settle out of the water column. When turnover of the water in the system is rapid, very large settling chambers are required to be effective. Water exiting the biofilter may also enter a settling chamber as additional solids will leave the biofilter component of the system as well. Settling chambers should have a bottom drain so that accumulated solids can be flushed out of the system.

Mechanical filtration is another way of removing solids. Sand filters have often been used and are very effective when the solids loads are not too high (Fig. 2.21). Sand filters tend to clog fairly quickly as the pore spaces between the sand grains are filled. Water flow will tend to channel through sand at that point and the efficiency of the filter will be greatly reduced. Backflushing of the filter to remove the accumulated solids is required periodically – sometimes as often as two or more times a day. Gravel filters are less efficient than sand but will function without backflushing for a longer period of time. Some facilities use gravel filters followed by sand filters so the large particles are removed by the gravel filter and the time required between backflushings of the sand filter is increased. Gravel filters also require backflushing when the medium becomes

Fig. 2.21. Large sand filters can be used in both flow-through and recirculating systems to remove suspended solids from the water.

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 sand filtration (Fig. 2.22).

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 to change the form of nitrogen in the water from a toxic to a basically non-toxic form.

Aquatic animals excrete nitrogen as a waste product. This 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 (NO_3^-). This is accomplished in two steps. One type of bacteria converts ammonia to nitrite (NO_2^-), which is also toxic. A second type of bacteria then converts nitrite to nitrate:

$$NH_3 \rightarrow NO_2^- \tag{1}$$

$$NO_2^- \rightarrow NO_3^- \tag{2}$$

It has been widely reported that reaction (1) involves bacteria in the genus *Nitrosomonas* and reaction (2) involves *Nitrobacter.* Recent studies have indicated that other genera of bacteria may also be involved. In any case, the bacteria associated with the reactions are cosmopolitan in nature and will colonize the biofilter medium within a few days to several weeks after water is put in the filter. Colonization proceeds most slowly in marine systems. Also, the two types of bacteria may not colonize at the same rate. If those responsible for reaction (1) begin working before the second bacterial population becomes active, the conversion of nitrite to nitrate will not occur rapidly enough to prevent toxicity. Thus, it is important to have well-established populations of both types of bacteria actively doing the conversions to take ammonia to nitrate before the culture animals are stocked at high density. Putting a few animals or some feed or fertilizer in the system to provide a nitrogen source will encourage development of the bacteria. Commercial mixtures of bacteria are available as well, though mixed results with those products have been reported; that is, they may or may not accelerate establishment of the desired levels 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.

As the bacteria build up on the filter medium, it will form mats, pieces of which will slough from the medium and contribute to the level of suspended solids in the water. That is why solids levels in biofilter effluent can be quite high and why a settling chamber and/or mechanical filter is often put in the system to remove solids from the biofilter effluent.

Various types of biofilter media have been used over the years. In most cases today the medium in each filter is some type of plastic. The demand for biofilter media is sufficiently high that commercial firms are selling products designed specifically for that use. Various shapes of filter media have been used. Included are plastic balls (Fig. 2.23), plastic rings, scrap PVC and sheets of fibreglass.

Fig. 2.22. Cartridge filters may be used to remove very fine particulate matter from the water.

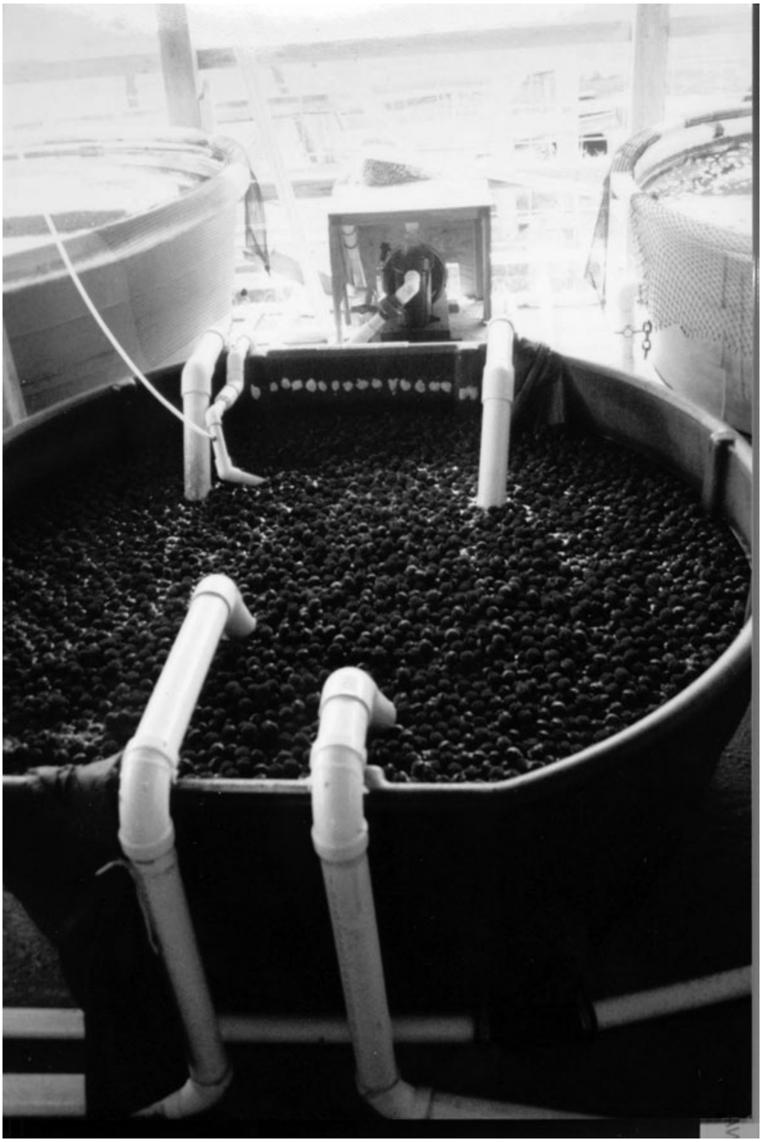

Fig. 2.23. A biofilter filled with commercially available plastic balls that serve as the filter medium. The system was designed to keep live shrimp at a bait shop.

The water entering the biofilter may flow in at the top and pass over the filter medium and then exit at the bottom. The medium may be submerged in water or the medium may not be submerged as the water is introduced but is kept moist through constant exposure to incoming water. The latter type is called a trickling filter. Examples can be found in many sewage treatment plants. The water may also be introduced from the bottom of the biofilter chamber and overflow near the top of the tank. This is known as an upwelling filter. Another approach is to flow water in one side of the biofilter chamber and out the other. The rotating biocontactor, or RBC, is a biofilter design in which the medium (usually circular sheets of fibreglass) is mounted on a rod and half submerged in water. A motor turns the rod at a few revolutions per minute. An example of an RBC is shown in Fig. 2.24.

Biofilters should be protected from exposure to sunlight and bright artificial lights to prevent the growth of undesirable algae. Algal growth can lead to clogging of the biofilter and, if blue-green algae become established, there is the potential of 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 algae are toxic.

Two types of biofilters that are distinctly different from those previously described are fluidized bed (Fig. 2.25) and bead filters. Basically, these types of biofilters are vertical units partially filled with some type of small medium. Fluidized bed filters are vertical columns that 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 bed filters. Water is flowed through the medium at a rate that puts the medium in suspension (the bed becomes fluidized; that is, it behaves like a liquid). Fluidized bed biofilters are used for ammonia removal but do not remove particulate material (Lawson, 1995). Anaerobic fluidized beds can be used to remove nitrate by converting it to nitrogen gas. That reaction is also produced by certain types of bacteria which thrive in environments that are oxygen depleted. While nitrate is usually not a problem in aquaculture systems, it can build up to toxic levels in 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. Some aquaculture species may also exhibit low tolerance for nitrate, though most can withstand concentrations of at least a few hundred parts per million.

Bead filters employ small plastic beads as the filter medium. Like fluidized bed filters, the medium is kept in suspension and constant motion at all times

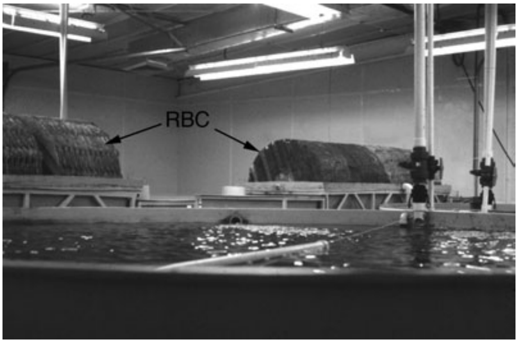

Fig. 2.24. A pair of rotating biocontactors associated with a recirculating system in an indoor red drum hatchery.

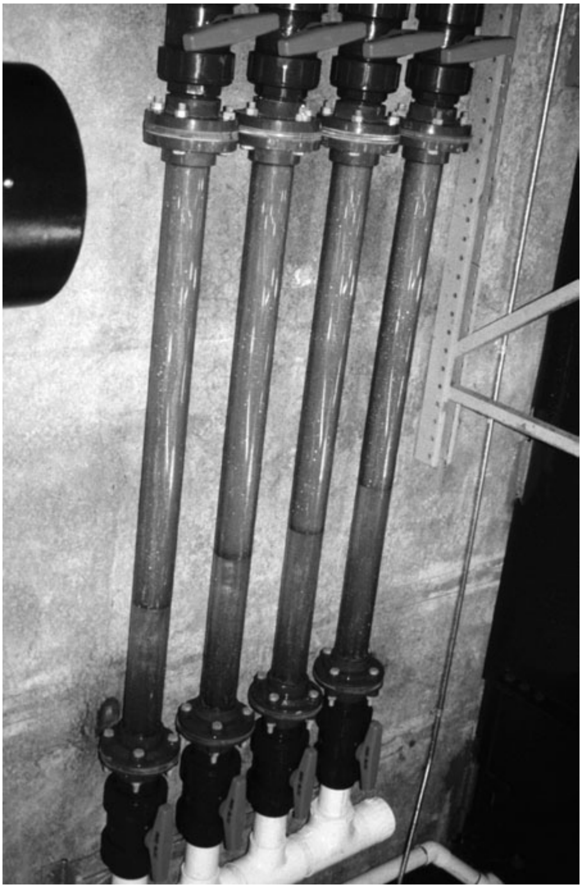

Fig. 2.25. Fluidized bed biofilters at a mollusc culture facility.

when the bead filter is in operation. Water enters at the bottom of the unit at the rate required to suspend the medium. 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 bead filters can function both as biofilters and settling chambers, when used in combination with an RBC or other type of biofilter, the bead filter's primary function may become sediment removal.

Well-designed systems require only one pump and utilize gravity as much as possible 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.

Supplemental aeration is generally provided in closed systems. A variety of aerator devices are available in the market. Included are agitators that mechanically stir up the water surface, air 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 that are often fitted with air stones which break the air into small bubbles. The way in which oxygen is dissolved in water is by diffusion. The greater the volume of air that is 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 become anaerobic, the beneficial bacteria will die and the filter will begin to produce toxins such as hydrogen sulphide as anaerobic bacteria colonize the medium. Obviously, it will be necessary to aerate water discharged from an anaerobic filter used to convert nitrate to nitrogen gas before that water can be exposed to other components of a closed system.

Sterilization with ozone (O_3) or ultraviolet (UV) radiation is sometimes used in conjunction with recirculating water systems (Fig. 2.26). 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 pathogens at low levels and may prevent epizootics.

Ozone generators are used to produce 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 compound. To avoid exposure, ozonation needs to occur in a separate part of the system into which a sidestream of water is flowed. The water is then allowed to stand, with or without aeration, for the

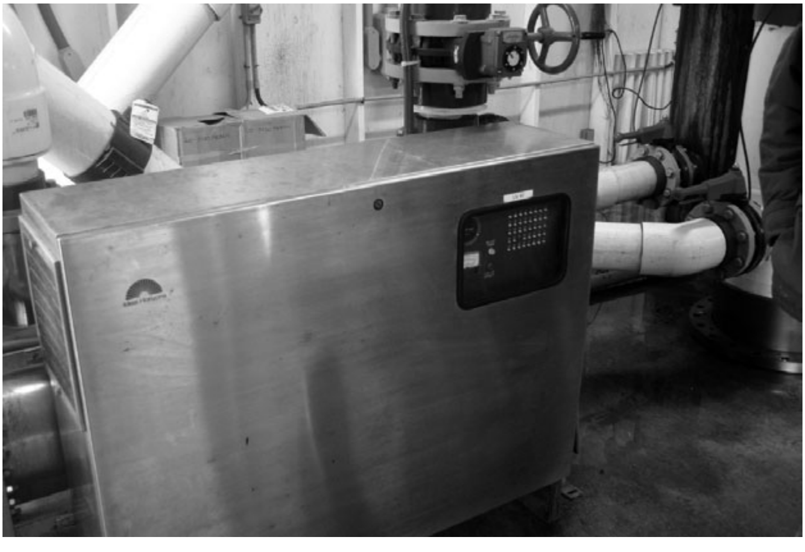

Fig. 2.26. A large ultraviolet light sterilization unit.

time required for the ozone to convert to molecular oxygen (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 outdoors as it is also toxic to humans and other terrestrial animals when breathed in at high concentration. The system should be designed by an engineering firm with considerable experience of working with aquaculture systems to ensure that it will function properly.

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, the most effective of 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 pass by the bulbs inside a clear glass or plastic pipe. Microorganisms exposed to the light are killed.

The drawback with UV sterilization is that the efficiency of the UV bulbs deteriorates with time. Also, particulate matter tends to become deposited 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, 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.

As dissolved proteins accumulate in recirculating systems, they will produce foam. Various types of foam strippers have been developed. Removal of foam reduces the level of dissolved organic material in the water.

Some other auxiliary features of recirculating systems include automatic water quality monitoring and computer control (Fig. 1.1). A variety of water quality parameters can now be monitored through the use of sensors placed in the water. Included are dissolved oxygen, 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 3 for details). 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 that is 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. It can also be archived so the culturist can look at fluctuations that may occur over any given period of time. The computer can be programmed to increase or decrease the rate of aeration depending on dissolved oxygen level, adjust the rate of chemicals being used to do such things as dechlorinate incoming municipal water or adjust pH, turn on or off heaters or chillers to maintain water temperature within set limits, adjust water flow rates and so forth.

Finally, a computerized monitoring system can be equipped with alarms to notify the culturist of problems such as pump failures, temperature changes, reductions in dissolved oxygen and other changes in the system that may require immediate attention. It is not even necessary to have a person monitoring the system all the time as the computer can also telephone the culturist to signal that a problem is occurring. The computer can be set up to operate on emergency power should normal electrical service fail and can activate back-up generators, pumps and other equipment automatically. Such 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, to 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 metal may be present as metal ionizes.

A variation of recirculating water systems involves outdoor ponds. One example was developed by the shrimp farming industry in Texas, in response to criticism over the release of nutrients and suspended solids into receiving surface waters (Treece, 2002). The industry, which had been pumping extremely large volumes of water through their ponds on a flow-through basis, responded by recirculating the water in their facilities rather than releasing it. The approach involved enlarging 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. Another variation on the same theme that has been developed elsewhere involves flowing effluent water through a pond where algae provide treatment. The water can then be returned to the culture ponds.

Cage and net pen systems

Cages and net pens are culture chambers that are designed for use in locations that are not suitable for pond construction or rearing animals in raceway systems. Basically, they are floating or submerged units that are placed in open water, such as within a lake, reservoir, river, estuary, fjord or the open ocean. Cages are sometimes used in large ponds that cannot be drained or are difficult to seine for one reason or another. The standard type of cage will have a rigid frame on all sides (Fig. 2.27), while traditional net pens only have rigid frames at the top (Fig. 1.4). Sea cages of various designs incorporate more framework than a net pen, but may still not have a rigid framework all the way to the bottom of the structure (Fig. 2.28). The part of a cage that holds the culture animals may be made of hardware cloth, plastic-coated wire, plastic mesh or stretched nylon netting. In standard net pens, large nylon netting bags are suspended below the frames. The framework is provided with floatation devices to keep the upper part of the cage or net pen at or above the water surface. Net pens are used almost exclusively in the marine environment, while cages have been used in both salt- and freshwater culture operations. As the mariculture industry begins to move from protected coastal waters to the much

Fig. 2.27. A typical tilapia culture cage in the Philippines.

more hostile open ocean, new designs for both cages and net pens have been, and continue to be, under development. Those cages and net pens must be able to survive storms that would quickly destroy their inshore counterparts. Some cages are designed to be operated below the water surface either throughout the growout period or during bad weather. Others float at the surface or are partially submerged. Open ocean cages and net pens may be equipped with feed bins and automatic feeders so the fish can be fed for several days without having an aquaculturist present. Figure 2.28 shows a partially submerged net pen design that incorporates an automatic feeder.

Fig. 2.28. A marine net pen in Scotland that was designed for offshore rearing of Atlantic salmon. While this net pen is located in a bay, it is exposed to the open ocean and has withstood waves as high as 5-6 m.

Cages of various shapes and sizes have been utilized by aquaculturists. Most have been square, rectangular or cylindrical in shape, but more complex shapes are becoming increasingly common, particularly in the marine environment. Examples are presented in Costa-Pierce and Bridger (2002). Cages used in freshwater are usually small, ranging in volume from less than one to a few cubic metres. Freshwater cages have been used in the culture of catfish, tilapia, carp and various other species.

Marine cages of several hundred to a few thousand cubic metres are becoming increasingly popular. These and smaller cages are being used in conjunction with research or commercial production of such species as Pacific threadfin, red drum, red snapper, sea bass, sea bream, yellowtail, striped bass and hybrid striped bass.

The use of cages in the marine environment is not new. It appears to have begun in China in the 1970s and there are now over one million cages in operation in that country. With the move toward offshore culture, the scale of cage culture is likely to change dramatically. Visionaries in Japan talk of floating offshore cities that will fill part of the food needs for residents through aquaculture of marine organisms in large sea cages. Less ambitious is a planned offshore cage installation in Spain that would produce 25,000 tonnes of fish annually. The facility would be a semi-submersible platform with decks on which broodstock would be maintained, spawning and early rearing would take place, and the crew would be housed. There would also be facilities for feed manufacturing, processing and of course, growout.

For cages that are at the surface, some type of floatation material needs to be provided. This may be in the form of Styrofoam®, some other type of 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, as is commonly seen, they may be tied to a dock which provides access to the culturist.

The topics of feed types and feed manufacturing are discussed in some detail in Chapter 6, but basically, most fish in growout facilities are fed pellets. 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 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 go to the surface to feed. Alternatively to a feeding ring, a layer of small mesh netting can be placed around the upper several centimetres of the cage to keep feed from floating out of the cage before the fish can get to it. Having the ring or mesh 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 submerged cages and in net pens which are much wider and deeper than most cages so the pellets can be consumed before they drift out of the pen. Feeding systems have been developed for floating cages which involve a central feed storage facility 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 6, the aquaculturist should check to ensure that fish are feeding actively, because if they go off their feed it is a sign that the fish have been stressed. Reduced feeding activity is also often a sign of an impending disease outbreak. It is a good idea to observe the fish in each culture unit at least once daily when they are being fed.

Net pen culture began in the state of Maine in 1970 according to the Maine Aquaculture Innovation Centre (www.maineaquaculture.org). By 1992, there were about a dozen commercial salmon net pen facilities in the state of Washington and a similar number in Maine. In the meantime, the industry became dominated by Norway, and it is in that country that modern net pen designs were developed. Net pen salmon culture was also adopted in Scotland, Chile, Japan, New Zealand and other nations. Chile has apparently overtaken and now may surpass Norway in total production of cultured Atlantic salmon. While the vast majority of the salmon cultured around the world are Atlantic salmon, there is at least some net pen production of Pacific salmon species such as coho and chinook in British Columbia, Canada. Pacific salmon are also grown in net pens in Japan. Rainbow trout are being cultured in net pens in North America, Great Britain, Scandinavia and perhaps elsewhere. 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 halibut.

Commercial net pens typically have galvanized metal platforms that provide access to the people involved in tending the fish. Pens of various sizes have been constructed, with most being 10 to 20 m on a side and as much as 20 m deep. The frame may be rectangular or circular. The nets typically extend one or more metres above the waterline to keep fish from escaping. Bird netting is often placed over the top of each net pen to prevent predation by fish-eating birds (Fig. 2.29).

Fig. 2.29. Bird netting provides protection against avian predators and helps keep fish from jumping out of the net pen.

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 penned 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 can be established in each location.

In Japan, it is common practice to catch low-value or trash fish and grind them up as feed for fish in net pens. The low-value fish are ground 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 a dry pellet.

Various forms of mollusc culture

The standard technique for most molluscs involves growing them at the bottom. In many cases the approach is not very different from hunting and gathering. To turn from hunting and gathering to a form of aquaculture, all one has to do is begin to manipulate the environment in some way. Taking oysters as an example, the most simple thing to do is to spread dead oyster shell at the bottom in a location where natural oyster beds are sparse, in order to provide additional substrate for the oyster larvae (spat) to settle on, attach to and grow to harvest size. The shell material that is distributed is called cultch. This approach has a long history; what has been called oyster culture began in Europe during the Roman Empire.

Moving up in terms of manipulation would be introducing predator removal. Starfish and oyster drills can exert significant losses on oyster beds and can be removed by hand by picking them during low tide or using an apparatus like a big mop that is dragged from a boat over the oyster bed where it will entangle predators.

Aquaculture scientists learned to spawn oysters during the last half of the 20th century and in the past few years commercial oyster farmers in some places have begun spawning their own oysters, though many culturists purchase spat from hatcheries (the hatcheries also typically have extensive oyster beds that they use for production of marketable oysters as well as broodstock). Hatchery production provides an opportunity for selective breeding to improve the stocks; for example, to breed for more rapid growth or disease resistance. The producers will also grow their own algae as food for 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. This method is being used in some parts of the Pacific Northwest in the USA. Hatcheries are used in France to produce cultchless oysters (oysters grown unattached to any cultch material). They are often grown in trays off the bottom as described in the next section. Those who purchase their oysters from a hatchery may obtain the spat in baseball- or tennis ball-size packages (containing several million individual spat) or as settled spat on oyster shell that is placed in mesh bags for shipment.[3]

The next step forward in the management of mollusc culture systems involves rearing them off bottom. This can be accomplished in a variety of ways depending on the species being reared and the location (traditional methods have been adopted in some countries that are not used in other nations to any extent). Descriptions of the off-bottom methods used in various nations today for the primary species being cultured can be found in Gosling (2003) and brief descriptions of some of them are provided in the following subsections.

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 are stocked in nature. 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

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 are comprised of horizontal metal pipes attached to the tops of other poles that are 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 where they will grow more rapidly than if thinning were not used.

Hanging rope culture in Europe apparently originally involved cementing 1-year-old oysters individually to ropes suspended in the water column. Long line culture, which involves suspending horizontal ropes between buoys or fixed structures, is also practised in Europe.

China is the world's leading oyster-producing nation according to the FAO (http://www.fao.org/). Nations in addition to China that produce in excess of 100,000 tonnes a year, in descending order, are Japan, Korea and France. Not much has been published on the techniques involved, other than publications in Chinese. Gosling (2003) wrote that her review of the literature indicated that line and raft culture are used in subtidal areas while intertidal culture depends on natural spat production that attaches to various types of substrates. Included were concrete, stone, wood and bamboo. A mollusc culture raft in Japan is shown in Fig. 2.30.

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[3] It has become common practice to refer to the young stages of invertebrates, in particular (though sometimes also with respect to very young finfish), as seed. I have avoided using that term in conjunction with animals as animals do not produce seeds. This is the only place you will see the term in this book.

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 'popped' by bending the cultch material. The individual oysters can then be reared on trays, as mentioned above, and cemented to a rope or pole for growout. The result is nicely shaped oysters that enter the halfshell trade.

Mussels

China leads the world in mussel production according to the FAO, with Spain, and in particular the Galicia rias in the northwestern portion of that nation, being the centre of the industry. 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 uses raft culture. The rafts are wooden structures from 100 to 500 m^2 that are anchored in place and kept afloat with fibreglass or steel floats (Gosling, 2003). 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 cycle. If the ropes were to make contact with the sediments, predators would be able to climb onto the ropes and prey upon the mussels. A single raft may hold as many as 700 ropes, and the Galicia region now supports some 3000 rafts.

Fig. 2.30. A mollusc culture raft in Japan.

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 mm shell length at a distant location and transported to the growout site. The small mussels are wrapped onto 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 on other ropes for further growout. A single raft with 700 ropes suspended from it can produce as much as 60 tonnes of mussels.

In France, Thailand and the Philippines, pole culture is a method used for rearing mussels. In Thailand and the Philippines, bamboo poles of 6–8 m in length are driven into the sediment and used for both spat collection and growout. The ropes may be either attached to the poles or strung between poles in what is called a rope–web configuration. A modification of this approach is used in parts of the Mediterranean Sea where pairs of metal poles are used with a wooden horizontal pole mounted between the poles in each pair. Ropes are then strung between 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 ropes are then taken to the culture area where they are wrapped around poles that have been driven into the sediment. The poles are made of oak and are about 4–7 m long and 12–25 cm in diameter. In the past, ropes were fastened to the vertical poles where growout took place. Today, the horizontal ropes are allowed to remain in place for a few months, after which the mussels are removed and placed in mesh tubes which 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 attach themselves to the wooden poles.

The location of a rope under a raft in relation to other ropes has a bearing on growth. This is also true of hanging culture of molluscan species other than mussels and applies to cage culture 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 that is in 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 due to the establishment of a thermocline.

Scallops

China has assumed the leading role in the world in terms of scallop production, followed by Japan. In Japan, scallop spat are collected 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 size of about 5.5 cm long, they may be hung by the ear of the hinge on a rope for suspension culture, placed in even larger mesh nets (lantern nets) or cultured on the bottom. Shell hinge hanging is the most labour intensive, as a hole needs to be drilled in 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 long lines 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 long lines.

According to a summary by Gosling (2003), in China the early stages of scallop rearing also take place in net bags, but instead of long lines, the bags are suspended from rafts. Lantern nets are used to suspend the larger life stages from long lines 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. This non-indigenous species now represents a significant portion of the scallops produced in China, many of which find their way back home by entering the US seafood markets as imports.

Clams

China also dominates the world in the culture of clams, with some 90% of the cultured clams on the market coming from that country (Gosling, 2003). 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 used to produce young clams. Following a nursery phase, the clams may be placed out in trays until they are 10 mm or so in shell length. The clams can then be put out at 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. In France, two layers of netting are used with the clams between them so that the net forms an envelope. Harvesting is facilitated because when the netting is raised, the clams come up with the netting and they can be washed and easily collected. Most clam farmers use mechanical harvesters pulled behind tractors.

Seaweed culture: the Nori example

Various types of seaweed are produced by aquaculturists around the world. Brown, red and green algae are all grown. Seafood markets in Japan feature a wide array of seaweeds for human consumption (Fig. 2.31).

Nori is extensively cultured in Japan. Ariake Bay in southern Japan, for example, is dedicated to nori rearing. Nori spores are collected on nets in static raceways from adult plants in an indoor facility (Fig. 2.32).

To prepare the bay for receipt of the nets, thousands of long poles are driven into the sediment (Fig. 2.33). 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

Fig. 2.31. Seaweeds on display at a Kyoto, Japan, seafood market.

Fig. 2.32. Raceway in Japan in which nets are placed to collect nori spores.

as the nori grows, the nets are spread out so that eventually there is only one net in each location. Fig. 2.34 is a closer view of some nets with the nori just beginning to grow on them. The nets are washed periodically to remove fouling organisms (Fig. 2.35). When the nori is about 15 cm long, the first cutting is taken. The nets are left in place until a second cutting is obtained. The original nets are then removed and new spore-covered nets that have been placed

Fig. 2.33. Poles in Ariake Bay, Japan, hold the nori nets in position. The nets float up and down the poles with the rise and fall of the tide.

Fig. 2.34. Stacked nori nets in Ariake Bay. The nori is just beginning to grow. Note the ring around the pole. These rings keep the nets in place as they rise and fall with the tide.

in cold storage are used to replace them. Ultimately, four cuttings per year can be obtained.

The challenges of marine systems

Management of any aquaculture system presents a number of challenges, but marine systems are somewhat more difficult to manage in a few respects than

Fig. 2.35. Nori net in Ariake Bay, Japan, being washed to remove fouling organisms.

are their freshwater counterparts. Three topics are of particular interest in this regard. They are the availability of fresh water, fouling and corrosion.

A source of fresh water is important in conjunction with saltwater facilities, particularly those that are static in nature (most ponds) or which draw upon hypersaline sources of incoming water. There are also instances where low-salinity culture of a euryhaline species[4] may accelerate growth or provide some protection against less salt-tolerant predators or disease organisms. Perhaps the most common role for fresh water is to provide dilution when the salinity becomes too high in a static pond. As we have seen, one source of water loss from ponds is through evaporation. When water evaporates, it leaves salt behind, thereby causing an increase in salinity. Adding seawater of the same salinity as that which was used to fill the pond will reduce the salinity to some extent, but the overall result will be increased salinity compared with when the pond was first filled. For example, if a pond contains 1000 m^3 of 35 ppt[5] water when filled and 100 m^3 evaporates, the same amount of salt that was initially present will be contained in 900 m^3 of water, so its salinity will go up. Diluting with more 35 ppt water will reduce the salinity to some extent, but the overall amount of salt will still be higher than what was present in the first 1000 m^3 of water. As the process is repeated a number of times, the salinity may eventually become high enough to affect the performance or even the survival of the culture species. To deal with the problem, replacement water of

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[4] Euryhaline species are those that can tolerate a wide range of salinities. Species that require a narrow range of salinity are called stenohaline.

[5] ppt = parts per thousand which equals 0.1%, so 35 ppt equals 3.5% salt content.

low salinity – preferably fresh water – needs to be available. Also, it needs to be available in sufficient quantity to deal with the problem.

Fouling can be a problem in freshwater systems. For example, I have operated raceway systems that had a surface water source that seasonally 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 hydrogen sulphide gas. This problem only occurred during the summer, whereas in the marine environment fouling can be, and often is, a year round problem. Also, there are many more types of fouling organisms in the marine environment than are encountered in fresh water. Sponges, bryozoans, tunicates, sea anemones, mussels, oysters and barnacles are among the fouling organisms that are commonly seen. They have been known to completely or nearly completely block the flow of water through cages 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 cages, net pens and pipes as well as the culture chambers is required in many instances.

With respect to small cages, the culture animals can be moved to another cage and the fouled cage can be removed from the water to allow the fouling organisms to die, after which they can be scrubbed from the cage with a stiff bristle brush. For larger cages, it may be necessary to have divers scrub the cage mesh while the cage is in the water. Cleaner fish such as wrasses have also been employed to help keep down fouling organisms. Net pen operators may maintain a second set of nets that can be placed over the sets that are first in use when those nets become fouled. The fouled nets can be removed without letting fish escape. The nets can then be dried, cleaned and then used again when the replacement nets become fouled. Antifouling chemicals have been used to coat nets, but may also be toxic to the culture animals or may be deposited in the meat of the culture animals and enter the human food chain. Therefore, such chemicals are not recommended.

Many shoreside mariculture facilities are constructed with paired inflow pipelines. One of the pair is used to bring water into the facility while the other is filled with fresh water to kill fouling organisms. When the pipeline in use becomes fouled, it is filled with fresh water and the second pipeline is used. 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 fouling problem becomes so severe that water quality or flow rate are significantly altered. Filtering incoming water as close to the source as possible will also reduce the fouling rate.

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 with a diameter slightly smaller than that of the interior of the pipe through the pipe to clean off the fouling organisms. Such objects are known as pigs. A photo of some pigs is presented in Fig. 2.36.

We have already seen that metal culture chambers should not be used in saltwater systems since they are subject to corrosion, although we have also seen that galvanized metal is widely employed in the framework of net pen systems. 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 salt water. The water does not have to come directly in contact with the metal as aerosols containing corrosive salts will be in the air. Metal that does come in contact with salt water should be rinsed in fresh water, dried and, if possible, stored away from possible interaction with aerosols. Buildings, metal plumbing, 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; and 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 in a storage building in conjunction with a pond facility. Light fixtures can be fitted with waterproof plastic covers.

Culturists should make sure that any pumps that are used in either fresh water or salt water do not contain any metal that comes in contact with the water that passes through them. Metal pump housings are appropriate for use in freshwater facilities and are used to pump salt water if they are kept outdoors. If the impeller in any pump has metal in it, that metal gets into the water at levels that can be toxic. This is particularly true in static systems such as are often seen in hatcheries. Submersible pumps should have no exposed metal that can come in contact with the water.

Fig. 2.36. The torpedo-shaped objects are called pigs, and are forced through water lines to scour out fouling organisms at the Monterey Bay Aquarium in Monterey, California, USA.

Other Issues

Before leaving the general topic of water systems and turning towards 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 drained from the system. In many cases, when that happens it will be necessary to dispose of that water in an environmentally sound manner. Regulations on water disposal vary greatly from nation to nation and even within nations. They also vary greatly with respect to water system type. For example, an open ocean cage system may be exposed to currents which 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 be carefully monitored and highly regulated, particularly if the effluent enters public waters such as the ocean, a stream or a lake.

In some cases, treatment of effluent water may be required. This can take the form of constructing and utilizing settling ponds, filtering the water mechanically, releasing it into a sanitary sewage system for treatment or some other requirement for disposal. If the water is used for irrigation as an alternative for flowing it into surface water, the nutrients will help fertilize the land and the regulations may be eased. Typically, aquaculture permits require no more than primary treatment (filtering the water or flowing it into settling ponds), though some authorities require secondary treatment (biological filtration such as passing the water through a sewage treatment plant that has a trickling filter, lagoon system or 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 at least one situation with which I am familiar – a constructed wetland receiving shrimp farm effluent – attracted so many birds that the actual level of nutrients present due to bird droppings may well have exceeded the nutrients entering the system from the shrimp ponds. In rare situations, tertiary treatment may be required. This involves nutrient removal and can be a very expensive proposition, and one that could preclude the culturist from profitability.

Faeces and waste feed from salmon net pens can build up on the bottom under those facilities and create anoxic zones that may extend beyond the footprint of the actual farm. Proper siting with sufficient current flows to disperse the solids is important if the problem is to be avoided (see Brooks *et al.*, 2002). Shrimp farms in south Texas were pumping millions of gallons of water a day and releasing high levels of suspended solids and nutrients. During the early 1990s, the use of new water was greatly reduced and recirculation was implemented.

Those changes led to virtual elimination of the problem (Treece, 2002), though increased production and industry expansion have continued to occur. The Texas shrimp farming industry in 2003, the highest year on record, was valued at approximately US$18 million (G.D. Treece, personal communication, 2005).

Pests and predators

If an unwanted organism is in your neighbourhood, it is a safe bet that it will find its way into your culture system. There is such a thing as biosecurity, which means that you have taken every precaution to make sure that the cultured species will not escape. Such systems are required in some places when exotic species are being reared or when genetically modified organisms 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 and highly filtered air, some types of organisms will find their way into the facility. Some of those are merely pests, but others can lead to significant losses through disease and predation.

The use of surface waters for aquaculture provides excellent opportunities for unwanted species to enter a facility. Spring and well water is typically sterile as it leaves the ground and unless it is stored in a reservoir before entering the aquaculture facility is usually not a significant source of undesirable waterborne species. 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, sterilization of the water is often neither practical, nor will it be effective, as airborne pathogens can quickly become established. 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 4.

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. Since 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-meshed screen or through netting. Screens and netting should be cleaned frequently because they tend to quickly become clogged to the extent that water flow is impeded.

Net pens and cages will frequently contain a number of species in addition to those that were initially stocked. Small fish and invertebrates can enter the cage or net pen through the mesh, 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 also become a predator on the culture species. Marine mammals have been known to rend pen nets, after which they may prey directly on the culture species in addition to providing an avenue through which the fish can escape. Marine mammalian predators are protected by law from being killed, harmed or even harassed in the USA and other nations. Stiff fines and jail sentences can be imposed for violations. Predator nets, as previously mentioned, are typically used in areas where marine mammals pose a threat.

Turtles and water snakes are common in freshwater culture ponds. Most turtles are harmless to people, though snapping turtles pose a danger. Many snakes that one finds in and around culture ponds are non-poisonous, though venomous snakes are common in some areas. A pond facility in the Philippines with which I was involved was constructed in an area that once held rice fields. During the time that the topsoil and vegetation were removed prior to pond construction, the bulldozer operators reported killing at least a couple of pythons and a large number of Philippine cobras. 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 the culture species, so it is a good idea to control their numbers.

Aquatic insects such as dragonfly larvae can also take a toll on aquacultured organisms, particularly larval and early juvenile fish. 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, natural inhabitants of coastal waters in many regions, have caused significant problems for Manila clam and Pacific oyster farmers in the states of Washington and Oregon. These soft-bodied shrimp, which have no commercial value, are found in very large numbers on the intertidal mudflats used for culturing molluscs. They destabilize the sediments leading to shellfish mortality because the molluscs sink into the mud and suffocate. The pesticide carbaryl (Sevin) has been an effective control chemical to which the shrimp are highly sensitive, but it has been shown to harm other desirable native species such as commercially valuable Dungeness crabs. Movements to ban carbaryl are under way so other control methods are being sought.

Raccoons, otters and various other four-footed mammals often prey upon aquaculture species. Wading birds can do significant damage in ponds and shallow tanks and raceways. Great blue herons have been a source of predation in catfish ponds in southern USA. There have been reports that a great blue heron takes a daily average of 12 10-cm long catfish fingerlings. Double-crested cormorants 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 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 been increasing in the state of Arkansas, where catfish production levelled off several years ago.

Pelicans were said to have invaded the trout farming area of northwestern USA one year and consumed a significant portion of the crop. Other birds considered to be a problem on fish and crayfish farms in the USA are ibises, gulls, terns and grebes. Some of these types of birds and others pose problems to aquaculturists throughout much of the world.

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.

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

In addition to being predators, birds have also been shown to 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. Stringing wires over culture chambers, such as raceways and relatively small ponds, has worked well in some cases, 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.

Human predators or poachers can also pose a significant problem. Some farmers hire watchmen to guard against poachers, but there is always the possibility that the watchmen also become involved in poaching. Hiring watchmen adds to the expenses of operating an aquaculture facility. High fences and perimeter lighting can be used to dissuade poachers, but those are also expensive alternatives and would still require the presence of humans or dogs as a further deterrent. Many net pen and cage culture sites are not manned 24 h a day and are subject to poaching and vandalism. The poacher may capture what he or she desires, then cut the net and release the remaining fish for good measure. Poachers are generally not considered to be ruthless criminals, except by the aquaculturist whose stock is being poached, and the threat of relatively insignificant punishment by the courts in many nations does not offer much by way of deterrence.

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3

Understanding and Maintaining Water Quality

The Range of Variables

Aquaculture 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 good water quality with respect to one species may be 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 species. Of course, one way to gain insight into the question is to look at where, in nature, each species seems to perform best. Those locations may actually change depending on the life cycle stage the organism is in, so this needs to be taken into consideration as well.

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) are the primary contributors to making the ocean salty. These elements can also found in fresh water, but at low concentrations. But salt water contains a wide variety of other elements and ions, many of which are required for good health and performance of both plants and animals. Minerals in sea water 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.

Water also contains a wide variety of chemicals that are not required by the species inhabiting the water and which, in many cases, are toxic when present at sufficiently high concentrations. High levels of even required elements, such as copper (an element that is required by many invertebrates), will produce 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, though most people think that all the oil found in the sea is due to spills or blowouts associated with drilling operations. Petroleum is also the source of a myriad of organic chemicals from plastics to pesticides, all of which can be found in water. These compounds can be picked up and concentrated in the tissues of aquatic organisms, leading to direct toxicity, or they may be passed up the food chain to humans who ingest contaminated organisms. Consumers are cautioned to avoid eating fish from some water bodies (e.g. salmon caught in the Great Lakes of North America) because of high levels of polychlorinated biphenyls (PCBs) in the meat of the fish.

Having a source of high-quality water is, as has previously been indicated, the top priority for the aquaculturist. Not only does the culturist need water of high quality for the organisms being reared, but also in order to produce the quality of product that consumers expect and demand.

How does one determine if the water is of acceptable quality for aquaculture? There are basically three ways. The most thorough 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. While it is unreasonable to test for every possible chemical individually, there are tests that can be run to screen for arrays of organic compounds that will at least provide an indication as to whether harmful levels are present. Some tests are simple and inexpensive, while others require sophisticated equipment and can cost a considerable amount of money. In some cases it may be possible to obtain the results of chemical analyses from others who have tested the water you intend to use. Water districts, municipalities, well drillers and natural resources agencies may be able to provide such data. The second way to determine if the water is suitable would be to collect a sample and put a few members of the species you intend to rear in it for a period of several days, with aeration, of course. While such a test will not reveal the presence of toxic compounds that are present in such low concentrations that they would not elicit even a behavioural response, it would reveal if there is something present that would be acutely toxic; that is, something that would kill at least some of the animals within a period of 96 h or less. 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 determine if they have had any unusual problems that might be related to the presence of contaminants in water.

If the water is found to reliably support the life of the aquatic species of interest, there are a relatively small number of important water quality parameters of primary concern to the aquaculturist. Of those, some may require frequent monitoring, while others may need to be determined only infrequently to demonstrate that 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.

Variables to Measure Frequently

There are nine variables (including three discussed below under the subheading of plant nutrients) that should be routinely measured in all or many water systems, though the frequency with which those measurements should be taken will vary. At the beginning of each subsection an indication of which types of water systems require monitoring for the variable to be discussed is provided.

Temperature

Temperature should be monitored in all water systems in which the variable is subject to change. Routine monitoring may not 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 on a daily basis in those systems.

The metabolic rate of poikilothermic (cold-blooded) aquatic animals and that of aquatic plants is controlled by 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 fairly broad range of temperature and survive, but performance is negatively affected at temperatures outside the optimum range.

Many warmwater species, such as channel catfish, can survive in fresh water that approaches freezing and will live at temperatures a few degrees above 30°C. Trout and salmon can also survive very cold water, but perform poorly when the water temperature approaches about 20°C. Tilapia and other tropical species do not survive in cold water. Their performance is impaired when the water temperature is below about 20°C and, in the case of tilapia, death generally occurs around 10–12°C, though there is some variation among species.

Since there is a strong tie 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. 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 those communities will change seasonally and productivity may actually be quite high during periods when the temperature is out of the range for optimal growth by the cultured 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 temperature. As we will see, the culturist can control plankton blooms to a large extent through fertilization of the water. Higher aquatic plants (macrophytes) tend to grow more 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. Grass carp are among the few animals produced in aquaculture that directly consume aquatic macrophytes and even that species is somewhat selective in what it will eat.

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 a number of years and are very precise; in fact, much more precise than is needed for routine measurements. The aquaculturists would typically like to know the water temperature to the nearest degree, while some instruments measure accurately to the nearest 0.1°C or less. Electronic thermometers are recommended since glass thermometers are easily broken.

The aquaculturist may wish to adjust the feeding rate as the temperature falls or climbs out of the optimum range. Temperatures outside of the optimum range, whether above or below, can act as stressors. When stressed, fish will not feed as actively as in a non-stressed situation, so some of the feed will be wasted if the culturist continues to feed at the same rate when the temperature is above or below the optimum range as when the water temperature is within the optimum range. Waste feed will decay and place additional demand on the dissolved oxygen level, which is the next variable to be discussed.

Temperature is often measured daily by aquaculturists. As with other water quality variables, it should be recorded for future reference. When a thermistor (temperature probe) coupled to a recording thermometer or computer is used, a graph of the diurnal (daily) fluctuation in temperature can be obtained. Using computer technology, the culturist can easily plot long-term temperature fluctuation patterns as well.

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 (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 to 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 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 heating up during the harvest process is effective at eliminating the need for tempering during harvesting. The rate of tempering should be no more than about 5°C/h. Observation over the years has led me to the conclusion that fish are less stressed when being moved from a temperature higher or lower than their optimum temperature for growth toward the optimum range than when being moved from the optimum range to water that is warmer or colder than optimum. It stands to reason that fish outside the optimum range are already experiencing stress and that the stress level is reduced as they are tempered in the direction of the optimum range.

Fish may also experience rapid changes in temperature 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 of the world.

Dissolved oxygen

Dissolved oxygen (often abbreviated DO) needs to be maintained at or near saturation in all culture systems in which aquatic animals are being reared in order to avoid the imposition of stress. The culturist should strive to maintain a DO level of no less than 5 mg/l at all times.

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 be only about 30 mg/l, which is still extremely small compared with 200,000 mg/l in the atmosphere.

The oxygen story

The amount of oxygen that can be dissolved in water at saturation depends on three primary factors: temperature, salinity and altitude. As each of those factors increase, 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 fresh water at sea level or below would hold the most. 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 typically perform well at levels somewhat below saturation.

In general, aquatic animals with gills will survive and grow without apparent stress so long as the DO level is maintained at 5 mg/l or higher. This level can usually be found even in warm sea water. Hypersaline warm waters may not have DO levels as high a 5 mg/l, however. At the other extreme, some high mountain lakes may have oxygen levels too low to support many aquatic organisms.

Oxygen can be measured in various ways. The first method that was developed involved wet chemistry with production of a straw-coloured yellow pigment in water samples to which a certain reagent was added. A titration procedure was used to determine how many mg/l of oxygen were in the water sample. This method took a few minutes per test and involved fragile glassware. Dissolved oxygen meters are now readily available and can be obtained fairly inexpensively. Most are temperature compensated and both temperature- and salinity-compensated models are available. A typical DO meter is shown in Fig. 3.1. DO meters not only have the advantage of making rapid measurements, but many can be combined with recording devices or linked with computers, so long-term continuous measurements can be obtained.

While saturated DO is desirable and 5 mg/l is acceptable, most aquaculturists begin to worry when the DO level falls to 3 mg/l. For salmonid culturists, that level may actually be the cause for considerable concern. Warmwater

Fig. 3.1. An example of a dissolved oxygen meter.

fish tend to tolerate lower DO levels, so 3 mg/l appears to be a point where culturists begin to take remedial action. Scientists who are studying hypoxic[1] areas that occur naturally in various places around the world have decided that hypoxia exists when the DO level is < 2.0 mg/l. Therefore, taking steps to increase the DO level in an aquaculture system makes sense when the 3.0 mg/l threshold is reached, for the animals can be considered to have been stressed at that point.

There are species of aquatic animals 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

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[1] Hypoxia is a condition in which the oxygen level is so low that mortalities will occur.

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 the interface is always saturated, so when the fish go to the 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 being highly stressed. That is not necessarily the case for tilapia, however, as they seem to have the ability to effectively obtain oxygen from the surface microlayer. I have seen tilapia survive for at least a few hours when the DO concentration is at 1 mg/l or even lower. Few other species have the same ability to work the microlayer and will not survive for more than a few minutes when the DO level becomes critically low.

Oxygen in ponds

Let us now look at the dynamics of DO in a pond, because large changes in DO over the course of a 24-h period are most commonly seen by pond aquaculturists. As previously indicated, the way atmospheric oxygen gets into water is 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 air) across the membrane into 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 a wind that blows across the water so that the water is circulated. The wind stirs up waves and creates currents that increase both the amount of water surface that is in contact with the air at any instant and also mixes 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 carbon dioxide and water into sugar and release oxygen:

$$CO_2 + H_2O \xrightarrow[\text{chlorophyll}]{\text{light}} CH_2O + O_2 \qquad (3.1)$$

The reaction continues throughout the daylight hours, but obviously not at night unless artificial light of the appropriate wavelength is provided.

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 the day until 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 will penetrate deeper the more directly it shines on the water.

All aerobic (oxygen-dependent) species of plants, animals and microorganisms consume oxygen through respiration. This process is continuous both day and night. However, if there is a good phytoplankton community established in the pond, daytime photosynthetic production of oxygen will put oxygen into the water more rapidly than oxygen is removed through respiration. At night, on the other hand, all the aerobic communities will continue to respire in the absence of photosynthesis, resulting in a decline in DO level.

The temporal changes in DO that might be seen in a typical pond are shown graphically in Fig. 3.2. 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 instances when DO falls to critically low levels. This 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. The cloud cover will reduce, but not eliminate photosynthesis, and while DO will rise during the day, it will not rise as much from one day to the next if the cloud cover persists. An indication of that is shown in Fig. 3.2 where the second day dusk DO level is slightly lower than that on the first day. After several days of such a pattern, the early morning DO level may fall to ≤3.0 mg/l and the animals may become stressed. 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 respiratory demand as the phytoplankton decay.

These problems occur most commonly during the summer and early autumn when primary and secondary productivity are highest. The culturist should, at least during that portion of the year, monitor DO daily during the pre-dawn hours at a minimum. Having a continuous monitoring system in place is a well-justified expense, as such systems can sound an alarm by telephoning the culturist when a problem is detected. Otherwise, someone needs to be present during the early morning hours to make routine measurements in the ponds. On a large facility, two or more personnel may be required to go around and take measurements on something like an hourly basis in each pond.

When a problem is detected, action needs to be taken to add oxygen to the water. This can be accomplished in a number of ways, including adding new well-oxygenated water to the pond, pumping water from the pond into the air 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, with paddlewheel aerators such as those shown in Figs 3.3 and 3.4 being very popular throughout the world. The ones shown are per-

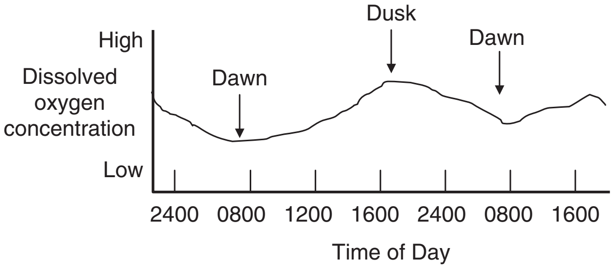

Fig. 3.2. Schematic representation of the type of fluctuations in dissolved oxygen that occur in a typical culture pond.

Fig. 3.3. A paddlewheel aerator in action.

manently installed in the ponds. In many cases, paddlewheels are used that run off the power take-off of a tractor. 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

Fig. 3.4. A row of ponds, each with its own paddlewheel aerator.

create a current that continuously brings new oxygen-depleted water to the surface where it is enriched. A variety of other aerator types are available, including the fountain variety (Fig. 3.5) which throws water into the air. Those aerators do not create a current across the entire pond, however, so the effect is localized, with basically the same water being cycled through the aerator repeatedly.

Fortunately for the aquaculturist, it is rare for more than a few ponds to experience an oxygen depletion on the same day. Thus, it is not necessary to have a paddlewheel in every pond. Those that are operated from tractors can quickly and easily be moved from one place to another.

In their attempts to get as much production from every pond as possible, a significant percentage of shrimp and fish farmers now have one or more dedicated paddlewheel aerators in each of their ponds. In some cases, the respiratory demand becomes so high that paddlewheels are operated 24 h a day, though that is quite expensive in terms of energy use. When in constant or part-time daily use, paddlewheel aerators are run by electric motors or by either petrol or diesel engines. It is not practical to have a tractor for every pond, though I am aware of one shrimp farmer who appears to have 25 or 30 tractors available to power paddlewheels. If the biomass in the pond leads to only night-time 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 a set minimum in DO would alert the system and activate the aerators. With the technology available today it is physically possible and economically feasible

Fig. 3.5. A fountain-style aerator.

to have an oxygen probe in every pond and have them all connected to a computerized control system.

Oxygen in systems other than ponds

In many raceway systems, such as those used for rearing trout, the incoming water may be well oxygenated and the flow is often sufficient such that there is plenty of oxygen in the water throughout the raceway and throughout the day and night to sustain the fish. In warmwater raceways with relatively slow flow rates and in recirculating water systems, aeration is usually required (walking catfish may be an exception as they can utilize atmospheric oxygen). Agitators, blowers, air compressors, bottled air or oxygen and liquid oxygen tanks are among the types of apparatus that are commonly used by aquaculturists.

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

pH

The extent to which water is acidic or alkaline is called the pH of the water. Routine monitoring – at least weekly – of pH is a good idea when recirculating systems are used. The same is true for water of low alkalinity and/or hardness (topics discussed later in this chapter).

The parameter known as pH is defined as the negative log of the hydrogen ion concentration. The pH scale runs from 0 to 14 with a value of 7 being neutral. Values below 7 are acidic, while those above are basic. The range of pH in most freshwater systems 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, for example an increase from pH = 6 to pH = 7, the water becomes 10 times less acidic (or 10 times more basic, depending upon how you want to look at it).

In recirculating water systems the accumulation of organic acids from such substances as tannins in the feed, along with the accumulation of carbon dioxide due to respiration, will lead to a reduction in pH. For freshwater 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, 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 place crushed limestone or oyster shell in the system. Both are comprised of calcium carbonate, which will slowly dissolve into its respective ions:

$$CaCO_3 \rightarrow Ca^{+2} + CO_3^{-2} \qquad (3.2)$$

The anion (carbonate, CO_3^-) will then combine with free hydrogen ions (H^+) to produce bicarbonate (HCO_3^-):

$$H^+ + CO_3^- \rightarrow HCO_3^- \qquad (3.3)$$

Removal of the free hydrogen ion will result in an increase in pH. Adjustment of pH can also be achieved by adding sodium bicarbonate:

$$NaHCO_3 \rightarrow Na^+ + HCO_3^- \qquad (3.4)$$

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 (described later in this chapter) can cause the pH to rise or fall dramatically. 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 or a pH probe connected to a pH meter (Fig. 3.6). Such meters can be purchased relatively inexpensively and should be a standard item in the water quality laboratory of an aquaculture facility.

Ammonia

Hochachka (1969) indicated that most of the nitrogenous waste fish produce is in the form of ammonium ion (NH_4^+), which is excreted through the gills. The source of the ammonium is the amino acids in proteins that are being used for energy rather than growth, so the ammonium is a by-product of metabolism. Ammonia in one form or another is also produced by invertebrates.

Ionized ammonia in the form of ammonium is relatively harmless, but if transformed to un-ionized ammonia (NH_3), very low levels can be toxic. At a minimum, elevated levels of un-ionized ammonia can lead to poor growth and gill deformities. Adding the two types of ammonia together provides a measurement of total ammonia nitrogen. This can be determined in various ways, with a common method in use today being ammonia probes. Colorimetric tests for ammonia have been around for many years. Salt water interferes with the colorimetric tests, but the problem is eliminated if the samples are distilled prior to being measured. Both probes and colorimetry measure total ammonia, but tables are available from which the fraction of un-ionized ammonia or NH_3-N can be determined (see Boyd, 1990; Lawson, 1995). In order to use the tables one needs to know at least the temperature and pH. Salinity also

Fig. 3.6. A pH meter.

plays a role, so this becomes an additional factor in saltwater systems. Other components of water quality that can affect the form of ammonia are dissolved oxygen, carbon dioxide, hardness and bicarbonate alkalinity, though their impact is less and typically ignored. The percentage of un-ionized ammonia increases with increasing temperature and pH and decreases as salinity, carbon dioxide or hardness increase.

Data on ammonia tolerance vary considerably with respect to the species evaluated and the history of ammonia exposure experienced by that species. Redner and Stickney (1979) found that the level of ammonia that will cause death in blue tilapia is higher in fish previously exposed, and apparently adapted, to sublethal levels of ammonia than in those that have not been exposed to elevated ammonia levels. This species will, thus, develop increased tolerance to ammonia based on prior exposure. Similar results have been shown in other species, including some invertebrates. Because temperature, pH and various 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 when other conditions prevail. 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 about 1.0 mg/l, while the level of total ammonia to which warmwater fish are exposed should not exceed about 2.5 mg/l.

Nitrite

Nitrite can reach toxic levels in recirculating systems, if the bacteria required to transform nitrite to nitrate are not present or are present in insufficient numbers. Nitrite can also occur in warmwater ponds and raceways that contain high fish biomasses.

Nitrite is rare in natural waters because it is an intermediate that is quickly transformed by bacteria to nitrate, but sometimes occurs in high concentrations in aquaculture systems. The problem has occurred in flowing water systems and in ponds, when very high densities of animals are being maintained. Catfish farmers in Mississippi, for example, have experienced nitrite toxicity during the late summer or early autumn, when fish biomass is at the highest level of the year, the water is warm and the feeding rate is extremely high.

Nitrite is measured through a colorimetric test. The proper reagents along with a spectrophotometer or colorimeter are required (for details see Boyd, 1979).

Tolerance to nitrite varies considerably by species and even the genetic strain of the animal, as well as by the life stage of the species being evaluated. Furthermore, 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 that carries oxygen throughout the body of the fish. Methaemoglobin, on the other hand, will not combine with oxygen, so the fish will be asphyxiated when it loses its haemoglobin. If nitrite toxicity is suspected, a fish should be sacrificed or bled and its blood should be examined. A chocolate brown colour of the blood is a sign that the haemoglobin has been converted to methaemoglobin. Channel catfish that succumb to nitrite toxicity die with their mouths open and their opercles closed. Nitrite toxicity was a significant problem in the USA channel catfish industry for several years, until research showed that increasing the chloride ion concentration in the water mitigated against the transfer of nitrite across the gill membrane of that species. Adding 25 mg/l of table salt (NaCl) for each milligram of nitrite that is 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 process of conversion of haemoglobin to methaemoglobin. Research has indicated that in addition to chloride, nitrite toxicity is affected by pH, sulphate, nitrate, phosphate and calcium.

Plant nutrients

Phosphorus is the first limiting nutrient for plants in freshwater systems, while nitrogen is the first limiting nutrient for plants in marine systems. Adding plant nutrients is important for establishing and maintaining phytoplankton blooms in ponds. Silicon is a nutrient required by diatoms.

There are three nutrients which are of potential interest to the aquaculturist who is interested in establishing and maintaining a plankton bloom. These are nitrogen, phosphorus and silicon. The latter is only important if the desire is to promote the growth of diatoms. Diatoms are benthic algae that have a hard test – much like the exoskeleton of many invertebrates – the structure of which is based on silicon. The nutrients phosphorus and nitrogen promote algal growth, which in turn promotes the growth of zooplankton. Either or both types of plankton are often the first foods of aquaculture animals. It is common practice to establish a bloom in a pond prior to stocking early life stages: e.g. the larvae or postlarvae of fish or invertebrates. Later stages, such as fry fish, will also benefit from having plankton available upon which they can feed. For example, species such as tilapia and channel catfish, which will accept prepared feeds when they begin to feed, will also forage on plankton. Since the plankton are distributed more evenly over the pond than prepared feed that might be thrown into the water, the young animals will be able to find food of one kind or the other.

It is not common practice to measure the levels of any of the three nutrients in the water, though that is certainly possible. Rather, 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 disk. A Secchi disk is a circular piece of metal on which alternating black and white pie-shaped sections are painted (Fig. 3.7). A string or light rope is tied to the middle of the disk, which is lowered into the water. At the point that the disk disappears from view, the length of string from the water surface to the top of the Secchi disk is measured. This is called the Secchi disk depth. A healthy plankton bloom in water with low clay turbidity should have a Secchi disk depth of approximately 30 cm. An alternative to the Secchi disk is for the culturist to put an arm in the water with the hand held parallel to the surface. In this case, the hand should disappear from view at about the depth of the elbow, which is approximately 30 cm in most adults. The bloom should be established and maintained through fertilization. Organic fertilizers can be used to induce either phytoplankton or zooplankton blooms, while inorganic fertilizers are used to induce phytoplankton blooms.

Organic fertilization

Organic fertilizers can be in the form of either animal wastes or plant material. Freshwater culturists have used such plants as hay, lucerne, rice bran and

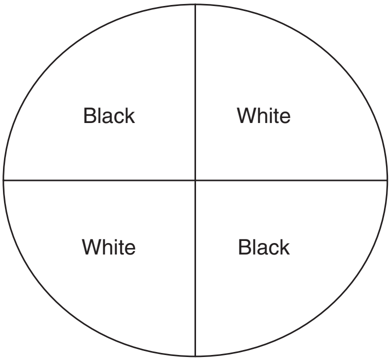

Fig. 3.7. Colour pattern for Secchi disk.

cottonseed meal as organic fertilizers. Cottonseed meal has also been used in saltwater ponds. Such fertilizers will often promote zooplankton blooms upon which larval and postlarval aquaculture animals can feed. The question then arises, if a zooplankton bloom is induced in the absence of a phytoplankton bloom, are not DO problems more likely to occur? The answer is that DO problems are not necessarily a result because zooplankton bloom induction is associated with feeding the early life stages of the aquaculture animals which, while they may be present in high numbers, do not amount to high biomass. Thus, there is not the respiratory oxygen demand on the system that exists in a growout pond where biomass is in orders of magnitude higher than in a larval and postlarval nursery pond. Typically, the 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.

When animal wastes are used as fertilizer, the intent is to produce a phytoplankton bloom. Ducks, geese, chicken, swine and cattle have all been used as sources of organic fertilizer. The terrestrial animals may be reared over or adjacent to culture ponds so their wastes are constantly added to the water, although care must be taken to avoid overdoing a good thing. Excessive waste levels will lead to anoxic conditions. The condition is caused by an increase in oxygen demand by the decaying manure. The approach will work if the number of animals providing the wastes is appropriate. It also helps if the culture species is tolerant of low oxygen levels (e.g. tilapia).[2]

A better approach may be to add known amounts of manure periodically. Research has indicated that 4000 laying hens/ha will promote good tilapia growth in the absence of prepared feed. If dry poultry manure is used, between 70 and 140 kg/ha/day will yield good results with tilapia. When the alkalinity of the water is high, the lower end of the range for dry poultry manure has

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[2] In the case of tilapia culture, production of the phytoplankton bloom is not primarily to provide oxygen to the system but for use as food by the fish.

been 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 salt water.

Inorganic fertilization

There are a number of inorganic fertilizers on the market today. Liquid and granular forms are available. Liquid fertilizer disperses immediately when applied to water, while granules release their nutrients as they dissolve. Some dissolve quickly and rapidly release their nutrients, while others are resistant to dissolution in water and release their nutrients more slowly. Both granular formulations have been developed for use on lawns or agricultural fields, so even the water-resistant form dissolves quite rapidly in water since it was designed to dissolve over a period of time when exposed to intermittent rainfall or to irrigation water, which may be applied on a schedule but also intermittently. Each formulation of inorganic fertilizer has a composition that is revealed through a numbering system that employs three numbers. Those numbers, always in the same order, refer to the percentage 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, blooms can be promoted with a fertilizer with the composition16-20-0.

If 16-20-4 or 16-20-0 are not available, some other formulation with the same relative ratios of 4 parts nitrogen to 5 parts phosphorus and either 1 part or 0 parts 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 days to two weeks 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 (Fig. 3.8) or in the form of filamentous algae (Figs 3.9 and 3.10). If, after becoming established, the bloom begins to decline (Secchi disk reading gets larger than 30 cm), additional applications of fertilizer may be required. When the culture animals get too large to consume plankton and have been converted to prepared feed, fertilization can be discontinued, though maintaining a phytoplankton bloom is still desirable. The reasons are that phytoplankton shade out unwanted plants and also provide a source of dissolved oxygen as previously discussed.

In the event that unwanted plants are stimulated at the expense of phytoplankton, fertilization should cease and it may be necessary to herbicide the pond, which will release the nutrients in the undesirable plants as they decay, and once the herbicide has become detoxified, the released nutrients may stimulate a phytoplankton bloom.

In some instances, plant communities other than phytoplankton are actually desirable. For example, various rooted aquatic plants are the primary source of nutrition for grass carp, and the culturist who is rearing that species will want to promote growth of plant species that are readily consumed by

Fig. 3.8. Pond with duckweed (a small floating macrophyte) on most of the surface. The arrow points out a small area of open water.

Fig. 3.9. Clumps of algae that probably formed on the pond bottom and broke loose to float to the surface.

grass carp. Another example is milkfish. In some places in Asia, ponds are filled to a depth of a few centimetres and fertilized. This will often result in the development of algal mats on the pond bottom. The ponds are then filled to the normal depth and stocked with milkfish, which 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 term is *Aufwuchs*.[3]

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[3] *Aufwuchs* is a German word that refers to the plant and animal communities found attached to surfaces in the aquatic environment. The term periphyton refers to the plant portion of the *Aufwuchs* community.

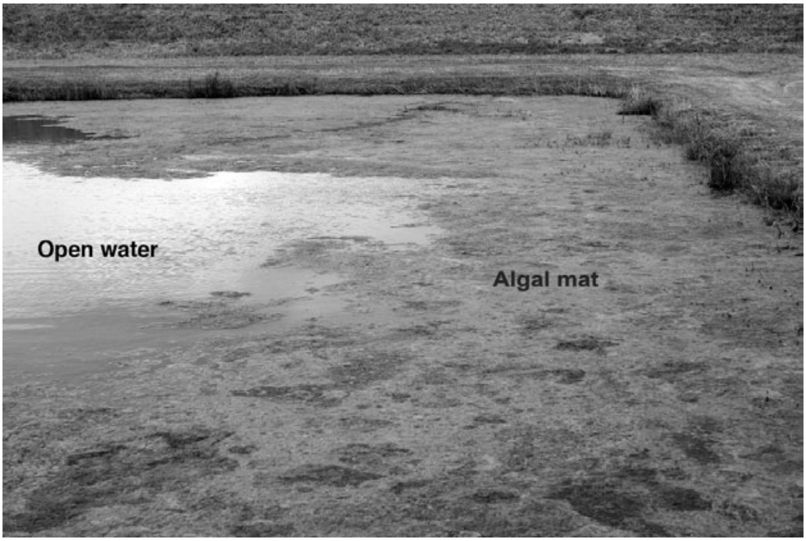

Fig. 3.10. Pond with much of the surface covered with filamentous algae.

Controlling undesirable plants

Undesirable aquatic vegetation may appear after the fish have been stocked in a pond that initially had a good plankton bloom. When that happens, some type of control measure should be employed. The methods available are biological, mechanical and chemical.

BIOLOGICAL PLANT CONTROL. By biological plant control, we do not mean putting a biologist in the pond to pull weeds. That approach falls under mechanical plant control (discussed next). What I am referring to is a variety of herbivorous animals that can be stocked to control aquatic vegetation. The most popular of these are fish of one species or another, some of which, such as grass carp – the most popular among them – are also marketable. Some species of tilapia, along with the Java barb, tambaqui and giant gourami have been used as weed control agents. Common carp have also been used. This species does not consume aquatic vegetation except, perhaps, incidentally, but it does root around at the pond bottom and causes increased turbidity, which can lead to reducing the amount of light reaching the plants and will reduce photosynthesis or even cause the plants to die back. The rooting around at the bottom by common carp will also damage pond levees, leading eventually to deterioration of the levees. Some species of turtles and birds, manatees, nutria and muskrats will also control aquatic vegetation, though the idea of having a several hundred-pound manatee or sea cow in a culture pond seems unrealistic and would be illegal in such countries as the USA, where manatees are on the endangered species list. 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.

There are species of snails and insects that eat aquatic vegetation and there has been at least limited use of them by aquaculturists. Their best use might be to stop establishment of unwanted plant populations, as snails or insects, unless present in very large quantities, would be unlikely to control a heavy infestation due to their small size.

The use of grass carp 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, including at least the upper reaches of estuaries where the salinity is low, prompted the promulgation of strict laws in as many as 30 states in the USA during the 1960s and 1970s.

Re-evaluation of the use of herbivorous grass carp has come in more recent years after the techniques were perfected for developing hybrids (grass carp x bighead carp being the most common) and triploid fish. Triploids are fish that contain three pairs of chromosomes instead of the normal two. Both hybrid and triploid grass carp are assumed to be sterile, thereby supposedly eliminating the chances of reproduction should they escape from an aquaculture system. Based on that assumption, many states modified their regulations on grass carp and approved stocking of the hybrids and/or triploids, if not normal diploid grass carp. However, grass carp appear to have become familiar with the concept, if not the famous line from the movie Jurassic Park, 'Nature will find a way.' The 'way' found in the case of grass carp is that the production of triploids is not 100% effective and some diploid fish have been found in supposedly triploid populations. Some states now require that each grass carp stocked be certified as being a triploid. This requires examination of a properly prepared tissue sample under the microscope to ensure that the cells do, indeed, have three pairs of chromosomes.

Stocking rates for grass carp vary from location to location. In many instances the maximum stocking rate is regulated by government agencies. More hybrids are often stocked per unit area of pond than non-hybrid grass carp because the hybrids are not strict herbivores, so they do not consume as much vegetation as do normal grass carp. Hybrids appear to consume the same amount of plant material in cold water as they do in warm water (Cassani and Caton, 1983). Stocking rates can also vary depending on the species of aquatic plant that is being controlled. Young *et al.* (1983) suggested that it might be necessary to stock twice as many hybrid grass carp to achieve the same level of vegetation control effected by grass carp. Of course, 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 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 numbers of grass carp stocked are in the range of 15 to 100/ha.

MECHANICAL PLANT CONTROL. This method usually 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. I was 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 out, or in the case of floating plants like water hyacinths, collect them by hand or in a net. This becomes increasingly more difficult and time consuming as the extent of the problem increases. There are mechanical plant harvesters available, but these are most commonly used in large water bodies such as lakes. Also, mechanical harvesters often do not uproot plants but merely mow them down, so they will often come back.

Dyes that are not toxic to animals or plants have been developed for use in aquaculture ponds. The most common of them will turn the water a deep blue in colour, thus reducing light penetration and shading out the plants. Establishing a phytoplankton bloom may also be difficult once the undesirable plant biomass has been reduced, because the shading effect of the dye will still be a controlling factor.

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 plastic, 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 – such 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 and for other applications, while others have very liberal or have no policies in place on the use of herbicides. Certain chemicals in the USA require the applicator to have a licence which is obtained after the individual has taken classes and passed an examination on the use of those chemicals, which may be herbicides or pesticides. Similarly, the types of vegetation present will vary from region to region and the appropriate herbicides to control the local types of vegetation present will also vary.

Herbicides must be used carefully as they may be toxic to the culture animals if improperly applied – which usually means being applied at too high a dosage. Interestingly, when it comes to such chemicals, more is not necessarily better. 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. These parameters include temperature, alkalinity and pH, among others.

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. This can be accomplished by turning on a paddlewheel aerator and putting the liquid virtually anywhere in the pond since the entire water column will be mixed by the paddlewheel. Another option is to use an outboard motor to mix the herbicide into the water. The liquid herbicide would be poured into the wake generated by the propeller. The motor can be affixed to a stationary stand or operated from a boat, which can be either tied up or underway.

When heavy plant infestations are present in a stocked culture pond, attempting to eliminate all the plant material at once (herbiciding the entire pond) can be dangerous. As the plant material dies and decays, it places a heavy demand on the supply of dissolved oxygen available and can lead to oxygen depletions with resulting fish kills. Spot treatment with granular or powdered herbicides in limited areas of the pond is recommended in such instances. Depending on the extent of the plant infestation, 5 to 25% of the pond might be treated at one time. Once the plants in the treated area have died and decayed to the extent that the oxygen level has returned to or remains normal, an additional percentage of the pond can be treated. The process is repeated until the entire pond has been treated.

Some commonly used herbicidal compounds are copper sulphate, 2,4-D, Diquat, endothall, fluridone, glyphosate, potassium ricinoleate, Simazine and xylene. All of them are labelled for use in ponds. Regulations may require that the fish or invertebrates being cultured cannot be marketed for a certain period of time after exposure to the herbicide. Package labels will instruct the user as to how much of the chemical to apply on the various types of plants that the herbicide will control. Copper sulphate is only effective in controlling algae, for example, while chemicals such as Simazine and glyphosate compounds are broad-spectrum higher aquatic plant herbicides. 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 on the plants. Endothall can be purchased as a powder that will dissolve in the water, but also comes adsorbed to sand grains. The latter form is excellent for spot treatment as it can be sprinkled on the leaves of the target plants and will remain in place as the chemical is released to be taken up by the plants.

Salinity

Salinity was defined by Sverdrup *et al.* (1942) as 'the total amount of solid material in grams contained in one kilogram 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 salinity is basically the amount of elements and ions in the water after organic matter and suspended particulate matter are removed. Since the original definition of Sverdrup *et al.* 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 'per mille,' ppt, or ‰). Recently, oceanographers have been involved in a debate as to whether salinity does have units or is a unitless number. Being trained to present salinity in parts per thousand, I am torn between accepting the new approach or sticking with the old. Since most aquaculturists are still familiar only with the notion that salinity is measured in ppt, I elected to use that terminology here.

Salinity can be measured in a number of ways. The original method of measurement 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. Electrical conductivity of a water sample also relates to salinity. Perhaps the easiest method of determining salinity is by measuring the refractive index of the water. This is easily accomplished with a salinometer, or refractometer (Fig. 3.11). A drop of water is placed on a glass plate (the bevelled portion of the salinometer to the right in the figure) and covered with the plastic plate to spread the water over the glass. The observer looks through the eyepiece (at the left in the figure) and will see a salinity scale. A shadow across the scale indicates the salinity of the sample. The measurement requires only one drop of water as indicated and the reading requires only one or two seconds of time. Accuracy is more than sufficient for aquaculture purposes as it is within ±1 ppt.

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. Marine waters are those with salinities ≥ 30 ppt and < 40 ppt, while hypersaline waters or brines are waters with ≥ 40 ppt salinity. Estuaries – regions where rivers enter the sea and the water is measurably diluted by fresh water – have salinities ranging between fresh water and sea water (>0.5 to 30 ppt).

Most freshwater species can tolerate a few parts per thousand salinity (typically as much as 10 ppt are tolerated). In fact, adding sodium chloride to the water to increase the salinity from 2 to 5 ppt has been used as a treatment that has been effective against the parasite Ich (*Ichthyophthirius multifiliis*) in a number of freshwater fish. Strictly marine fish (those which spend their entire lives in offshore waters) require oceanic salinities (30 ppt and higher – the average open ocean salinity is around 35 ppt). 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 inhabit estuaries as part of their

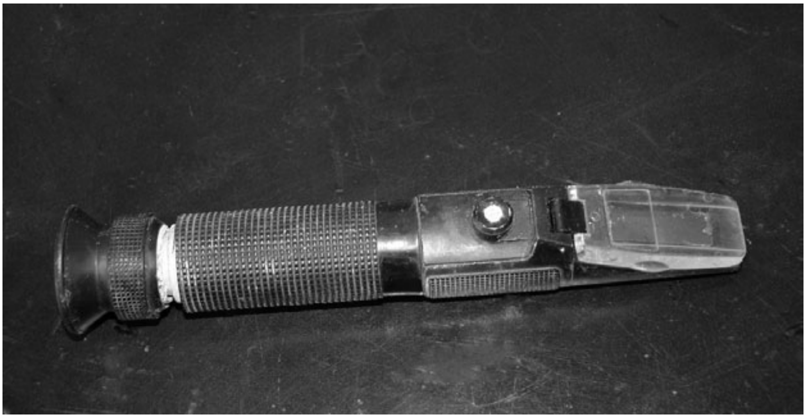

Fig. 3.11. A hand-held refractometer.

life cycle, along with anadromous and catadromous species[4], have a wide tolerance of salinity. These species are called euryhaline.

The blood of a fish has a salt composition that is similar to that of ocean water, but certainly not identical. Fish blood has a salinity that is typically around 10–12 ppt. 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, the external salt concentration is lower than that in the tissue fluids and blood, so water constantly enters the fish. In order to maintain its internal salt concentration, and to keep from blowing up like a water balloon, the freshwater fish must continuously eliminate the water that is passing through its skin. This is the job of the kidneys. Freshwater fish do not drink water as their bodies are continuously taking it in. Instead, they produce copious amounts of very dilute urine as they need to retain the minerals required for proper growth and metabolism. The main source of the minerals in freshwater fish is their food.

Marine fish are just the opposite of their freshwater counterparts. In their case, the salt concentration in the water is higher than that in the tissues, so the movement of water is from the inside of the fish to the outside. To compensate for the water loss and keep from dehydrating, saltwater fish drink a lot of water, which means they also take in excessive amounts of salts, including some minerals that they require. 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 salts. Adjusting and maintaining the tissue composition with respect to minerals is called osmoregulation.

Anadromous and catadromous species must obviously be able to move between osmoregulating like a freshwater fish to osmoregulating like a marine fish during the stages in their life cycles when they either enter or leave sea water. Switching from fresh water to sea water or vice versa requires significant physiological changes. In the case of salmon, the process of adjusting from the natal fresh water environment to being able to enter sea water is known as smoltification. Salmon smolt at different ages depending upon species. They may stay in fresh water for a few weeks to up to a year before entering the ocean. Young salmon have dark vertical bars along their sides, which are called parr marks, and that stage is known as the parr stage. When smoltification occurs, the fish become more silvery and are called smolts. That is the primary visual sign associated with the process. Significant hormonal changes are also associated with the smoltification process. Smoltification in salmon has been discussed in detail by Folmar and Dickhoff (1980).

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[4] Anadromous species are those which spawn in fresh water and migrate to the ocean to mature (salmon and steelhead trout [the sea-run strain of rainbow trout] are examples), while catadromous species do the opposite: that is, they spawn at sea and migrate to fresh water for most of their lives (the Amercan eel and the European eel are good examples).

Some euryhaline species can tolerate a remarkable range of salinities. For example, the Mozambique tilapia is a species found naturally only in fresh water, but it will tolerate hypersalinities up to several times the salinity of sea water. Marine shrimp and various fish species thrive in the Laguna Madre of Texas[5] during periods when very high salinities occur. Salinities of <50 ppt are not uncommon in the Laguna Madre and can be much higher in tide pools, yet a number of animal species are found under those hypersaline conditions. Hybrids between various species of tilapia (including some three- or four-way crosses of tilapia species) are currently being reared in sea water 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 fish are reared in fresh water. Salinity in relation to aquaculture production has been reviewed by Stickney (1991).

Variables to measure periodically

There are a few water quality variables that should be measured monthly or even less frequently as their levels tend to be stable over time, so long as environmental conditions do not change sufficiently to give the culturist an indication that the situation has been altered, thereby prompting more frequent measurements. The two variables discussed here are alkalinity and hardness, which are related, but quite different. Others that should be measured initially when a water source is considered include hydrogen sulphide, iron and carbon dioxide, all of which may be elevated in well water. Of course, it is incumbent upon the culturist who uses municipal water to continuously monitor the system for chlorine or chloramines and make sure 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 of chemical reactions that occur in the water. The carbonate:bicarbonate buffer system is virtually the only one present in fresh water and is also dominant in salt water, where there is also a borate buffer system and a phosphate buffer system. Normally, only the carbonate:bicarbonate alkalinity is measured by aquaculturists.

Alkalinity is measured through a simple titration technique that involves determining how much dilute sulphuric acid is required to change the colour of a water sample to which two indicator chemicals, phenolphthalein and

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[5] The Laguna Madre is perhaps one of the best examples in the world of a negative estuary, which means that it is an estuary where the salinity is actually higher than in the open ocean. That is because evaporation exceeds freshwater inflow. Salinities in the Laguna Madre often exceed 50 ppt and may be in excess of 100 ppt in tide pools.

methyl orange, have been added. The methyl orange endpoint provides the total alkalinity value, while the phenolphthalein endpoint indicates the bicarbonate alkalinity. The difference between the two is the carbonate alkalinity. The results are reported in mg/l or parts per million as calcium carbonate.

When carbon dioxide is added to water (largely through respiration in aquaculture systems) it forms carbonic acid:

$$CO_2 + H_2O \rightarrow H_2CO_3 \tag{3.6}$$

Carbonic acid can then dissociate to form hydrogen ion and bicarbonate ion:

$$H_2CO_3 \rightarrow H^+ + HCO_3^{2-} \tag{3.7}$$

The release of hydrogen ions would 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 as we saw in formula (3.3). The result is that the pH will not change until the carbonate pool is exhausted.

Aquaculturists like to see freshwater alkalinity levels of between 30 and 200 mg/l, though 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 comprised of calcium carbonate, can be added to water systems to provide a source of carbonate ion as previously shown in formula (3.2).

Hardness

The concentration of divalent cations in a water sample is called hardness. The dominant divalent cations are calcium and magnesium. Hardness is determined through a titration process and, like alkalinity, is reported in mg/l or parts per million of calcium carbonate. Because both alkalinity and hardness are reported with respect to calcium carbonate, many consider the two to be the same thing, which they are clearly not. One (alkalinity) deals with anions, while the other (hardness) concerns cations. It is quite possible, and routinely happens, that one is high while the other is low.

Very hard water with high alkalinity is found in some areas. In that instance, if the hardness is due to a high concentration of calcium (which is common), a reaction will occur which produces calcium carbonate as shown by the following reaction:

$$HCO_3^{2-} + Ca^{2+} \rightarrow CaCO_3 \tag{3.8}$$

Precipitation of calcium carbonate can and does occur in natural waters as well as in aquaculture systems. I 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 can be used to dissolve the precipitate, but it will reform again when the glass is exposed to highly alkaline, hard water.

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

Some estuarine/marine fish perform well in fresh water, particularly when the water is fairly hard. An example is the red drum. It is likely that the ability of those species to osmoregulate is enhanced in hard water. Studies have shown that some species and life stages of certain species require fairly low hardness levels, while others may need to be exposed to relatively hard water during certain life stages.

As a general rule, freshwater fish 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 which have life cycles that involve one or more stages associated with low salinity water, may require much harder water for survival or even acceptable performance. 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 limestone (comprised of calcium carbonate as previously indicated). Boyd (1990) discussed the topic in some detail. Limestone or oyster shell will not be effective in waters of high pH because it will not dissolve rapidly enough to provide the necessary buffering capacity. To increase only hardness, lime (CaO), can be added. To determine the amounts of chemicals to add, the culturist should consult published information such as the publication cited above.

Other Factors

There are various other factors associated with the culture system that can significantly affect water quality. The more important ones are considered in the following subsections.

Light

The quantity and quality of light, along with the photoperiod, influence the growth of plants in aquatic systems. Since the aquaculturist may be interested in establishing and maintaining a phytoplankton bloom, or in growing seaweed or higher plants as a primary or secondary product, they will need to ensure that sufficient light is available for good plant growth. Animals may also grow better under proper light conditions. During egg development and larval rearing, light may play a significant role in producing hearty animals. Light also plays a role in the smoltification process in anadromous salmonids as discussed earlier.

Light quantity will vary depending upon water depth and turbidity. Light penetration diminishes with depth, even in clear water. The rate at which light penetration diminishes is enhanced as turbidity increases. The depth at which the light level is about 1% of the level at the water surface is called the compensation depth, which means it is the depth at which photosynthetic productivity and plant respiration cancel one another out and there is no net increase or loss in oxygen. 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 such as paddlewheels is an effective means of accomplishing that task in ponds. In tanks it is common to use compressed air or air blowers.

Light quality refers to the wavelengths of light that are present. Having evolved under natural light from the sun, plants are best adapted to the full light spectrum that is available during 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 they not only provide the necessary wavelengths, but also are very bright, and the light penetrates water much better than fluorescent or incandescent lights.

The various wavelengths of light are absorbed in water differentially. The first colour to disappear is red. Many marine organisms that live below the depth of red light penetration are red in colour, which makes them virtually invisible – at least with respect to colour – to predators. Blue and green are the last colours to be absorbed in water and thus these wavelengths penetrate more deeply than the others.

Photoperiod refers to the number of hours of light that the plants and animals are exposed to each day. Natural photoperiod changes seasonally, with the greatest fluctuations occurring in the Arctic regions and the least in the tropics. As many aquaculture species are tropical or subtropical, typical photoperiods used in indoor culture facilities are 12:12 (light:dark) or 14:10. Photoperiod is commonly a controller, usually along with temperature, of gonadal development in fish and other aquatic animals. The gonads of many species develop in the spring or autumn. In the spring, daylengths are getting longer and temperatures warmer, while the opposite occurs in the autumn. These 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, are multiple spawners and can spawn every few days for months once the proper conditions are established and maintained. Other species, such as catfish and salmonids, spawn once a year though it is possible, at least in the case of catfish, to recycle them and produce at least two spawns a year. However, since channel catfish are predominantly pond reared under natural conditions of photoperiod and temperature, and are almost exclusively reared in temperate regions where the growing season is of limited duration, there is not much advantage to having multiple spawns, particularly if one of them is several months out of phase with the normal spawning time.

Light also stimulates gonadal development in shrimp. The eyestalk of marine shrimp is the site of production for many hormones associated with spawning. Researchers found that by removing one or both of the eyestalks (a technique known as ablation) of the female, the animal can be induced to spawn. This process can only be done once per female, then new broodstock must be obtained. Since shrimp spawn in nature without eyestalk ablation, it is only a lack of establishing the proper conditions that has held up progress. In fact, Wurts and Stickney (1984) hypothesized that maintaining brood shrimp under extremely low light conditions at the proper temperature could induce them to spawn. The theory has been shown to have merit in at least some cases, but the light levels required are so low that observing and working with the shrimp becomes very difficult for culturists, and even very low light levels or complete darkness have not led to gonadal maturation in some cases; thus, ablation continues to be widely employed in shrimp hatcheries.

Some stages in the life cycle of animals, particularly the early life history stages, may require either a lot of light or no light. 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 conditions under which the adults mature and spawn – 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 indicate that they should not be hatched under bright light. Salmon egg incubators (Fig. 3.12) 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 containers periodically during development).

The influence of light on egg development in fish may be related to either intensity or wavelength. For example, a higher percentage of Atlantic halibut eggs will survive to hatching if incubated in the dark or at low light levels than when exposed to relatively high light levels (Bolla and Holmefjord, 1988). When sac fry of the same species were exposed to white, blue, green or red light, there was no influence of wavelength on growth (Karlsen *et al.*, 1998).

Photoperiod effects on aquaculture animals are not limited to vertebrates. For example, roe (egg) quality in terms of larger gonads can be affected by either controlled (12:12) or ambient photoperiod in green sea urchins according to a presentation made by Devin and Walker (2001) at a meeting of the World Aquaculture Society. Fixed photoperiod was effective in increasing gonad size during winter only. In a related study, out-of-season roe quality was increased by exposing urchins to June photoperiods during March (Walker and Lesser, 1996).

A major problem associated with the rearing of striped bass has been poor swim bladder inflation (reviewed by Kirby, 1993). If the swim bladder does not inflate at the appropriate time during larval development, the fish will die. Research has indicated that a number of factors are involved with proper swim bladder inflation and that one of those factors may relate to photoperiod.

There has not been a great deal of research conducted on the effects of photoperiod on the growth of fingerling fish or postlarval invertebrates, but the information that exists shows a good deal of variation from species to species.

Fig. 3.12. A battery of Heath incubators used for hatching salmon eggs. The eggs are placed in drawers out of direct light. Oxygen-rich water is flowed into each stack of trays at the top and trickles down the stack, so the eggs are constantly submerged in high-quality water.

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. This 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 which does not occur in nature.

Aquaculture animals, particularly motile species, should not be exposed to rapid changes in light intensity. For example, if the aquaculturist enters a darkened indoor tank facility in the middle of the night and turns on 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 a good deal of 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 after an appropriate time interval by higher-wattage lights. If the facility does not have windows that will allow natural light to diminish slowly as the sun sets after the indoor lights have been extinguished, the lights should be extinguished over a period of time sequentially, or via a rheostat, to simulate natural conditions.

Substrate

In nature, animals of aquaculture interest would not commonly be found living in contact with bare fibreglass, plastic, metal, concrete or milled lumber – certainly they would not have been found in conjunction with those types of materials before humans began manufacturing them. In the wild, however, many species are associated with some type of substrate. Fish and invertebrates in both the marine and freshwater environments are found in association with some type of structure. Examples include a wide variety of fish, and such invertebrates as spiny lobsters that are associated with coral reefs. Artificial reefs have been placed in both marine and freshwater bodies to attract fish. Some species are most commonly found in mangrove swamps, in and around the mangrove roots or in association with kelp beds, marshgrass areas or seagrass beds. Other 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? The answer is: sometimes, but not too often.

Hard substrates are required for the larvae of such species as oysters and mussels that attach to surfaces, though they can be removed from the cultch material and reared without attachment in the case of cultchless oysters. Some species burrow into the substrate, though few aquaculture species fit into that category. Flatfish such as flounders are often found partially buried in soft sediments or on sandy bottoms. Many flatfish species have the ability to adjust their body colouration and mottling pattern to match the substrate. When some species of flounders are reared in tanks, a high percentage of them may become ambicolourate: that is, they will develop dark pigment on the lower side, which is normally white. While having dark pigment on the lower side (which may be the left or right side depending upon the family to which the fish belongs) does not affect the quality of the flesh, it does make the fish less marketable if sold in the round. In early studies with summer flounder, we 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 the problem (Stickney and White, 1975). However, Tuckey and Smith (2001) saw no difference in pigmentation in the same species when reared on bare tank bottoms compared with sand substrate. So, the jury still seems to be out on the issue of ambicoloration development in relation to the presence or absence of natural substrate.

Halibut are among the species that can be reared in marine net pen facilities. In the open ocean, halibut (and other flatfish for that matter) often swim up into the water column, particularly to feed and during spawning. In tanks, halibut and other flatfish tend to lie on the bottom much of the time, though 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 the tanks. During some of the early experiences that my graduate students and I had with halibut we thought it would be necessary to provide a hard substrate at the bottom of net pens for the fish to lie upon. We did some modifications to standard net pens by placing solid floors in them, but that was not particularly successful and was difficult to accomplish. We learned it was also not necessary when a ship with some newly captured halibut offloaded the fish into the wrong – unmodified – net pen where they adapted quickly and seemed to be quite at home. We abandoned any notion of putting hard bottoms in net pens thereafter.

Structure is often provided by the culturist in instances where cannibalism may occur following ecdysis, or moulting, in crustaceans. This is certainly the case with freshwater shrimp, as well as with crabs and lobsters. High rates of mortality associated with newly moulted individuals is the main reason why the culture of crab and American lobster – the ones with the large claws, more properly known as chelae – is almost non-existent. It is often said that if you start out with a tank full of lobsters or crabs, you may end up with one big one! The solution is to provide lobster condominiums. That is, each animal should have its own container so that it cannot have access to newly moulted tank mates which are vulnerable to cannibalism for a few hours while the new exoskeleton hardens. Crab condos have not to my knowledge been developed, probably because the value of crabs is much less than that of lobsters, so the expense would not be warranted. In fact, there is very little lobster culture being conducted in any case.

Freshwater shrimp are less aggressive than crabs or lobsters, but a significant rate of cannibalism will occur in culture tanks or ponds. This mortality rate can be reduced by providing some type of shelter where newly moulted animals can hide until their exoskeleton hardens. Pieces of PVC pipe, and even window screen suspended vertically in the culture chambers, have been used successfully to provide protection from cannibalism. Marine shrimp are much less cannibalistic than are their freshwater counterparts, so provision of shelter for the less aggressive species is not required.

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 rapidly flowing water, sand. Organic particles such as plant and animal detritus of various sizes will also be seen suspended in 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 pieces of particulate matter larger than 0.45 μm that occur in the water column. If a particle is smaller than 0.45 μm it 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 place each cell in the light 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 for filter feeding molluscs and other types of aquaculture species, particularly the early life stages.

Establishing and maintaining a good phytoplankton bloom can be important even if the 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 keeping a good phytoplankton bloom present, has been widely employed in Taiwan, where successful larviculture has been demonstrated on over 90 species of finfish (Liao *et al.*, 2001). In Europe and North America, green water has also been used in the culture of a variety of species (Bengtson *et al.*, 1999; Planas and Cunha, 1999; Shields, 2001).

Establishing a phytoplankton bloom in ponds with turbid water can be very difficult because of greatly reduced light penetration. If it is necessary to reduce the turbidity, there are a couple of methods that have been developed. One is to spread hay over the pond surface, though I must admit that my success using that technique has been limited at best. A better approach, at least to my way of thinking, is to apply gypsum or calcium sulphate ($CaSO_4$) at the rate of 250–500 mg/l (Wu and Boyd, 1990). Depending on the results, it may be necessary to repeat the treatment at 7-day intervals. Alum has also been used with some success. This chemical ($Al_2(SO_4)_3 \cdot 14H_2O$) was found to be effective when used at 15–25 mg/l by Boyd (1990).

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 outdoor ponds can be buried and smothered, and feeding may be impaired due to low visibility for sight-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 very expensive, so we are once again back to selecting a water source that has the proper quality, including with respect to suspended solids levels.

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. Ultimately, that approach will produce problems, the least of which might be reduced average growth rate of the species under culture. Worse yet would be sufficient deterioration of water quality to induce a disease epizootic or direct mortality. Each water system will have an upper limit in terms of the biomass of animals that can be reared optimally. The density of animals that can be reared within a specified water surface area or volume is called the carrying capacity.

Whether grown on the bottom; on poles, strings or longlines; hung from rafts; reared in ponds; produced in raceways, cages or net pens, the concentration of animals an area or 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 is different. 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 a 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 grading and redistribution). 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, experience 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.

Some recommendations exist with respect to carrying capacity in trout raceways. Tables and formulae have been developed to inform the culturist of the proper stocking density when flow rate or water turnover rate, temperature, initial fish size and perhaps other factors are known (see Piper *et al.*, 1982; Wedemeyer, 2001). Recommendations, or at least targets, for other species also exist. Catfish are stocked at densities which will result in biomass levels in ponds from 3000 to as much as 8000 to 10,000 kg/ha at harvest. The range is associated with whether aeration is provided or not and whether aeration, when applied, is used periodically or routinely. Routine stocking rate information for various other species is also available. Such recommendations tend to be conservative as they are often applied over a variety of water quality conditions and in various types of systems.

Many production systems employ step-wise stocking: that is, very high densities in terms of numbers per unit area or water volume are initially used because total biomass is 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 redistribution of the harvested animals to other culture units at a much reduced stocking density for further growout. Depending upon the 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. It involves harvesting marketable fish as many as several times a year followed by restocking with fingerlings. The number of fingerlings restocked is the same as the number of fish harvested, plus 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 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 even far in excess of what might be considered to be the appropriate number with respect to the carrying capacity of the pond. I was once present during the partial harvest of a catfish pond where the farmer thought he had a small number of marketable fish left as he had removed a large number not many weeks earlier. He had brought in a seine crew to complete the task of removing the marketable fish that he thought remained. The ‘small’ partial harvest 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 and he obviously was far off on his estimate of the amount of fish present.

As technology advances, the natural instinct is to take advantage of that technology and try to produce more product in the same amount of water area or volume. Once problems develop there will be pressure on the research and engineering communities to develop newer technologies to overcome those problems. At some point this will be self-defeating, as there are ultimately going to be upper limits on the carrying capacity of any water body or water system.

We have even seen one incidence of the development of what we are convinced was an autoimmune response in one species of tilapia (Henderson-Arzapolo *et al*., 1980). What happened was that when the biomass of the fish in a number of 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 to a level that did not exceed the carrying capacity of the tank. 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 it 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 we were able to extract a high-molecular weight compound from the water that, when injected under the skin of a healthy fish, created an inflammation at the injection site that was indicative of an allergic response. Also, anecdotal information from people involved in the ornamental fish trade indicated that they had seen fish dying for reasons they could not determine when the fish were maintained in overcrowded conditions. Those producers, too, felt that there was a self-limiting factor involved in the deaths as mortality ceased once a certain biomass level was reached. More research on the topic is certainly warranted.

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4

The Healthy Fish is a Happy Fish

Disease Array and Role of Stress

Sources of mortality in aquaculture systems include cannibalism, predation, degraded water quality, nutritional imbalance, toxicants in the water as well as in improperly stored feed, poaching, pollutants and disease.[1] In this chapter, the concentration is on the diseases that occur in aquaculture species, and I include shellfish within the term ‘fish’ mentioned in the chapter title. Included among the groups of organisms that cause disease in aquatic species are viruses, fungi, bacteria and parasites. The latter involve cestodes, nematodes, trematodes and protozoans. There are also nutritional deficiency diseases that sometimes arise in aquacultured animals.

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 humans are. Yet, diseases often fail to manifest themselves, either in the wild or under culture conditions. In the case of fish, there is a fairly well-developed immune system, but immune systems are virtually lacking in many, if not most, invertebrates. In spite of that fact, disease incidence is arguably less common in invertebrates than in vertebrates, at least in culture situations. The reason relates to exposure to some extent, particularly in the wild where there may be a significant distance between an infected animal and uninfected animals occupying the same part of the ecosystem. The same cannot be said of aquaculture species, where close proximity of one animal to another is a constant.

There are literally thousands of diseases that can affect aquaculture species, and that is not limited to animals. Plant diseases also occur, though those are not addressed here. Some pathogens are species- or species group-specific. For example, shrimp viruses, in general, do not attack other decapods – at least not the viruses that have been identified to date. Catfish virus disease does not attack salmon or trout, and trout viruses do not attack catfish. 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.

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[1] Parasites are included under our definition of diseases.

Despite the large number of diseases that exist – and more are being identified almost daily as researchers begin to look more carefully for them – the incidence of diseased fish either in nature or aquaculture systems is relatively low. In aquaculture, diseases seem to be of little importance during the early stages of culture: that is, when the first attempts to culture the species are being made. As an industry develops around a particular species, the incidence and array of diseases observed increases. This is probably largely due to the fact that as culturists learn to rear a new species they begin to increase the density of animals raised per unit area or volume of water, and increase the level of exposure of the fish in the system to disease through proximity of animal to animal, as well as to increased exposure to stress.

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 dissolved oxygen, a significant diurnal fluctuation in pH or any of a number of other stressors. Animals may also be stressed during periods of physiological change such as smoltification, or alteration of normal activity such as that associated with the establishment of territories (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 on the animals in the culture system. This does not mean diseases can always be avoided, but the incidence can be dramatically reduced if procedures that keep stress to a minimum are adopted. The following example is illustrative of what I mean.

When I first started conducting aquaculture research, I was working in a facility where a colleague had designed a recirculating system in which he had stocked channel catfish at extremely high density, a density so high, in fact, that it was nearly like the proverbial sardines in a can! My colleague claimed the fish density was about 150 kg/m^3. 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 which shut down the system for sufficiently long that the DO dropped and the fish were exposed to low-oxygen stress. A few days later, a very heavy infestation of a parasitic protozoan (in this case one known as *Trichodina* spp.) erupted. The gills of the fish were covered with the microscopic parasites. 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 a number of different problems associated with both bacterial and parasitic infections. I should also mention 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 either entered from the atmosphere, or the healthy fish that were being reared had long been carriers of the disease organisms, but the bacteria and parasites were present at extremely low, virtually undetectable, levels and the diseases were not manifested until the fish became stressed. Both of those sources of infection probably operated in the situation just described, though we will never know for certain. Detailed information on the relationships between fish stress and health can be found in Iwama *et al.* (1997).

The above story reveals a pattern that is often seen when stress occurs. As often happens, an epizootic will not appear until some time after a stress event. Frequently, the period of time between when the animals are stressed and a disease is detected will be either 72 h or 2 weeks, depending upon the type of disease that develops (bacteria and some parasites have short doubling times, while other types of diseases require more time to reach epizootic levels). In many instances, the culturist will fail to make the connection between a stress event and a disease outbreak that occurs several days later as the two might appear to be unconnected. It is important to carefully monitor the animals for at least 2 weeks after they have been stressed to ensure that a disease outbreak is detected as early as possible. Going about business as usual after the animals have been stressed, but seemed to survive with no difficulty a day later, is likely to be a critical mistake if a full-blown epizootic appears some time later and the culturist did not see it coming.

While I have indicated that the incidence of diseases is relatively low (some authorities have said no more than about 5% of aquaculture facilities experience a disease epizootic in any given year), the global cost of disease incidents to the industry is not insignificant. According to the Food and Agriculture Organization (FAO) of the United Nations, diseases cost the global aquaculture industry over US$3 billion annually. In some years, disease can be devastating to an industry. Shrimp virus diseases have caused significant problems to the commercial marine shrimp industry in various Latin American and Asian countries, though they do not occur every year. In 2004, the heart of the commercial marine shrimp industry in Texas experienced serious losses due to a virus outbreak in shrimp that were produced in a hatchery that, from all reports, was 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 could have been consumed by birds that later defaecated into shrimp aquaculture ponds, thereby infecting them. That conclusion is conjecture, but plausible.

If you refer to Chapter 1, you will see that there is considerable controversy associated with the transmission of diseases from cultured to wild fish and vice versa. 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 salmon anaemia (ISA) virus disease and increased incidence of high body burdens of sea lice on wild fish are the result of concentration of those diseases 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 diseases they experience are due to transmission from wild to farmed fish.

While some universities and government laboratories around the world provide disease diagnostic services with respect to aquaculture species, in most places such services are not available or the laboratories are not conveniently located for most aquaculturists to get specimens to them in a timely manner. Since diagnosis and treatment can usually not await a period of even 1 or 2 days following identification that a problem exists before treatment is initiated, it becomes incumbent upon the aquaculturists to learn how to diagnose and to treat any disease epizootic that may occur – assuming it is a widely known disease and treatments are available. As we shall see, some diseases defy treatment at this time. As we will also see, and it cannot be repeated too often, only approved treatment chemicals and protocols should be used. In places where regulations on treatment have not been promulgated, recognized best management practices should be employed. Disease treatments should not be used that place the health of consumers in jeopardy. Such practices are unethical and place the public at risk.

Frequent examination of the animals in captivity is important, so early recognition of the signs of a developing epizootic is possible. Relying for long periods of time on automatic feeders has the potential for disaster if at least daily visual observation of the fish, particularly when they are feeding, is not a part of the routine on the aquaculture facility. The importance of observing the animals while feeding when possible – since making that observation is difficult with respect to some species – cannot be overemphasized, though it is not always possible. Indirect methods of checking on feeding activity have been developed as discussed in Chapter 6.

Because there are such large numbers of diseases that impact aquaculture systems, space does not permit examination of any of them in detail. Examples of a few books that are exclusively dedicated to the topic or contain a good deal of information on diseases are Sindermann (1970), Sindermann and Lightner (1988), Tucker (1995), Plumb (1999), and Hoole *et al.* (2001).

Keeping it Clean

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. The first is to produce or purchase healthy animals for stocking. Some producers of postlarval invertebrates or fry, or fingerling vertebrates rear them in a manner that allows the producer to market the animals as being specific pathogen free with respect to one or more particular diseases. That guarantee is based upon frequent testing of samples for specified disease(s), for example, one or more of a group of viruses specific to marine shrimp. At one time there were those who claimed they were producing pathogen or disease-free animals for sale, but such claims are difficult or impossible to substantiate, so the terminology today involves assurance that one or more specific pathogens has not been detected. Certification of specific pathogen-free status may require examination by a certified aquatic animal pathologist or even a veterinarian. It is worth noting that most schools of veterinary medicine do not spend much, if any, time on aquatic animal diseases. There are a few veterinarians who have specialized in aquatic animal medicine, and we can anticipate that more will adopt that specialty as the need for such service expands. When a culturist spawns and rears juveniles for stocking within his or her own facilities, the question of ensuring that the animals are healthy prior to stocking is still critical and the culturist may have an expert in aquatic animal diseases check the animals prior to stocking to ensure their health status.

A second way in which the culturist can avoid disease outbreaks is to maintain a culture environment that exerts a minimum amount of stress on the animals in the system. We have already discussed that concept both above in this chapter and elsewhere in this book. Stress avoidance cannot, if you will pardon the pun, be overstressed. It is something that needs to be continuously kept in mind.

Vigilance is the third 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), gulping for air at the surface, and so forth are obvious signs of problems in finfish. Changes in behaviour are often much more difficult to observe in invertebrates, particularly filter feeding species.

Increased mortality is an obvious sign that something may be wrong, though a low, and often continuous rate of mortality is not uncommon under even the best of conditions. Regardless, moribund or dead animals should be removed from the culture system immediately upon discovery and should be examined both by the naked eye and under the microscope for signs of pathology. The earlier a potential disease problem is detected, the sooner a treatment protocol can be initiated.

Procedures need to be implemented and maintained throughout the culture period that will reduce the potential for spread of a disease around the facility 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. Supplies that are used on a day-to-day basis should each be dedicated to a specific culture chamber, except in the case of culture chambers that share the same recirculating water system. Items such as dip nets (Fig. 4.1) and cleaning brushes should not be used in more than one culture chamber unless they are disinfected between uses. In pond systems, items such as waders and seines should be disinfected before being moved from one pond to another.

People can carry disease organisms on their clothing and shoes. Some facilities, or parts of them, are treated like clean rooms. People who enter may be required to wear special coveralls, or at the least, wear booties over their shoes or walk through an iodine bath to sanitize the bottoms of their shoes

Fig. 4.1. A group of culture tanks, each with its own dedicated dip net, an approach that may help reduce disease transmission from one tank to another.

before entering the culture chamber room. This procedure is not usually employed by growout facilities but is commonly seen in hatcheries, particularly when specific pathogen-free animals are being produced. Note that the item should be rinsed to remove the disinfectant before being used again since the sterilizing solution could be directly toxic to the animals being cultured. Such large things as seines can be dried in the sun between use, or if they are to be moved from one pond to another while wet, they can be dipped into a large vat of disinfectant and rinsed before reuse. One of the most readily available disinfectants is chlorine bleach, though a number of other products, such as Betadine which has an iodine base, can also be used.

At some facilities, such as biosecure hatcheries, there are restrictions on who can enter. There may also be a requirement for all those who enter the facility to wear clean coveralls over, or in lieu of, their street clothing, put on a hat and exchange street shoes for rubber boots. At the most extreme, different colours of coveralls are worn in different rooms and no-one is allowed in a room unless they are wearing the appropriate colour so as to avoid cross-contamination.

Diagnosing the Problem

A disease problem may first be suspected when there is a change in behaviour 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 in the case of shrimp viral diseases, no good treatments are available and the culturist may just have to be prepared to accept significant levels of mortality.

When a disease strikes in a larval or postlarval tank, raceway or pond, it may be economically most advantageous to destroy the entire group of animals in the culture chamber. By being mindful of the need for good sanitation and preventing spread of the disease by not using potentially contaminated items in uncontaminated culture units, it may be possible to contain the disease, whether the animals experiencing an epizootic are destroyed *en masse* or treated.

It is important to precisely identify the cause of the disease if the 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, for example, on a nutritional deficiency problem or virus.

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 may be a secondary infestation that have nothing to do with the cause of the mortality. Thus, it is better to examine living, but perhaps moribund animals that appear to be infected than to focus attention only on dead animals.

External examination usually comes first. If there are open lesions on the body or gills, swabs should be taken. Some culturists maintain laboratories that are capable of incubating culture plates and identifying bacteria, but most culturists do not have that capability and would send their samples out to a fish diagnostic laboratory. As we shall see, the number of antibiotics approved for use in treating aquatic animal diseases is small, particularly in developed nations,[2] so those compounds are frequently used immediately when a bacterial infection is suspected. Waiting for a specific diagnosis may be impractical since by the time the results come back the level of infection may have accelerated to the point that little benefit will result from treatment.

A variety of external parasites may also be found on the body or gills of an infected aquatic animal. Gill problems, both with respect to bacteria and 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 indicated, fungus infections are often secondary to an infection of some other type, though primary infections of fungus can occur. The most common fungus infections are caused by *Saprolegnia*. The problem appears as cottony

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[2] While there are many nations in which little or no control on antibiotic use is imposed, some nations have regulations that prohibit imports of aquaculture species that have been exposed to certain antibiotics, or to antibiotics that are not approved for use in the importing nation. Residue testing is now common so the importing nation can ensure that the regulations are being followed.

patches on the body surface. The presence of fungus can be easily verified through microscopy.

Many parasites attack the various organs within the body of aquatic animals. Cestodes and nematodes will occur within the digestive tract, while trematodes may infest the liver or other internal organs, along with possibly being present in the musculature. Trematodes may occur as intermediate-stage cysts as well as in the adult form. White patches in the liver may be due to parasites though fatty livers can be caused by nutritional deficiencies; a close examination will reveal the differences between those causes of liver problems.

Viruses are usually identified through the symptoms they cause since they are difficult to observe directly without extremely expensive equipment. A wide variety of viruses that attack fish or invertebrates have been identified. The viruses are often species specific and rarely infest two or more phyla of organisms. More viruses are detected each year, many of which do not appear to cause problems in aquatic species of current aquaculture interest.

Once the 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 ameliorate the problem. The first step is to isolate the problem as much as possible. Extra care should be taken to make certain no items that come in contact with infected populations of animals are used in conjunction with healthy populations. In instances where the water supply to each culture system is separate, achieving isolation is possible. Once a group of animals or culture chambers has been isolated, it is especially important to avoid contamination through transfer of disease organisms on nets, feed scoops or other supplies from one culture chamber to another. If the culturist is following the recommendations outlined in the ‘Keeping it Clean’ section above, few changes in protocol will be needed.

Treatment Options

The modern world has become dependent upon a wide variety of pharmaceuticals to treat human and livestock diseases. This approach is also being widely applied in aquaculture. In addition, there are some non-pharmaceutical chemicals that have found wide use in aquaculture. While the range of treatment chemicals and drugs that have shown efficacy in relation to their use in aquaculture is broad, the use of many of them is strictly regulated by some countries both with respect to internal use within each nation and more broadly in regulating residues in imported seafood, including those of aquaculture origin. Because the regulatory environment in this area 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 will certainly change. However, an example list of what the recent situation is with respect to drug use in aquaculture in the USA (Table 4.1) is illustrative, but should not be assumed to reflect the situation at the time you look at the table. As you can see, only a

Table 4.1. Drugs approved for use in food fish species in the USA in 2004 (Source: United States Food and Drug Administration, www.usda.gov.)

Drug	Species	Use	Limitations/Comments
Chorionic gonadotropin	Brood finfish	Spawning induction	Limited to no more than three doses not to exceed 24,000 IU[a] in fish intended for human consumption
Oxytetracycline (Terramycin®)	Pacific salmon	Marking skeletal tissue	In feed for fish <30 g
	Salmonids	Certain bacterial diseases	In feed, water temperature not below 10°C, 21-day withdrawal time
	Catfish	Certain bacterial diseases	In feed, water temperature not below 17°C, 21-day withdrawal time
	Lobster	*Aerococcus viridans*	In feed, 30-day withdrawal time
Sulfadimethoxine ormetoprim (Romet-30®)	Salmonids	*Aeromonas salmonicida*	In feed, 40-day withdrawal time

[a] IU = International Units

few drugs have been approved for use with foodfish, and approval may exist for one species or species group and not another. Less regulation exists with regard to non-food fish (baitfish and tropicals for example) and new species may be exempted from the regulations while under development. Such exemptions may be granted by the US Food and Drug Administration through an Investigational New Animal Drug (INAD). Other nations may typically have significantly different regulations (or no regulations at all), so the aquaculturist needs to become familiar with the local situation and follow those regulations judiciously.

Specific diseases and treatments for them are mentioned only superficially in this chapter. For detailed information, please go to the appropriate references listed in the References and Additional Reading sections.

However, chemicals are not always the best approach to disease control. Indiscriminate use of antibiotics is now not only being questioned, but strict controls on amounts that can be used, amount of time they can be used and withdrawal time before the animals can be marketed have been imposed in some nations. 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.

A recent example is illustrative. Shrimp farms in Asia and Latin America have used a broad array of antibiotics to prevent and treat various diseases, particularly during the hatchery phase of production. Among these antibiotics were some, like chlorphenicol, to which some humans are allergic. In fact, some people will die if exposed to even minute amounts of that antibiotic. While the use of chlorphenicol was outlawed in imported shrimp in countries such as the USA, many exporting nations ignored the law. Methods were developed to quickly and accurately detect the presence of chlorphenicol and other banned antibiotics, prompting the shrimp culture industry in the offending nations to search for other ways of preventing or treating diseases. The use of probiotics (live microbial dietary supplements that beneficially affect the host animal by improving its intestinal microbial balance) appears to be working well in some hatcheries and provides a widely accepted and safe way of dealing with a major issue.

Various chemicals that have been, and in many cases are still being used by aquaculturists, can be harmful to the animals being treated or may place the health of the culturists 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.[3] Caution should be used by the applicator to avoid skin contact and breathing the fumes of formalin when using the chemical. 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 employed. This is true of any treatment chemical. More is not necessarily better. More, in fact, may exacerbate the problem or create a new problem – direct mortality.

A once popular treatment chemical that is now banned in some nations is malachite green. This alanine dye has been used to treat fish eggs against fungus. It was widely used by channel catfish farmers in the USA. It was once said that you could tell a catfish farmer because of his green hands. The hands of catfish farmers were dyed when they dipped catfish egg masses in malachite green solutions using their bare hands. It was determined that malachite green is carcinogenic (cancer-causing), which led to banning the use of the chemical in US aquaculture.

Treatments do not always involve the use of chemicals applied to the culture species. Sometimes, chemical control of another species may be effective. For example, some parasites use snails as intermediate hosts. Elimination of the snails in culture ponds can disrupt the life cycle of the parasite and protect the final host, which is the fish being cultured.

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[3] Formalin is what many refer to as formaldehyde. Actually, formaldehyde is a gas, which when dissolved in water produces formalin. It is formalin that has been used to preserve specimens in museums, for example. Because of is toxicity to humans, exposure to the chemical is not advised, though the chemical is still used in aquaculture.

Modifying the environment can also control some diseases. Certain diseases of oysters flourish best within a particular salinity range. 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 the disease while still allowing the oysters to grow well. In the case of oysters, the diseases occur at fairly high salinities, so rearing the oysters in a relatively low salinity environment may be effective.

While rearing oysters in low salinity can be effective at reducing disease instances, the opposite can be true for freshwater fish. A major parasite that attacks freshwater fish is the protozoan *Ichthyophthirius multifiliis* or Ich. By rearing fish, at least channel catfish, at a minimum of 2 ppt salinity, the parasite can be avoided as it cannot tolerate that level of salt in the water.

Another complementary approach involves stocking animals at the proper densities, sizes and time of year. This approach was discussed in a paper presented by Davidson *et al.* (2002). They looked at the occurrence of white spot syndrome virus (WSSV) outbreaks in shrimp ponds and concluded that survival could be increased if the ponds were stocked with older postlarvae, if small pond sizes were employed, if stocking densities were reduced and when the shrimp had reached large size before an outbreak of WSSV, or similarly, when the outbreak occurred late in the production cycle. Seasonal temperature regime was another factor that influenced survival during WSSV outbreaks. A year later, Montgomery-Brock *et al.* (2003) found that exposing Pacific white shrimp to elevated temperatures led to significantly reduced mortality when the animals were exposed to taura syndrome virus (TSV). This virus has been responsible for massive mortalities of shrimp in many nations around the world.

There are a variety of ways to actively treat aquaculture animals. Some of those methods will work for some species and/or culture systems and some will not. The following subsections provide information and some examples of what I am talking about.

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 a few parts per thousand to eliminate an Ich infection, it would be possible 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.

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 in order to treat them 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 may appear.

Treating fish in cages or net pens using chemicals is especially problematic, particularly when large culture chambers are involved. It is theoretically possible to put an impervious bag around a cage or net pen into which a treatment chemical is placed. 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 is actually 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 pollution regulations.

Small cages could be floated to shore where, if they are properly constructed, they could be lifted from the water and immersed in a tank containing the treatment chemical. That approach is labour intensive, stressful to the animals and if there is any weakness in the cage, it may rupture when raised from the water, thereby releasing the ailing fish into the environment or, if you are 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.

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 needs to be allowed to pass for treatment to be effected. The water can then be turned on and the chemical would be flushed out of the system through dilution. Any dip treatment should include aeration during the period of exposure when static conditions exist.

Flush treatments involve allowing the water to run continuously into the tank or raceway. The chemical is added at a concentration calculated to remain sufficiently high to effect control of the disease before the concentration 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. 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 during the treatment process.

Aquaculturists should use only approved chemicals in treating aquatic animals' diseases and they should be meticulous in following dosage recommendations and not treat for longer than recommended periods. The same admonishments apply to drugs such as antibiotics as discussed in the next subsection. What is available for use in a given country will vary.

Antibiotics

While antibiotics are certainly types of chemicals, they deserve separate consideration since these are basically in a different category from the other chemicals that have been mentioned. There are three approaches that can be used when using antibiotics. One is to dissolve the substance in water and use it as a dip, bath or flush treatment. 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 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 fingerlings, for example, are to be injected. For broodfish or other valuable fish such as large ornamental koi carp, individual injections may be appropriate, and may be the most efficacious treatment method. The numbers of animals involved is 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®) is commonly employed in that way. A few grams of antibiotic per tonne of feed will be sufficient. Feed companies can supply diets that contain the antibiotic at the appropriate level. As in the case of other disease treatments, chemicals should not be used unless you are convinced a problem exists and you know that the treatment you plan to use is the correct one. Applying an antibiotic to fish that have a viral disease or have been parasitized will be a waste of time and money. The protocol for terramycin involves feeding the animals for 10 days and 10 days only. In some instances, regulations are in place that indicate 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).

At one time, many culturists routinely fed antibiotics to fish and used them in shrimp hatcheries. The situation with respect to shrimp hatcheries has changed as previously described. So too, has the situation changed with respect to fish culture. Producers 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 is also concern being expressed about releasing those types of drugs into the natural environment. Impact on the natural microbiology may occur, though significantly higher levels of a much larger number of antibiotics enter natural waters through sewage treatment plant effluent (the source being antibiotics excreted by humans) and from land runoff (antibiotic residues excreted by livestock).

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 4.2).[4] The effects have been highly positive with respect to treating

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[4] Some of the references may be difficult to obtain from most libraries, but are included in the References section of this chapter for completeness.

Table 4.2. A partial list of aquaculture species and diseases for which vaccines have been developed. (Citations can be found in the References section of Chapter 4.)

Aquaculture species	Disease	References
Invertebrates		
Lobster, American	*Aeromonas viridans* (Gaffkemia)	Keith *et al.* (1988)
Shrimp, black tiger	*Vibrio alginolyticus*	Teunissen *et al.* (1998)
Indian white	*Vibrio harveyi*	Alabi *et al.* (1999)
Kuruma	*Vibrio* sp.	Itami *et al.* (1989)
Fish		
Ayu	*Vibrio* sp.	Itami and Kusuda (1980a,b)
Carp, Catla	*Aeromonas hydrophila* (Infectious abdominal dropsy)	Azad *et al.* (1999), Shome and Shome (1999)
Common	*Aeromonas hydrophila*	Azad *et al.* (1999)
Rohu	*Aeromonas hydrophila*	Azad *et al.* (1999)
Catfish, channel	Channel catfish virus (CCV)	Awad *et al.* (1989)
	Edwardsiella ictaluri (enteric	Shoemaker *et al.* (1999)
	septicaemia of catfish; ESC)	Wise *et al.* (2000), Delbos *et al.* (2001), Wise and Terhune(2001)
	Ichthyophthirius multifiliis (Ich)	Wang *et al.* (2002)
Eel, European	*Vibrio vulnificus*	Fouz *et al.* (2001)
Flounder, Olive	*Vibrio vulnificus*	Park *et al.* (2001)
Halibut, Pacific	*Vibrio anguillarum*	Bricknell *et al.* (2000)
		Bowden *et al.* (2002)
Salmon, Atlantic	*Vibrio salmonicida*	Lillehaug (1990, 1991)
	Renibacterium salmoninarum (bacterial kidney disease = BKD)	Griffiths *et al.* (1998)
	Infectious haematopoietic necrosis virus (IHNV)	Traxler *et al.* (1999)
Sea bass, European	*Vibrio anguillarum*	Pneumatikatos and Pneumatikatou (2000)
Sea bream, Red	Red sea bream iridovirus (RSBI)	Nakajima *et al.* (1997, 1999)
	Vibrio alginolyticus, V. anguillarum	Zhou *et al.* (2002)
Tilapia, Nile	*Streptococcus iniae*	Klesius *et al.* (2000)

continued

Table 4.2. (*continued*)

Aquaculture Species	Disease	References
Trout, Rainbow	*Vibrio* sp.	Lillehaug (1989)
	Aeromonas salmonicida	Rodgers (1990)
	Streptococcus iniae	Eldar *et al.* (1997)
	Lactococcus garvieae (Streptococcosis)	Ceschia *et al.* (1997, 1998)
	Yersinia ruckeri (enteric red mouth disease)	Gravningen *et al.* (1998)
	Furunculosis	Durbin *et al.* (1999)
	Viral haemorrhagic septicaemia (VHS)	Lorenzen *et al.* (2000) Lorenzen *et al.* (2001)
	IHNV	Corbell *et al.* (2000)
	Rhabdoviruses	Lorenzen *et al.* (2002)
	Renibacterium salmoninarum (BKD)	Penn *et al.* (2003)
Turbot	Streptococcosis	Romalde *et al.* (1999)
Yellowtail	Streptococcosis	Ooyama *et al.* (1999)

some finfish viruses and bacteria in both finfish and some shellfish. Finding vaccines for treating shrimp viruses has not been successful to date, perhaps because shrimp have a poorly developed immune system that reduces the effectiveness of vaccines.

Vaccines can be provided to fish through individual inoculations, by means of dip treatments or orally. Injecting individual fish with vaccine faces the same problems mentioned above 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.

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 the appropriate period of time to allow the vaccine to be absorbed.

Administering vaccines orally can be effective so long as the vaccine is not destroyed by digestive enzymes. A review of delivery methods and the cost-effectiveness associated with vaccines was produced by Dunn *et al*. (1990). Since that review, a technique called ultrasonic immunization has been developed as a means of delivering vaccines (Zhou *et al*., 2002).

Nutrients

A few diseases are attributable to nutritional deficiencies. Signs[5] of nutritional deficiencies associated, in particular, with vitamins are mentioned in Chapter 7 where you will see that a variety of manifestations of problems can occur. In some cases, nutritional deficiencies may first be diagnosed as being attributable to a disease caused by a virus or other pathogen. The culturist should rule out nutritional deficiency as being the cause of a problem by making sure that some other cause is at fault.

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 may lead to direct toxicity, so the culturist needs to know which nutrients can be safely supplied to excess and which should not be used in that manner.

If the farmer suspects that the feed is deficient in one or more nutrients, he or she can have a sample analyzed to verify that suspicion. A new batch of feed that contains the proper levels of all nutrients can then be ordered. 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.

Several years ago I was asked by a feed company to look at some fish that one of their customers claimed were showing a nutritional deficiency. The fish were being grown in cages in a lake. What I discovered was some very skinny channel catfish that, in many cases, had severe scoliosis or lordosis.[6] There was also some indication of bacterial infection. When I looked at the feed formulation that was being offered the fish, I found that it was an old recipe designed as a supplemental food[7] for pond-reared catfish raised at low densities. There were no supplemental vitamins in the formula. The misshapen and often broken spinal columns of the fish were a sure sign of vitamin C

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[5] Humans have disease symptoms, while aquatic animals show signs of disease. The difference is that symptoms can be communicated to physicians, whereas the aquatic animal disease practitioners need to identify signs on their own.

[6] Both are abnormal curvatures of the spine. Scoliosis is lateral or side-to-side curvature, while lordosis is anterior–posterior or front-to-back curvature. The condition can become so severe that the spine actually fractures.

[7] Supplemental feed is provided in cases where a portion of the diet comes from natural foods. Supplemental feeds are typically lower in protein level than complete feeds and supplemental feeds are usually not fortified with vitamins and minerals.

deficiency, so I instructed the feed company to provide organ meats such as calves' liver in an attempt to provide a rapid infusion of the vitamin into the fish. It turned out that one of the company's feed salesmen had convinced the 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. The company's feed was certainly less expensive, but it was also totally unsuitable for caged fish. A reformulation of the feed followed that led to a ration that did provide the proper nutrients for rearing catfish under virtually any conditions that were in use at the time. The feed company ended up paying fair market value to the farmer, and I was later told that the farmer was allowed to keep the fish, many of which did recover and were ultimately marketed – so the farmer was able to sell at least some of them twice.

Toxins

Natural toxins, such as from red tides and brown tides occur as the result of blooms of various types of algae. A related phenomenon, in that it is caused by algal blooms, has been incidences of salmon mortalities in net pens associated with clogging of the gills and asphyxiation. If a toxin is detected that might be being pumped into a flow-through facility or one that is using partial recirculation, it may be possible to operate the system in the closed mode until the problem is no longer a threat to the fish. In open raceway systems and in cage and net pen facilities, it may not be possible to prevent exposure to toxins.

Another problem that is probably more widespread than algal toxins in natural environments in terms of causing disease problems is consumption of mouldy feed. *Aspergillis* sp. is a common mould that attacks feed. This and other moulds can produce toxins that will negatively affect fish performance and can lead to mortality. Proper storage of feed pellets is 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. 1.11, are exposed to sometimes dramatic temperature fluctuations temporarily, particularly during summer and winter in temperate climates, and the feed in bins is certainly exposed to high temperatures fairly consistently in the tropics. Low temperatures are not a problem, but heat certainly can be, in that some nutrients are heat labile. Storage of feed in bins or silos is not a significant problem since such bins are normally used only on large facilities where turnover is rapid. New supplies of feed are typically obtained every week or two at the most, so there is little opportunity for mould formation. Of course, the culturist should use up the old feed on hand before using feed from the newly delivered batch in order to reduce the amount of time the feed is stored on the farm.

Common Aquaculture Diseases

The following subsections provide brief descriptions of some of the more common aquaculture diseases. Information on the diseases of marine and estuarine species can be found in Couch and Fournie (1993). More focused are books on microbial diseases (viruses and bacteria) by Plumb (1999), and one that includes information on diseases of bivalve molluscs (Gosling, 2003). A variety of general aquaculture texts and those that are focused on particular species or species groups also contain information on diseases. Many of those books are listed in Table 1.2. The following subsections provide a brief overview of some common types of diseases with a few examples.

Viral diseases

Viral diseases have posed significant problems in aquaculture for a number of years. Disease syndromes that devastated trout and salmon for decades could not be treated with drugs and chemicals that were available at the time and frustrated fish pathologists who searched for ways to halt epizootics. The best approach was often associated with good management practices that included reduction or avoidance of stress. Once it became known that some of the untreatable diseases were caused by viruses, new approaches to prevent epizootics could be developed.

Viruses that went by the initials of the first letters of their common names, such as CCV for channel catfish virus, were discovered and studied in some detail. A number of viral diseases have been found in association with coldwater fish. They include IHVN in salmonids and VHS in trout. A virus called ISA appeared in Atlantic salmon being cultured in the northeastern Atlantic region in the 1990s. Outbreaks of significant proportion 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 Maine, USA. With no treatment available, the toll on cultured salmon was extremely high in some cases. Fish farmers blamed wild fish for transmitting the disease from Canada to Maine, while critics of salmon farming expressed concern 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 greatest extent possible and keep the farms fallow for 90 days after which restocking was allowed. The economic impact was reduced, but not eliminated, through provision of some buyout funds provided by the federal government.

In the marine and estuarine environments, lymphocystis, caused by an iridovirus, is commonly seen in both wild and cultured finfish. There have also been some incidents of lymphocystis in a few freshwater fish. 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 most of the body and fins. During the 1970s, when my colleagues and I 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 1% or 2% of the fish bodies – 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.

The shrimp culture industry worldwide suffered a devastating series of problems in the 1990s that were associated with a variety of viruses. 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, Ecuador and several other countries. Outbreaks of viruses such as Taura, whitespot and yellow head devastated the industry after it had become well established as a primary source of the commodity in international trade. Many farms were forced out of business, and production in those that survived was often greatly reduced. In China, where the industry was developed in the north using the coldwater shrimp species *Penaeus chinensis*, disease virtually wiped out the industry. Shrimp farming was re-established in southern China using warmwater species. The industry has recovered to the extent that it is now second only to Thailand in global aquacultured shrimp production and China may soon assume world leadership (George Chamberlain, personal communication, 2003). Implementation of best management practices, which include reducing stocking densities and developing specific pathogen-free hatchery stocks, 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. South Texas coastal shrimp farms suffered significant losses due to viruses in 2004, though farms further up the coast did not experience viral problems that year (Granvil Treece, personal communication 2004).

Protection of fish from viral diseases can be provided through the development of appropriate vaccines. During the 1980s, the first effective fish vaccines were developed against certain pathogenic organisms. To date, no vaccines appear to be available for shrimp viral diseases, due as mentioned above to the primitive immune system of those crustaceans. However, a number of viruses that are effective to one degree or another in treating fish viral diseases continues to grow (see Table 4.2).

Bacterial diseases

Bacterial diseases in fish are rather common and can be attributed to a wide variety of species of the microorganisms, many of which target a particular species or species group. For example, the gram-negative bacterium *Aeromonas salmonicida* targets salmonids, while *Edwardsiella ictaluri* attacks ictalurid catfish. Other bacteria are not so specific. There are a number of species within the bacterial genus *Vibrio*, for example, that attack a variety of aquatic organisms. Some of them, such as *V. vulnificaus* and *V. parahaemoliticus*, can cause pathology in humans as well, so they pose a public health threat.

Molluscs are particularly good at concentrating bacteria by filtering them from the water as a part of the normal feeding behaviour of the shellfish. In addition to vibrios, molluscs exposed to polluted water can concentrate the organisms associated with such problems as viral diseases including those associated with the 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. Humans who eat raw shellfish, in particular, can contract bacterial infections and especially in the case of people with compromised immune systems, may die as a result. While not widely recognized by fish culturists, the movement of pathogenic bacteria from one area to another in frozen processed fish has been recognized by some people as a possible means of transmission. Public health issues associated with shellfish, including biotoxins such as those that cause paralytic shellfish poisoning, amnesic shellfish poisoning and diarrhoeic shellfish poisoning, have been discussed by Gosling (2003).

Tilapia can typically resist diseases unless they are cold stressed. Once the water temperature falls to around 20°C or below, various diseases, including bacterial problems, can increase dramatically. However, as has been the case with other aquaculture species, as production increases the incidence of disease outbreaks seems to follow, so that currently tilapia diseases during warm weather appear to be on the increase. Plumb (1999) reported on a number of bacterial diseases that have been found in association with tilapia and indicated that *Streptococcus* has become a major problem in North America, South America, Asia and the Middle East.

Fungal diseases

The most common fungus found in association with freshwater aquaculture is *Saprolegnia* 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 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 which shines on each of them in turn. Opaque (dead) eggs do not allow the light to pass. These eggs are removed from the stream with a puff of air that blows them into a bucket. Translucent eggs pass along to a collection area and are returned to the hatching trays. For channel catfish eggs, which are laid as cohesive masses, dip treatments to control fungus are used.

A number of ulcerative diseases associated with fungi in the marine environment have been reported from various parts of the world. Among the fish of aquaculture interest that have been found with so-called water moulds are barramundi, mullet, walking catfish, snakehead and ayu. Estuarine species of aquaculture interest in North America that have been attacked by ulcer-causing fungi include southern flounder, striped bass and red drum (Couch and Fournie, 1993).

Protozoan parasites

A wide variety of protozoans have been found in association with aquaculture fish in fresh water. Examples of a couple that have already been mentioned are the ciliated protozoans *Ichthyophthirius multifiliis*, commonly known as 'Ich' or 'white spot disease,' and *Trichodina* spp. Another is *Costia* spp. Then there are the ever-present myxosporidian protozoans such as *Henneguya* sp. All of them pose problems with respect to warmwater fish. Some, 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*, attack the gills, while *Costia* can make itself at home on the body surface, gills or both. Dinoflagellate protozoans, such as *Amyloodinium* sp., 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 infested red drum in estuarine waters (Overstreet, 1993).

A killer of the American oyster 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 is now known 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 (reviewed by Perkins, 1993). Another disease of oysters is caused by the sporozoan parasite, *Haplosporidium nelsoni.* The common name for the disease, MSX, stands for Multinucleated Sphere Unknown (Sparks, 1993). Also first reported in the 1950s, MSX has been responsible for high levels of mortality in American oysters. The lack of good treatments for Dermo and MSX has led researchers to attempt developing disease-resistant oysters, though that effort has not been very successful to date.

A move is on to introduce an exotic oyster that is resistant to Dermo and MSX to Chesapeake Bay on the east coast of the USA from Asia, because of the demise of the oyster industry, particularly in the bay. Several states border the Chesapeake and there has been a political and scientific battle under way with respect to whether the exotic oyster should be introduced and what consequences there might be for native species other than American oysters. It appears virtually certain that at least one state will soon begin planting the exotic oyster, if it has not already done so by the time you read this.

Helminth parasites

Parasitic worms are internal parasites which may be found in the internal organs or flesh of fish and other organisms. In fresh water, helminths are represented by nematodes, trematodes and cestodes. Most nematodes (roundworms) are non-parasitic, but parasitic ones can often be found in the intestinal tracts of fish. The flatworms in the trematode and cestode groups are parasitic. In the marine environment, not only do the same three groups mentioned occur, but there are also parasitic acanothocephalans, turbellarians, nemerteans and leeches. Finfish are not the only group of species likely to be infected. Shrimp, crabs and lobsters are also susceptible (Stewart, 1993).

Helminth epizootics are usually not lethal in themselves, but they can lead to secondary infections, thereby increasing the chances for mortality. A successful parasite does not kill the host, it merely takes advantage of the opportunity to infest and feed on 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 may be mayfly larvae, which when eaten, pass along the parasite to the final host – the fish. Eliminating aquatic insects in ponds can also break the life cycle of certain parasites. Monogenetic trematodes have a simpler life cycle that involves only one host. Most monogenetic parasites are, as mentioned, 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. Others, however, can be found on the body and fins (e.g. *Gyrodactylus* sp.) or on the gills of fish (e.g. *Cleidodiscus* sp.).

Copepod parasites

Finally, there are a number of parasitic copepods that can be found in species being reared in aquaculture systems. Parasitic copepod problems appear to be most common in freshwater aquaculture, with fish being the most susceptible. Among the copepods that are found in fresh water are *Ergasilus* sp. and *Argulus* sp. Another parasitic copepod, *Lernaea cyprinacae*, often called the anchor parasite or anchorworm, has been a problem for various species with respect to freshwater fish. When the free-swimming parasite comes in contact with a fish, it attaches itself and its head becomes modified so that it is permanently embedded in the flesh of the host animal.

Argulus is known as the fish louse. While predominant in fresh water, Overstreet (1993) speculated that an estuarine species, *Argulus nobilis*, may also be parasitic. There is little doubt that marine copepods called sea lice have caused serious problems in Atlantic salmon culture. Other species of current or potential aquaculture importance attacked by sea lice are halibut, rainbow trout, Pacific salmon and Arctic charr. The species of sea lice that have caused problems for the salmon industry include *Caligus elongates*, which has global distribution, *Lepeophtheirus salmonis* in the northern hemisphere and *C. teres* in Chile. With the high concentrations of salmon in net pens, infestations can develop quickly and may become very severe. Critics of salmon aquaculture believe that sea lice incidence in wild fish increases near net pens due to the high abundance of the copepod on the cultured fish and in the water. Treatment involves the use of organophosphates or pyrethroids.

The Cooperative Extension programme at the University of Maine (www.Umaine.edu/livestock/publications/sea_lice_bullets.htm) has put together information on the life cycle and other characteristics of sea lice. Their recommendations for managing the problem include the following:

- Stock only a single year class of fish at a time. Apparently, infestations occur very quickly when two or more year classes are stocked.
- Allow the site to lie fallow for a period of 30 days or more before stocking an additional year class.
- Treat all the net pens on a facility at the same time, as the problem will spread from one net pen to another.
- Coordinate treatment among facilities in bays where two or more operations are located.
- Use wrasses when possible to help control the copepods.
- Maintain a reduced stress level on the fish.
- Employ integrated pest management techniques.

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5

The Basics of Reproduction and Early Rearing

How Aquaculture Animals Reproduce

Aquatic animals of aquaculture interest and importance reproduce sexually. In nearly all the species currently being cultured, the sexes are separate and once sex has been established, it remains constant for life. The last part of that sentence may seem strange and requires further elaboration. Initially, the sex of some aquatic species is not differentiated in the early life stages. This 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 later in this chapter under the topic of sex control.

There are a number of families of fish 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 type first and the other type 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 being looked at as candidates for aquaculture. Included are the families Sparidae (porgies) and Serranidae (sea bass).

Now that we have established that species of animals currently being cultured have separate sexes, we can look at the various ways in which reproduction actually takes place. Reproductive strategies in aquaculture species vary considerably. Some, in fact most, species of fish produce very small eggs, and may produce millions of them each year. This is particularly true of marine fish, the eggs of which may be only a few hundred microns to a millimetre or so in diameter. A few produce relatively large eggs, which may be a few millimetres in diameter. Species with large eggs may spawn only a few hundred to several thousand eggs. As a rule, species that produce large numbers of eggs broadcast their eggs and milt into the water column. They may spawn once per year or they may be multiple spawners. In either case, they do not provide parental care to the fertilized eggs or later life stages. Fish species that produce large eggs often prepare a spawning site and may guard the eggs and even protect the larvae for a period of time. They, too, may spawn once annually, or in the case of Pacific salmon, once in their lives. They may also be multiple spawners.

Turning 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. Examples of each of the strategies mentioned with respect to fish and invertebrates are presented in more detail later in this chapter.

Closing the Life Cycle

One of the most critical goals of the aquaculturist who is working with a new species is to maintain the entire life cycle of the organism in captivity. A major step in that process is to be able to initiate and have control over reproduction. Before the culturist has developed the ability to reproduce the animals in captivity, he or she may be forced to collect postlarvae or juveniles from the wild for stocking. This is still being done in some instances where the life cycle has actually been closed. Some marine shrimp farms, at least in Latin America, stock their ponds by filling them on incoming tides when postlarval shrimp are abundant, even though captive spawning is widely practised. Certainly, the cost of stocking wild postlarvae is attractive, since it is basically free, but the incoming water will also contain predators which may consume a large number of the shrimp before they reach market size. Milkfish fry or small fingerlings are still being collected in parts of Southeast Asia and sold to aquaculturists. Again, milkfish can be reproduced in captivity, but it is less expensive to purchase wild caught fish than to get them from a hatchery. In the case of shrimp, reductions in shrimp harvest from the capture fishery due to the taking of postlarvae for aquaculture have been reported. This may or may not also have been the case with milkfish, though it does not appear to be well documented.

Once the life cycle is closed in captivity, it is possible to begin selective breeding programmes and perhaps some genetic manipulations which, over time, will produce animals that are not only 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.

Trial and error is one way in which the culturist can work out how to spawn and rear the young of a species for which the life cycle has not been controlled. Another way is to study the literature that may exist on the life history of the species, and if there is insufficient information available in the literature, to make field observations. The struggle to close the life cycle of the freshwater shrimp, *Macrobrachium rosenbergii* (commonly called the giant Malaysian shrimp or prawn[1]), is illustrative, so I am relating it here rather than saving it for another section of this chapter. The story was presented in more detail by Stickney (1996).

During the 1950s, a scientist by the name of S.-W. Ling was working in Southeast Asia under the auspices of the FAO, which you may recall is the Food and Agriculture Organization of the United Nations. Ling became interested in freshwater shrimp as a potential aquaculture species. He took a number of freshwater shrimp into the laboratory and soon found that they would readily spawn in captivity. After fertilization and extrusion from the gonad of the female, the eggs are carried on her abdomen during incubation. This protects the developing embryos from predators.

Once the eggs hatched they would live for a few days and then die. Ling quickly figured out that some environmental variable was missing or that 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 in watch glasses filled with fresh water and added various chemicals that were on hand in his laboratory to individual watch glasses to see if any of those compounds would promote larval survival.

Alas, as they say, nothing worked. One day, after experiencing another in a long series of frustrations when his latest groups of larvae were dying, he turned to his lunch, which his wife had prepared for him. Ling, being Chinese, had been provided soy sauce with his lunch. On a whim, he poured a bit of 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 supplies of soy sauce prior to spawning their animals? And, where would freshwater shrimp find soy sauce in nature?

Of course, the answers had nothing to do with the fact that it was soy sauce, but had everything to do with one of the ingredients in soy sauce – common salt, sodium chloride. Now we can speculate that it is surprising that Ling did not have some salt 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 the 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, I do not know. But we now know that the adults spawn in fresh water, but that the females migrate to the estuaries, seeking a salinity of around 12 ppt where the eggs complete development and hatch. As the larvae go through the various stages in their development and ultimately moult into postlarval shrimp, they can tolerate lower and lower salinities until they can survive in fresh water.

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[1] Many aquaculturists refer to freshwater shrimp simply as prawns. However, the term prawn refers to any large shrimp, whether freshwater or marine. To avoid confusion I prefer to distinguish between the two simply by calling them either freshwater shrimp or marine shrimp.

In order not to repeat Ling's saga, and with a great deal more natural history information being available today than it was 50 years or so ago, it behoves the modern aquaculturist who is trying to close a life cycle to consult the literature as previously mentioned.

Reproduction in captivity may be a very simple matter of allowing nature to take its course. That might involve putting broodstock in a pond and allowing them to spawn naturally when environmental conditions are such that gonad development and the release of gametes occurs without any human intervention. On the other hand, there are various amounts of human intervention that may be called for. Included are such things as manipulation of environmental conditions – most commonly adjusting temperature and photoperiod – or induction of gonadal development through hormone injections.

Identifying the Sexes

For some species, sex identification is relatively easy, particularly when the fish are approaching spawning condition. Males will often develop bright colours during the spawning season, which is thought to be a means of attracting females. Male Pacific salmon will grow an extended upper jaw, called a kipe, when they are approaching 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 the petasma, which is an organ located on the first pair of the male's pleopods. Freshwater shrimp males have larger chelae than the females and develop more colour. Behavioural differences may also occur, as with nest-building tilapia. For the tilapia species of aquaculture interest, the nests are constructed and defended by the males (Fig. 5.1).

Following spawning, it is very easy to identify the females of at least some species. As previously indicated, female freshwater shrimp carry their eggs on their abdomen. The same is true of spiny lobsters and crabs (when carrying eggs, the latter are called sponge crabs). Many species of tilapia are mouthbrooders and in case of aquacultured species mouthbrooding is the job of the female. The male will be back guarding the nest and trying to attract another female.

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

Fig. 5.1. A drained tilapia spawning pond showing nests that were constructed by males.

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 eggs (Galtsoff, 1964). The sperm slurry is mixed with the eggs to provide fertilization. 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 at the same time 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. It should be pointed out that hormone injections and so forth will not work if the animals are not physiologically approaching full ripeness. Hormones can serve as a trigger, but gonadal development is generally triggered by environmental cues and only the final release of gametes can be induced by hormones.

As mentioned above, temperature and photoperiod tend to be controlling factors, though in some cases the phase of the moon is also an important factor, with spawning in various species occurring at night during the full moon. Most aquaculture species have a particular time of year when spawning occurs. That is often in the spring or autumn when water temperature is rising or falling and when day length is getting longer or shorter. Once again, knowing what the environmental conditions are in nature when a particular species spawns will help the culturist recreate those conditions in the laboratory and should help reduce the amount of trial and error required to get things right.

It is not always necessary to control photoperiod as well as temperature to induce gonadal development. 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 will spawn about once a month. In the tropics they have been known to spawn at least eight times in a year. While channel catfish females spawn only once a year, the period over which they spawn begins in March or April at the southern end of the species' range (southern USA) and may extend into August, even at the southern end of the range, with different females spawning at different times over that several-month spawning period. Male catfish are able to fertilize multiple batches of eggs, though I have not seen information on whether the same male can participate in spawning through the entire protracted spawning period. It is possible to put channel catfish through an artificial winter and induce gonadal development. I did that once several years ago. However, the way in which the industry is configured does not provide any significant advantage with respect to off-season spawning of that particular fish, so natural spawning seems to be exclusively relied upon.

Stickney (1994) provided information on species that have been spawned using temperature and photoperiod manipulation. Included are American lobster, ayu, southern flounder, gilthead sea bream, milkfish, some species of rabbitfish, red drum and turbot. Oysters can be induced to spawn with temperature shock. As noted earlier in this book, marine shrimp can be induced to spawn by maintaining the proper temperature and extremely low light levels.

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. This has been demonstrated convincingly with red drum, which were first spawned in captivity by Arnold *et al.* (1977) and are currently being produced in commercial hatcheries in the USA and parts of Asia, most notably China, as well as by the tens of millions annually for enhancement stocking by public hatcheries operated by the Texas Parks and Wildlife Department in the USA. Adult broodstock are collected from nature in the case of enhancement programmes and are replaced periodically so as to maintain the genetic diversity of the population. In the case of commercial culture, the initial broodstock were collected from nature, but second generation and beyond broodfish are now being employed as selective breeding programmes become established.

The first step in preparing red drum for spawning is to take the fish through a brief annual cycle that ultimately will get them into temperature and photoperiod conditions that mimic those that are present during the spawning season. The fish may be exposed to temperatures and photoperiods to simulate winter, with that simulated season being truncated into no more than a few weeks. Similarly, spring, summer and autumn conditions are simulated sequentially. When autumn conditions are in place, manipulation is stopped and the temperature and photoperiod are held constant. If the process is done properly, the fish will begin spawning. Each female may spawn every few days for up to several months, even a year. As prolonged spawning is stressful and can lead to death, it is more common to spawn the fish several times over a period of weeks, then recycle them again. The enhancement programme produces fish most of the year, while commercial hatcheries will produce only the number needed to meet their stocking needs and to fill any orders from other producers.

The use of hormones for controlling spawning has been around for at least several decades. The first hormone to be developed was carp pituitary. The pituitary gland from common carp was removed, desiccated in acetone, ground into a powder, dissolved in sterile water, and injected into a gravid female fish to induce spawning in a variety of fish species. Carp pituitary and pituitary hormone from other species are still used today, though various other hormone sources are available. Two common ones are pregnant mare serum (PMS) and human chorionic gonadotropin (HCG), which is obtained from the urine of pregnant women. Others are luteinizing hormone-releasing hormone (LHRH), gonadotropin-releasing hormone (GnRH) and follicle-stimulating hormone (FSH).[2] The hormones can be purchased from drug and chemical supply companies. Various hormones mentioned have been used to induce ovulation in various carp species, including some of the Indian carps, milkfish, channel catfish and walking catfish, seabass, mullet, striped bass and hybrid striped bass, Atlantic salmon, red drum, rabbitfish, and gilthead sea bream, among various others (summarized by Stickney, 1994).

Examples of Spawning Methods

A few methods associated with spawning have been described and in this section the purpose is to build upon the examples already provided. In the subsections below, some reiteration, with embellishment of information on species previously mentioned, is included along with information on species for which no previous information on spawning needs and methods has been provided in the preceding pages. The discussion is limited to commercial foodfish species and is not meant to be comprehensive, because that would involve over 100 species and a great deal of repetition since the same approaches often apply quite broadly.

Builders and burrowers

A number of species construct nests, find existing depressions or structures in which to find concealment during spawning, or burrow into the sediments during

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[2] You will not see the abbreviations for the mentioned hormones again in the text of this book, but I put them in so you will recognize them if you run across them in other publications.

some part of the reproductive cycle. The following examples are illustrative and include some information on rearing the early stages of the animals discussed. By early stages I mean larval, postlarval and fry rearing – whichever term is appropriate. Some explanation of what I mean by the various stages might be illustrative.

For many species, when the eggs hatch, the animal that emerges is still in a relatively early stage of development. Often, the mouth and digestive system have not formed, and in the case of many fish, the fins will not be fully developed. These primitive life forms, which become members of the zooplankton community, are referred to as larvae. They show little resemblance to the adults as is clear from Fig. 5.2, which is a photo of an Atlantic halibut larva.

Larval finfish 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. I have often compared them with eyelashes, except they are shorter than the typical eyelash in that in many species the larvae are no more than a few millimetres in length. During the stage when finfish are reliant on the yolk in the yolk sac for food energy, they are called sac fry.

Some fish – tilapia, trout and salmon being examples – are similar in appearance to the adults when they hatch, the major difference being that they are born with a large yolk sac, which appears as an enlargement of the abdomen (Fig. 5.3) which gets smaller and smaller as the yolk is metabolized. Once the yolk is absorbed, sac fry are called fry. 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. Young salmon are an exception to the terminology that is used in conjunction with other

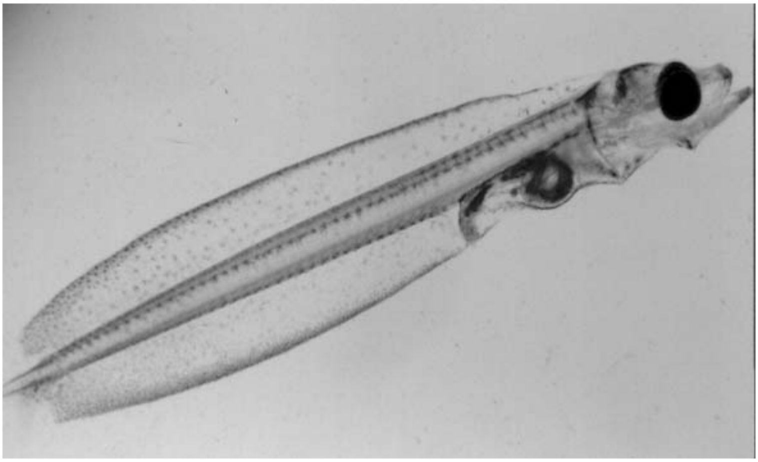

Fig. 5.2. A larval Atlantic halibut. Note that its mouth has formed but the fins are not developed. There is one eye on each side of the head, unlike postlarval halibut. [Photograph courtesy of Michael Rust.]

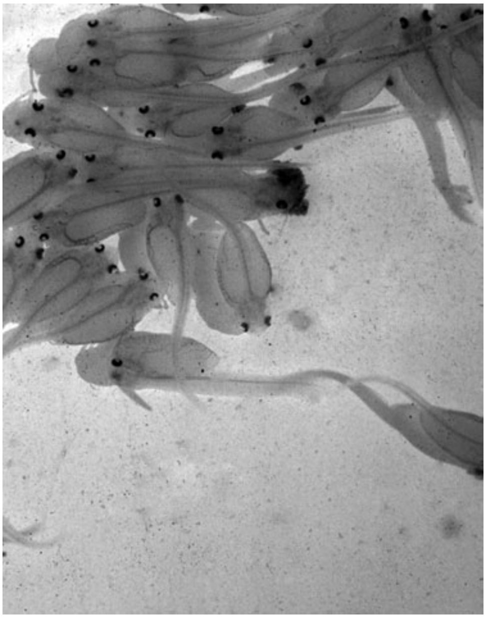

Fig. 5.3. Channel catfish sac fry.

species, since after the sac fry stage they are called alevins. Fingerlings in the freshwater phase of the life cycle are called parr, and they become smolts when they migrate to salt water.

Invertebrates often have a considerable number of larval stages that they go through. Once the animals take on the appearance of the adult in terms of basic shape and structure, they are called postlarvae.

Tilapia

Male tilapia are nest builders (Fig. 5.1). In very soft sediments they will actually dig quite deep nests, and when stocked heavily in ponds, many of the nests may actually have common walls. The males defend their nests so they do not swim around the pond during the spawning season, which may actually be virtually year round in the tropics. Females are courted by the males until a selection is made. Once a pair has formed, the eggs, which are a few millimetres in diameter, are expelled from the female and fertilized by the male as they fall into the nest. The female picks up the 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 they can dig to construct a nest. While some species of tilapia can be reared in salt water (the salinity tolerance varies among species), spawning is conducted in fresh water.

While somewhat variable depending on temperature, the eggs will hatch within about 5 days on average. There is an additional 5 or so days during which the sac fry remain in the mouth of the female during yolk absorption. 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 there is a period of two weeks or more during which the female does not feed and she spawns about every 30 days under the proper conditions, so there is little time to make up for the lack of growth that occurred during egg and sac fry incubation. The males, on the other hand, continue to eat normally during the spawning season. Also note that tilapia, depending upon species, will first spawn in as little as 3 months after hatching, so there is a good chance that at least two, and possibly three generations could be spawning within the same year in the same pond. Because they mature so young, adult tilapia females may not reach marketable size within a growing season.[3] The result can be overcrowding and stunting of the pond population. That problem has led, as we will see in the sex control section of this chapter, to the desire on the part of tilapia foodfish producers to stock all-male populations.

Tilapia eggs and fry can be incubated outside of the mouth of the female in much the same way the eggs of many other species are incubated. By capturing, opening the mouth and gently shaking the female, she will drop her eggs or fry, which can then be put in an appropriate incubation unit; typically some type of hatching jar or modification thereof, such as a clear plastic tube. Hatching jars should be provided with frequent replacements of water or slow flow-through and also receive aeration to maintain an appropriate dissolved oxygen level.

Strip spawners

Many species of finfish are spawned by stripping. This 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. For most species, modest pressure on the abdomen near the vent will cause milt or a small number of eggs to be expressed. When that happens, the culturist can apply greater pressure to the abdomen from the sides, beginning at the anterior belly and moving toward the vent. The eggs can be expressed into a bucket with or without water, after which milt is added using the same stripping method. If the bucket 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, a feather has been used to mix the gametes, though that approach is not widely employed today. Hand mixing works just as well. In the dry method, water is added after the eggs are fertilized. The eggs may then be washed to remove the milt after which they are placed in an appropriate incubator such as hatching jars or Heath trays (see Figs 1.2, 4.11 and 5.4). An alternative to hatching jars and other

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[3] I say they may not reach marketable size because in some cultures, small tilapia of 10 cm or so in length can be sold into the marketplace. I have seen tilapia and other fish of that size, and often smaller, in fish markets in the Philippines, for example.

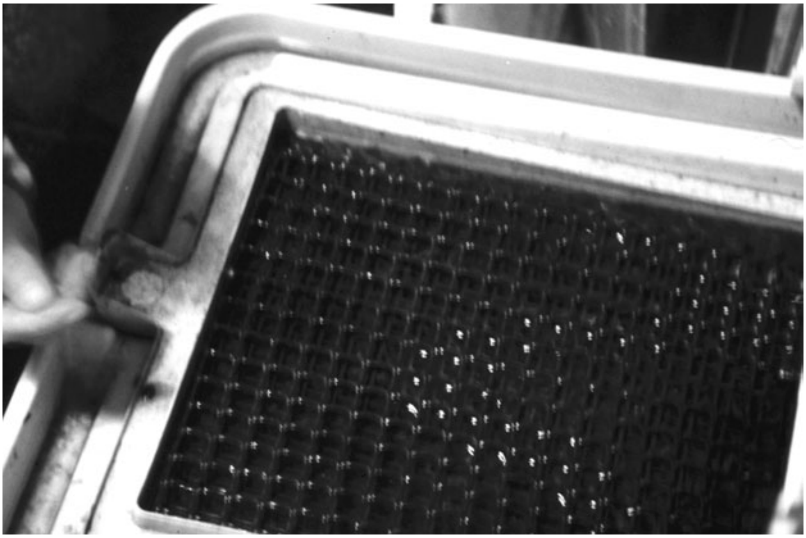

Fig. 5.4. Close-up view of a Heath tray removed from the stack. The screen on the bottom should be of the proper size to retain the eggs but let the sac fry drop through into the bottom of the tray after the eggs hatch.

types of incubators is to hatch the eggs in a larger chamber such as a circular tank. Frequently, such tanks have conical bottoms. It should be noted that some species are amenable to either stripping or tank spawning (described later in this chapter). Striped bass and hybrid striped bass are an example.

Hormone injections may be used to help induce ovulation and, in some cases, may also be used to promote spermiation, though the injections need to be made at the proper time: that is, when the fish are nearly ripe. Injecting them at other times will not be effective.

For most species, there is a fairly large window of opportunity for the culturist to strip the fish once they are spermiating and ovulating (a condition known as running ripe). This window of opportunity may be up to several hours. 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. As described by Kirby (1993), females that are to be induced to spawn are injected with 275–330 IU of HCG per kilogram of body weight in the musculature. Males may also be injected at a lesser dose (110–164 IU/kg) of the same hormone.

To determine how the eggs are developing, samples of a few eggs can be collected with a 3 mm outer diameter glass or plastic catheter that is inserted through the vent and into the ovary. The eggs are examined under the 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). Knowing the stage, the culturist will have some idea as to how many hours the eggs are from being ovulated. The process of egg collection may be repeated as the apparent time of ovulation approaches. To make sure the eggs are obtained in good condition, the culturist needs to be there at the time of ovulation to strip the females. Pressure on the abdomen will cause premature ovulation and loss of the eggs, so extrusion of eggs with pressure is not done until the eggs have been released from the ovary.

Examples of species that are routinely striped to obtain eggs and milt, in addition to striped bass and hybrid striped bass, are common carp, Atlantic and Pacific halibut, rainbow trout and Atlantic salmon. Pacific salmon are a special case and are described in the next subsection. Once the eggs hatch, they will be removed from the incubators and may be stocked into fertilized ponds or, as is now common, stocked into nursery tanks or raceways before being stocked in ponds, growout raceways and tanks, cages or net pens.

Atlantic and Pacific halibut are an excellent example 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 those eggs are usually hatched in tanks of static water. Hatching requires about 1 month because the metabolic rate is very low in the cold water used during hatching (typically around 6°C). During hatching and larval development the fish are maintained under virtually static conditions. If eggs bump into one another or hit the tank walls during development, they will die. The larvae have very poor swimming ability and will also die if they contact each other or the tank walls. The larvae do not begin feeding for nearly a month after hatching, but live off their oil droplet. Metamorphosis does not occur until 3 or 4 months after hatching (Fig. 5.5). 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.

Pacific salmon

Pacific salmon could be stripped like their trout cousins and Atlantic salmon. However, since all Pacific salmon die after spawning, the technique with females is to open the abdominal cavity with a knife and to pull out the ovaries (known as skeins). The skeins are opened and the eggs are poured into a bucket where milt is added from stripped males. In US government hatcheries where the objective is to produce smolts for release and eventual recruitment into capture and recreational fisheries, the milt from three males is used in conjunction with each batch of eggs in order to help maintain genetic diversity. Hatching of Pacific salmon follows the same methods as are used for trout and Atlantic salmon: that is, hatching is usually done in Heath trays. Rearing of swim-up fry and fingerlings to the smolt stage occurs in raceways.

Channel catfish

The description of catfish spawning and early life history that is presented here can be used for blue and white catfish equally, since both those species have virtually identical life cycles, differing primarily in the ultimate size that can be attained by adult fish. While there was considerable interest back in the 1960s and early 1970s in commercially culturing blue and white catfish, and possibly even hybrids among these species and channel catfish, that interest

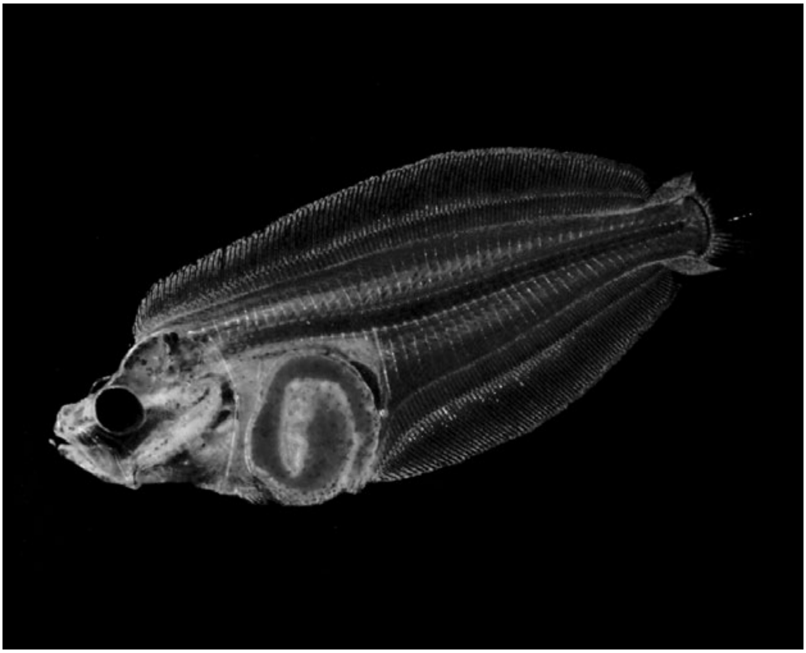

Fig. 5.5. A metamorphosing Atlantic halibut larva. Note that the body shape is similar to the adult but eye migration is not complete. [Photo courtesy of Michael Rust.]

declined when it became apparent the channel catfish was the most amenable species to culture.

Channel catfish mature in their second or third year of life. Farmers tend to use adults that are only a few years old and weigh only a few kilograms as they are relatively easy to handle. The spawning season occurs, you may recall, in spring and early summer when the water temperature is in the range of 21–29°C.

In nature, channel catfish prefer to live in rivers, though they are now found in reservoirs as well as natural lakes where they have been stocked, as well as in myriad farm ponds and aquaculture facilities around the USA. Early interest in stocking channel catfish outside North America seems to have waned. In its natural environment, the male catfish will find a depression in a stream bank, a hollow log or some other hiding place and will establish a nesting site. Males do not construct nests but will clean up debris from the nesting area.

Early attempts to spawn channel catfish in hatcheries failed for a period of time until one of the early hatcherymen discovered the fact that the male needed a hiding 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.

Channel catfish broodstock can be stocked in open ponds and allowed to select their own mates. Usually, two females are stocked for each male. The fish may be stocked at a few hundred per hectare. Spawning nests are distributed around the sides of the pond in about a metre of water with the openings facing the middle of the pond. If the culturist wishes to selectively breed the fish, they can be stocked as pairs in pens, each of which should be equipped with a spawning nest (Fig. 5.6).

The male catfish will remove any debris from the nest and entice a female into the container. The eggs are laid in a gelatinous mass that may contain several thousand eggs, each a few millimetres in diameter. The eggs are laid in batches that are immediately fertilized. Once the process is complete, the male chases the female from the nest as she would disrupt or eat the egg mass if allowed to remain. To help accomplish that task, it is wise to stock larger males than females.

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. They will hatch into sac fry a week or so 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 may be

Fig. 5.6. A row of catfish spawning pens along the side of a pond. Alternatively, pens can be constructed in the middle of the pond as well.

redistributed to other ponds at reduced densities. The broodfish can be seined from the pond after the spawning season and placed in a holding 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 have abundant food in the form of plankton as described in the previous chapter.

Prepared feed is broadcast over the pond surface a few times daily after fry are observed swimming at or near the water surface. The feed is finely ground so the fry can easily swallow the particles. As the fry grow, larger particles (crumbles) are fed.

When pen spawning is used, and in many instances where the open pond method is employed, the nests are checked for eggs at intervals of 3 to 4 days. When an egg mass is found it is collected and moved into the hatchery. It is not necessary to check the cans daily since at least 5 days are required 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 nest, that activity may be disrupted and a complete spawn may not be obtained.

To check a nest it is common practice to slowly lift it to the surface, pour out some of the water and visually inspect for an egg mass. Some nests are designed with removable tops. If placed in fairly shallow water, visual inspection is simplified. The lid can be removed and the eggs collected without having to move the nest. 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. It is best to pour the male out of the nest before placing a hand inside to check for eggs. If the inspection is from the top of the nest, the male can be coaxed out from above.

Since the eggs will stick to the nest floor and some eggs can be damaged or destroyed when being scraped from the nest, many culturists place a piece of roofing material (tar paper) in the nest to make egg collection easier. The eggs are collected by merely removing the roofing material to which they are attached. Another piece of roofing material can then be placed in the nest and it is ready for another batch of eggs. The egg mass should be placed in a pail of water for transport to the hatchery.

The traditional way that channel catfish eggs are hatched is in a hatching trough (raceway). The egg masses may be broken up into two or more pieces to provide better exposure of all the eggs to oxygenated water and placed in hardware cloth baskets that are suspended in the trough (Fig. 5.7). Paddles attached to an axle running down the middle of each hatching trough are slowly turned, using an electric motor to move the water through the egg masses, an action that mimics the fin fanning action of the male catfish. A slow rate of water exchange is used in such hatcheries. An alternative is to do away with the paddles and just increase water flow through the trough. In the latter case short troughs should be used, as oxygen will be depleted as the water passes from one end to the other if the trough is too long.

When the eggs hatch, the sac fry will pass through the openings in the hardware cloth and fall to the bottom of the hatching trough, where they

Fig. 5.7. A channel catfish hatchery with hatching troughs full of baskets of incubating eggs.

remain during yolk sac absorption. Once the yolk is depleted, the fry, now black in colour, swim to the water surface in search of food (Fig. 5.8). At that time they may either be stocked in a fertilized pond or provided with finely ground prepared feed for a period of several days or longer in the hatchery to get them established on prepared feed before being stocked into ponds, tanks or raceways.

Crawfish

The culture of crawfish[4] is basically associated with pond management. The species of interest in the USA are the red swamp and white river crawfish. The highest levels of production occur in Louisiana, Texas and South Carolina. Crawfish culture has expanded in Southeast Asia in recent years to the degree that processed tails are no longer being produced in Louisiana (Terrance Tiersch, personal communication, 2003), though there continues to be a good market for live crawfish in that state.

Reviews on the culture of crawfish have been produced by, among others, de la Bretonne (1988) and de la Bretonne and Romaire (1989). The brief description of the procedures used by crawfish farmers that follows is drawn from these publications.

Broodstock are placed in the ponds during the spring. A few weeks after stocking, the ponds are drained. This causes the adults to burrow into the sediments where reproduction takes place. The mating process involves the male

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[4] The term crawfish is used primarily in the southern US, and in particular in Louisiana, in preference to crayfish, which is the term used in most of the USA and in other countries.

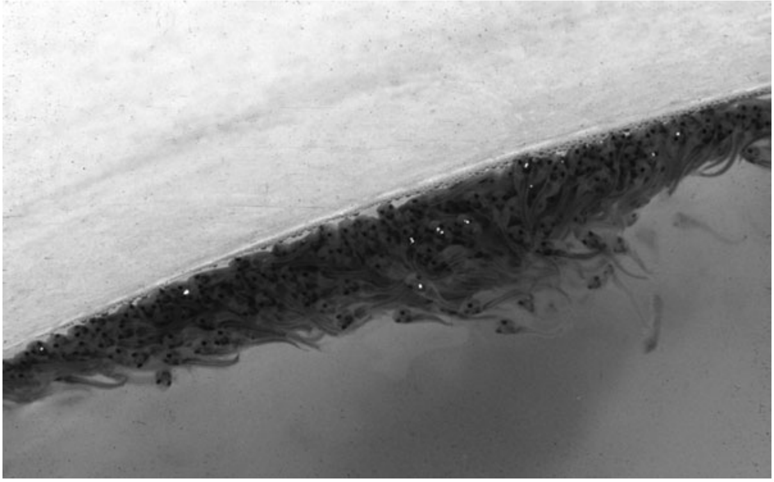

Fig. 5.8. Channel catfish fry swimming at the water surface in search of food.

depositing sperm into a receptacle organ on the female. The sperm remains there until September, when the eggs are actually fertilized and extruded from the female to become attached to her swimmerets. The eggs will hatch within about 2–4 weeks.

During the summer, while the crawfish are in their burrows, the culturist will typically plant forage in the pond. Included are such plants as rice, smartweed, water primrose and alligatorweed. During the early autumn (October–November) the ponds are flooded. This activity coincides with the time of crawfish egg hatching. The crawfish are harvested from November to May or June using baited traps (Figs 5.9 and 5.10).

Tank spawners

Many species are routinely spawned in tanks from which the eggs are collected and moved to a hatchery. A few examples that demonstrate some of the various methods that have been developed are described in the following subsections.

Red drum

The steps taken to get red drum broodstock in spawning condition were described earlier in this chapter (see the section entitled ‘Controlling Spawning’). Red drum broodstock are maintained indoors in rooms without windows so that photoperiod can be adjusted using artificial light. The broodfish are usually held in circular tanks with solid tops on them. The tanks are usually fitted with one or two windows in the side to allow observers to view the fish. The solid tops keep activity by humans from startling the fish. Each

Fig. 5.9. One of many crawfish trap designs.

tank is fitted with a light that is used to control photoperiod in that particular tank. This allows the culturist to have broodfish in various stages of development simultaneously. The water supplies to the tanks are temperature controlled. Red drum spawn in the autumn when the temperature is cooling and photoperiod is getting shorter, so those are the conditions that are maintained once the fish have been put through an abbreviated annual light and temperature regimen.

Fig. 5.10. A crawfish pond with several traps visible.

Each brood tank is stocked with a small number of fish. Two males and four females in a 2–3 m diameter tank is probably typical. Each tank is equipped with an egg collection box attached to the outside. When the fish spawn, the fertilized eggs will be carried out of the tank with the effluent and captured in the egg collection box in a fine mesh bag. The collection boxes are inspected every morning and when eggs are found they are moved to hatchery tanks where they will hatch within 2–3 days following fertilization.

Prior to the time the first spawns are to be obtained, 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 inorganic fertilizer. Soon after the eggs hatch the larvae are stocked in ponds, though they can be reared in the hatchery for an extended period if provided first with live feed (see 'Providing Live Feed' below) and then being weaned to prepared feeds. By stocking them as larvae, the culturist can avoid having to maintain live food cultures. This is unusual and rather unique to red drum culture, as you will see in the following examples where a protracted period of time in the hatchery is standard practice.

Red drum culturists have found that stocking larvae in ponds will typically yield at least 25% survival, which is quite high for any marine/estuarine species with very small eggs and larvae. Much higher yields are often seen, and interestingly, there may be one pond on a facility that consistently outperforms the others. To date, no explanation for that phenomenon has been found in terms of differences in water quality, nature of the plankton bloom or 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. This 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 identical methods. The difference in production in red drum ponds does not seem to be attributable to the skills of one culturist over another as all ponds are usually managed in the same way by the same people and individual ponds are not typically assigned to specific individuals.

For enhancement, the fingerlings are harvested after about a month when they have exhausted or nearly exhausted the natural food supply (some prepared feed may also be provided). At that time they are about 3 cm long. When used in conjunction with enhancement programmes, they are stocked in nature to supplement natural populations. The Parks and Wildlife Department in Texas produces and stocks somewhere in the neighbourhood of 30 to 40 million fingerlings a year to augment the sport fishery. The department is currently examining whether they might obtain higher survival rates after release if they keep the fish in the hatchery longer, which will mean employing more prepared feed, but if post-stocking survival can be increased, it may be possible to stock fewer fish to achieve the goals of the programme.

Commercial red drum farmers may keep the young fish in the hatchery until they are well established on prepared feed before stocking them in ponds, or they could use the method previously described. The fish may be initially stocked at high density since their total biomass is low and can be captured after a period of time, 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 catfish and 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 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 the striped bass and the white bass as these fish perform better than pure striped bass under culture conditions. Both types of crosses are made; that is, the male can be from either species and the female from the other species. Which cross is used seems to be based on the preference of the culturist as neither appears to have a distinct advantage over the other.

Fertilized eggs are often incubated in hatching jars. The larvae can be maintained in tanks within the hatchery and provided live zooplankton after yolk sac absorption. A critical period in the life of striped bass and hybrid striped bass is the time when the swim bladder is supposed to inflate, as previously mentioned. Improper inflation leads to heavy mortality in the fry. Again, that issue has been reviewed by Kirby (1993). After swim bladder inflation and establishment of the young fish on prepared feeds has been achieved, they can be stocked into rearing ponds.

Halibut

Adult Atlantic and Pacific halibut are extremely strong animals that have been known to virtually destroy small boats when landed by anglers. Adult females have been known to reach 200 kg or more. Yet, as has been described, the eggs and larvae of halibut are extremely fragile and the period from egg laying to metamorphosis is protracted.

Both male and female halibut can be stripped of their gametes. Temperature and photoperiod control can be employed in the laboratory to help promote development of the adults with respect to bringing them into spawning condition. In Norway, females exceeding 100 kg and even approaching 200 kg have been used as broodstock. Male halibut of both species grow to much smaller sizes than females. In the research my students and I were involved with, in our attempts to spawn and rear the larvae of Pacific halibut, we used much smaller adults – usually no more than 15 kg in weight. We found that all the Pacific halibut we worked with that were in excess of 1 m in length were females. Since 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 fish smaller than 1 m in length on the assumption that at least some of them were adult males, which turned out to be the case.

Spawning in nature occurs during the winter and it is during that season the culturists conduct their spawning activities. Maintaining developing eggs in low-light conditions in static water and providing a salinity gradient in the hatchery tanks so the eggs can be suspended at the salinity of neutral buoyancy were important during the egg hatching and early larval stages. Under such conditions, bacteria tend to build up in the hatchery tanks, so antibiotics have been used and other techniques have been developed (Grotmol and Totland, 2000) to keep these organisms under control, as they will lead to heavy mortality in the developing halibut. More detailed information can be found in publications by Skiftesvik *et al.* (1990), Liu *et al.* (1993) and Stickney and Liu (1993).

After the approximately 2-month period from egg fertilization until full yolk absorption, the larvae must be provided with food of the proper, very small size. First-feeding halibut, like many other marine fish with very small larvae, require zooplankton that are considerably smaller than the tiny fish themselves. Rotifers are commonly used as a first live food for first-feeding marine fish. The relative sizes of larval halibut and the rotifers being fed can be seen in Fig. 5.11. Once the halibut larvae become large enough they can be converted to other types of zooplankton, such as brine shrimp nauplii (*Artemia* sp.) or wild zooplankton that is sieved to the proper size. Weaning to prepared feed is also possible. In conjunction with halibut, as with other species that go through a weaning process, live food continues to be offered when the prepared feed is first introduced. The amount of live food relative to the prepared diet is reduced over time as the animals adapt to the formulated feed.

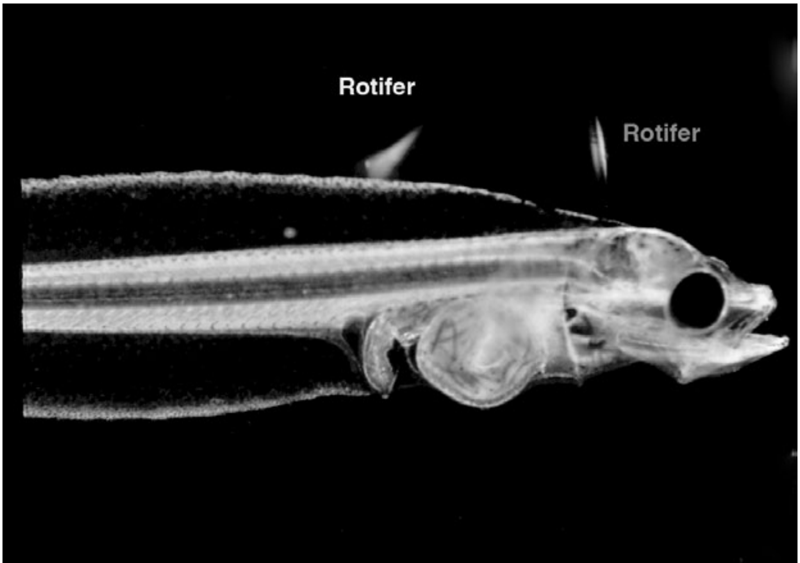

Fig. 5.11. A larval halibut and the rotifer used as first food. The blurred items near the words 'Rotifer' are live rotifers in motion. (Photo courtesy of Michael Rust.)

Marine shrimp

The practice of ablating one or both eyestalks of adult female marine shrimp to induce spawning was described in the ‘Light’ subsection of the previous chapter. Another similar technique is known as enucleation, wherein an incision is made in the eye and the fluid is evacuated. This technique will produce the same result as ablation. As you may recall, the hormones involved with reproduction are located at the base of the eyestalk in marine shrimp. 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 actually does is stop the production of a hormone that inhibits maturation of the 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 and gonadal maturation can occur. There is no similar problem associated with male marine shrimp, so they are not ablated or enucleated.

While the results of research have been somewhat mixed, photoperiod appears to have minimal influence on maturation in marine shrimp. A study conducted by Hoang *et al.* (2002) led to the conclusion that temperature and light intensity were more important factors than photoperiod with respect to maturation in banana shrimp.

The female marine shrimp may carry the spermatophore for some period of time after which the sperm are released to fertilize the eggs, which are broadcast into the water. A single female may produce in the order of a million eggs. The eggs are hatched under conditions previously described for marine fish eggs: that is, tanks (usually with conical bottoms) that feature a very slow water exchange rate. The larvae go through a number of stages before developing into postlarvae. Live feed, usually in the form of brine shrimp nauplii, is offered during the larval development period. The green water technique is often used in shrimp hatcheries. Recall that the green water technique 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 a number of zoeal stages they go through several mysis stages before becoming postlarvae. Weaning to prepared feed is as described above.

Freshwater shrimp

The most recent detailed information on the culture of freshwater shrimp is a book by New and Wagner (2000). Freshwater shrimp culture is overwhelmingly dominated by the rearing of *Macrobrachium rosenbergii*. An early book on the culture of freshwater shrimp was written by Hanson and Goodwin (1977).

In nature, tropical freshwater shrimp such as *M. rosenbergii* can spawn all year round. This will also occur in culture systems established in temperate environments if the proper temperature range is maintained. As you may recall, females move into brackish water to spawn (remember the soy sauce tale?), thus 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 postlarvae, which are often referred to as PLs (which is also the case with marine shrimp postlarvae). The process from hatching to the PL stage takes from 35–40 days at 29°C. When they reach the PL stage the animals can be moved to fresh water. As is true of marine shrimp, freshwater shrimp, which begin feeding a day or two after hatching, can be provided with a ration of brine shrimp nauplii or some other zooplanktonic species. The animals can later be weaned to prepared feeds.

Oysters

Techniques associated with spawning oysters have also been described in some detail previously, so the methods will not be repeated here. Since there are both warmwater and cold or coolwater species of oysters, the proper temperature range for the species in question needs to be used. For the American oyster, which is a warmwater species, the eggs will hatch into a larval form called a veliger larva within about 48 h after fertilization, when the temperature is at or very close to 30°C. They remain in that stage for a period ranging from 10 days to 2 weeks, when they metamorphose into spat which seek out suitable surfaces on which to attach. In the hatchery, rearing of the larvae through spatfall and attachment is usually conducted in tanks.

Recall that oysters are fed live food in the form of phytoplankton. Feeding begins during the larval stage. A variety of species of phytoplanktonic algae has been successfully employed. Once the spat have been settled on some suitable cultch material, they may be retained in the hatchery for a period of time before being placed in the environment. While in the hatchery they must be fed, which almost always involves continued use of cultured algae. Once the oysters are transferred to their growout location, no matter whether that is associated with bottom, raft, basket, tray or some other culture approach, cultured algae are no longer used so it is important to stock the oysters at the proper density for the natural food resource that will be available to the animals.

Providing Live Food

There has already been considerable discussion about the use of live feed, and details of producing algal cultures have been described in conjunction with other sections in this book. Therefore, this section focuses on the production of zooplankters that are used for feeding the early life stages of aquaculture animals in the hatchery. It is very important to understand that in the case of zooplankton species that must be fed, such as rotifers, there may actually be three cultures that need to be maintained: (i) the algae, (ii) the zooplankton and (iii) the fish or shellfish that will ultimately be grown out for marketing. If both rotifers and brine shrimp are involved in the feeding protocol, then four cultures will need to be maintained. A problem that causes any of the three (or four) to fail can spell disaster for the operation. A back-up method for a potential phytoplankton crash would be to have frozen or freeze-dried algae on hand to meet the demand until a new culture can be initiated. Maintaining more than one tank of each type of zooplankton will also serve as a back-up.

Depending upon the location of the facility and the characteristics of local zooplankton populations, it may be possible to pump fresh sea water that contains zooplankton through sieves to concentrate the animals and sort them to the desirable size range and then put them in the culture chambers. This technique 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, there may be delayed predation by these animals.

Among the commonly used live feeds by aquaculturists, rotifers, copepods (particularly copepod nauplii) and brine shrimp are the most frequent. Information on rotifer and brine shrimp culture is provided in the next two subsections. Copepod culture is similar to that of rotifer culture.

Rotifers

Rotifers within the genus *Brachionus* are widely used by aquaculturists, with *B. plicatilis* being perhaps the most popular. Starter cultures can be obtained from scientific supply houses or from other aquaculturists. It is not common for culturists to search around in nature for wild rotifers to initiate their culture activities. Rotifers can be reared in batch culture or continuous culture. Continuous culture is probably the best method when a consistent supply of animals will be required for long periods of time.

Rotifers are usually reared in one or more tanks with a total combined volume sufficient to produce the number of animals required as food for the fish or shrimp being cultured. An alternative that has been used is to rear rotifers in earthen ponds. This might be most appropriate when extremely large numbers are required. It is wise to have at least two tanks or ponds of rotifers. In the event of a population crash for some reason in one culture unit, the second and any additional units will ensure that a supply of rotifers remains available. Rotifers can be fed either algae or yeast.

The adult rotifers in the tank 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 salt water (upper 20s–30°C seems to be fairly ideal). Full-strength sea water is not required. The animals may be grown at 15, or perhaps more desirable, 20 ppt salinity. The lowest temperature which *B. plicatilis* will tolerate is about 10°C. It has been recommended that the pH be slightly alkaline (around 8.0), though rotifers will grow over a pH range of about 6.5 to 8.5.

For our purposes we will look at culturing rotifers in tanks and not focus on pond culture. Batch culture involves stocking a tank and allowing the population to grow until a concentration of the order of a few hundred rotifers/ml of water is reached (500/ml seems to be a reasonable number). Depending on the number of rotifers that hatch and water quality conditions, the batch culture should be ready for harvest from 2 to 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 every day once the population has grown to several hundred rotifers/ml. When rotifers are 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 screening outflowing water difficult, though a percentage of the tank water can be exchanged each day during partial harvest. A rotifer culture system is shown in Fig. 5.12.

While densities at harvest of a few hundred rotifers/ml are perhaps standard, high-density cultures of 2000/ml are sometimes maintained. Super-high densities of 20,000/ml have actually been achieved, but it would probably not be desirable for the aquaculturist to attempt maintaining such densities in a production facility due to the great potential for water quality problems to develop.

Fig. 5.12. A small rotifer culture facility in a larval fish-rearing laboratory.

Brine shrimp

Shrimp and many species of fish of aquaculture interest have the ability to consume brine shrimp nauplii as a first feed. For animals that have to have rotifers or some other extremely small live food early in their lives, they may be converted to brine shrimp as they grow. There is at least one distinct advantage of feeding brine shrimp nauplii: that is, you do not have to maintain an algal culture to feed them unless you want to grow juvenile or adult brine shrimp. Even in the latter case, you could feed frozen algae paste or freeze-dried algae and eliminate algae culture by purchasing one of those forms of phytoplankton.

The reason you do not have to provide algae to brine shrimp is that you can purchase brine shrimp cysts (sometimes mistakenly called eggs) and do not have to maintain a self-sustaining population of the animals. The cysts are a resting stage of the brine shrimp. The two original major sources of brine shrimp cysts were the Great Salt Lake in Utah, USA and 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. In the San Francisco Bay area, brine shrimp have been produced in ponds. Many places around the world have established populations of brine shrimp, though the major source continues to be the Great Salt Lake.

Seasonally, the adult brine shrimp in the Great Salt Lake produce cysts by the billions. The winds blowing across the lake cause the cysts to become locally concentrated in such numbers that you could literally walk across the water on them. Boats with vacuum systems are used to collect the cysts, which are then washed, dried and canned. The dehydrated cysts have a fairly long shelf life and can be easily shipped around the world. The major problem in recent years has been an unreliable supply, which has caused the price to increase in some years to the point that the economics of aquaculture, particularly marine shrimp culture, have been jeopardized. Competition for the cysts that are available is sometimes fierce, thereby driving the price up even more and leaving some hatcheries without a supply of cysts.

When the culturist needs live brine shrimp nauplii, all that needs to be done is to place the cysts in well-aerated sea water (35 to 40 ppt salinity is typical) at room temperature (about 25°C). The cysts will hatch into nauplii in about 24–36 h. The nauplii are positively phototaxic, so they can be attracted to and concentrated by a strong light source which accommodates netting or siphoning them from the hatching tank. The cysts 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.

Yeast slurries alone, or in combination with algae and/or various types of lipids have been used to fortify both rotifers and brine shrimp. Examples of studies that have been conducted on that topic are Kitajima *et al.* (1980a,b), Rainuzzo *et al.* (1989), Oie *et al.* (1994), Ozkizilcik and Chu (1994), Coutteau and Sorgeloos (1997), Lie *et al.* (1997) and Cabrera and Hur (2001). Culturing rotifers or brine shrimp on properly selected algae or a combination of algae and yeast appears to produce better quality animals, at least for some larval fish.

Controlling Sex

The primary reason an aquaculturist would want to control the sex of the animals being stocked is to enhance growth rates. Sometimes males grow more rapidly than females as we have seen in conjunction with tilapia. In some species of tilapia, the females become reproductively active before reaching market size and may produce a large number of progeny that overpopulate culture ponds, which can lead to stunted populations. In that case, the culturist may wish to stock only males. In other species, such as flounders and halibut, the males grow more slowly and it may be desirable to stock females.

There are a number of methods by which all-male or all-female populations can be reared. The oldest method involves visual inspection which requires each individual animal to be examined. 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 shrimp sex, there is no advantage in stocking one sex over the other, which tends to be the case in 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 can be used. That approach has been used with tilapia, for example. There will always be human errors, so the approach is not 100% effective though it will reduce the number of females that are introduced into a pond. 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 hand sexing is employed.

A few other techniques have been used to control sex. Some of them, and mention of a species or two to which each technique has been applied, are described in the following subsections.

Hybridization

In some instances, the hybrids produced when two closely related species are crossed will be predominantly of one sex or the other. In many cases, the fish are sterile, another approach that is sometimes used in aquaculture is discussed below. Crosses between some species of tilapia produce high percentages of males, sometimes approaching 100%. There are two drawbacks to this approach. First, it does not always produce the percentage of one sex or the other that is desired and secondly, human errors will occur in which the male of one species, after being spawned, will be put back with the females of the same species, thereby being able to spawn with what at that point is considered the ‘wrong’ species.

Feeding hormones

Interestingly, the sex of some fish 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 was in conjunction with aquaculture, involving research conducted by Guerrero (1975) in the Philippines. He dissolved a type of testosterone in alcohol, mixed the alcohol–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 virtually all the fish produced were 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 in order to produce all-male progeny.

The hormone feeding technique has been widely adopted by tilapia producers, though there are objections. Some are concerned that hormone residues may get into humans who consume the fish that have been treated early in their lives. 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 to during the sex-reversal process, but sceptics remain, so some regions will not allow production or sale of hormone sex-reversed fish.

Gynogenesis

If an ovum develops following sperm penetration but without fusion of the gametes, the embryo is produced by gynogenesis. In most cases, the number of chromosomes will be haploid ($1n$) because only the female half of the total will be present. These 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. Since all the chromosomes are from the mother, the fish will be XX or female. The technique has been applied to grass carp where the desire is 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. Since all the gynogenetically produced fish are females, they will not be able to reproduce if they escape from aquaculture or if they were intentionally introduced into nature. This assumes an absence of males in nature that may have been introduced by other parties or escaped into the wild.

Various techniques have been used to produce gynogenetic fish. Using the sperm of a distantly related species has been effective in some instances. Further, 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 them may develop as gynogenetic animals. Weak electric currents and low levels of UV 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 treatment ever develop into viable animals.

Sterilization

It is sometimes desirable to stock sterile fish. Various techniques have been used, with hybridization and production of triploids (those containing 3*n* chromosomes) being among the most popular. Certain crosses will produce sterile hybrids, one example being grass carp and bighead carp as has previously been mentioned in conjunction with the discussion of aquatic vegetation control, earlier in the book. 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 from a different species from those already present. Geneticists express great concern that genetic integrity may be lost if the genes from one population of a species are mixed with that of another of the same species that comes from a different locale. A good example is stocking Atlantic salmon 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 their 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 the local 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 many cases, the introductions of aquaculture species represent a truly exotic species: that is, one that does not have an existing natural population. Examples are the rearing of tilapia outside of its native range of North Africa and the Middle East, rainbow trout anywhere in the world besides the western USA, Atlantic salmon culture in western North America and Chile and red drum in China.

By using various chemical and physical methods that interfere with meiosis in one of the parents, it is possible to produce triploid offspring. Triploids are sterile since they cannot produce haploid gametes. Triploids may grow faster than normal individuals, which is a bonus to sterility but usually not the most important factor. Triploidy can be induced in various ways. Included are exposure of eggs to temperature or hydrostatic shock (Brydges and Benfey, 1991) as well as through exposing eggs to certain chemicals, such as cholchicine and formalin (Chernenko, 1985).

There has been considerable interest in the use of triploidy in conjunction with oysters, particularly in the Chesapeake Bay area of the USA, where the American oyster population has been devastated from disease and alternative species are being sought. One of the fears has been that if the introduction of an exotic oyster is not carefully controlled and studied before a reproducing population becomes established, there could be unanticipated environmental consequences that could not be reversed. Triploid oysters have been produced and stocked into Chesapeake Bay, but it turned out that not all of them were sterile. All of that may be moot now in any event, as at least one state is pushing ahead with stocking diploid non-indigenous oysters from Asia.

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 for the technology are development of reagents and vaccines from molecular cloning (Powers, 1995) and the expression of specific genes leading to increases in aquaculture production (Dunham, 1999). The latter could be particularly important in developing nations where the income of poor farmers could be improved. The environmental risks associated with the use of transgenic aquatic animals need to be assessed on a case-by-case basis (Sin, 1997; Dunham, 1999).

A number of transgenic animals of aquaculture interest have been created and used in research in recent years. Some examples are Atlantic salmon (Cook *et al.*, 2000a,b,c; Cogswell *et al.*, 2001), coho salmon (Devlin *et al.*, 2000; Hill *et al.*, 2000), channel catfish (Dunham *et al.*, 2002a), common carp (Fu *et al.*, 2000; Dunham *et al.*, 2002b), rainbow trout (Yoshizaki *et al.*, 2000) and tilapia (Rahman and Maclean, 1999; Rahman *et al.*, 2000, 2001; Maclean *et al.*, 2002). Transgenics are not, insofar as is known, being produced to any extent by commercial aquaculturists, though requests to employ genetically modified organisms have been and are currently being made to permitting agencies in some places.

While transgenic aquatic animals could revolutionize aquaculture production, their potential impact on wild populations, should they escape, is unknown, which has prompted governmental agencies, at least in the USA and Europe, to proceed very cautiously with the approval of such animals for use in aquaculture or to ban them outright. Opponents of transgenic fish have coined the term ‘Frankenfish’ and have circulated implausible stories of transgenic fish having been produced that grow up to 400% larger than normal. Such claims are often picked up by the media and put out to the public without any attempt having been made to determine the validity of the stories.

The maintenance of transgenic fish in US research facilities is carefully controlled to prevent escapement and the mixing of the genetically altered animals with wild stocks. The American Fisheries Society policy statement on the development of transgenic fish also cautions against uncontrolled release because the potential ecological impact on natural ecosystems has not been determined (Kapuscinski and Hallerman, 1990).

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 cannot be ignored. Extremists would prohibit all production of transgenic animals, but the realistic approach seems 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.

Molecular biology techniques can also be used to develop vaccines to combat diseases. For example, viruses such as the infectious haematopoietic necrosis (IHN) of salmon can be obtained from an infected fish, amplified through polymerase chain reaction (PCR) and the strain of the virus can then be identified. That may allow the development of a vaccine to combat the disease.

Genetics and genetic engineering are major foci of both those supportive of and opposed to aquaculture. The topics discussed above, and others, were discussed in detail by Dunham (2004). As we have seen there is also a great deal of concern being expressed by geneticists concerning the maintenance of genetic diversity in hatchery fish destined for enhancement stocking. A recent book (Beaumont and Hoare, 2003) discusses these topics in detail.

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6 Prepared Feeds

Rationale and Material Covered

Economic analyses of modern aquaculture facilities that 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 the operation are expended for feed. This is even true when at least some fertilizer is used to provide live food during the rearing of early life stages. Feed costs are insignificant when fertilization is the sole approach used, as is often the case in subsistence culture operations, particularly in underdeveloped nations.

Prepared feeds are sometimes, incorrectly,[1] called artificial feeds. There is little that is artificial about them as they are produced from natural ingredients for the most part. So, terms such as prepared feed and manufactured feed are preferred. 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 preparation of a nutritionally complete diet, the aquaculturist can anticipate good performance, unless water quality problems or disease intervene.

If there is a feed mill fairly near the aquaculture operation that makes aquatic animal feeds, and better yet, is one 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 expenses associated with feeding.

In this chapter we look at the types of prepared feeds that are available, as well as the various processes that are used to manufacture the feed. Feed storage is mentioned again and some feed ingredients are described. Additives are also discussed. We then take a look at feeding practices and calculation of feeding rates. Some of the topics have been mentioned in passing or in some

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[1] Yes, I have been known to incorrectly call prepared feeds 'artificial' feeds. I have broken that habit, though it appears in various publications for which I have been responsible.

detail in other chapters in this book, but repetition of some of the material is actually important to drive home certain points.

Types of Prepared Feed

Prepared feeds come in various particle sizes and forms. There are also differences with respect to nutritional value.

Particle size

For feeding fingerling fish and juvenile shrimp, pellets are used. The pellets may be round or cylindrical. They are usually 3 to 5 mm in diameter and cylindrical ones may be a centimetre in length, though there is some variability. For broodfish, larger pellets may be appropriate, though even large fish can, in most cases, easily consume standard pellets of the sizes mentioned.

We have already seen that some fish will consume prepared feeds when they first begin to take food after yolk sac absorption. Examples are trout, salmon, channel catfish and tilapia. Those species have large eggs compared to most fish and as a consequence, large fry that can accept prepared feed of the proper particle size at first feeding. Smaller fry are first provided with live food organisms as discussed in Chapter 5 and are weaned to prepared feed when they are large enough to consume the particles.

Feed ingredients are finely ground before being formed into pellets. Subsequently, the pellets can be ground into fine particles and used to feed fry fish. 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 will not be uniform with respect to their composition. Presumably, the small fish will eat enough particles of varying composition to provide them with the suite of nutrients they require. Having natural food available, as in a pond situation, can help ensure that the animals receive the proper nutrition. (Nutritional requirements are the subject of Chapter 7.) Microencapsulation is a method of providing a complete ration in a very small particle as described in the next subsection.

Weaning aquatic animals from live food to prepared diets may be a rather simple process, or it may require a considerable amount of time and effort. In most cases, the process begins by adding the prepared feed to the culture system while still providing live food. As time passes, the proportions of live to prepared feed can be gradually changed so that 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 so that only prepared feed is provided. The culturist should closely observe the feeding behaviour and may examine individual animals for feed in the stomach to ensure that the weaning process is proceeding satisfactorily.

Many years ago, when we were first trying to develop culture methods for southern and summer flounder, we collected postlarval 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 postlarval flounders brine shrimp nauplii, then very finely chopped shrimp. After that we fed freeze-dried shrimp which were crumbled into suitably sized particles. Once the fish had been converted from live to freeze-dried food, we introduced finely ground dry feed particles and ultimately were able to wean the fish onto only the prepared diet. The process took a few weeks and involved a lot of labour. It was probably unnecessary as we undoubtedly could have used the technique previously discussed and bypassed the freeze-dried shrimp phase of the process.

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 (Baskerville-Bridges, 1999), eel (Kastelein, 1983; Knights, 1996), milkfish (Duray and Bagarinao, 1984), sharptooth catfish (Verreth and Van Tongeren, 1989; Haylor, 1991), sole (Gatesoupe and Luquet, 1982; Gatesoupe, 1983; Person-Le Ruyet *et al.*, 1983; Bromley and Sykes, 1985), striped bass and striped bass hybrids (Tuncer *et al.*, 1990), summer flounder (Bengtson, 1999; Bengtson *et al.*, 1999), turbot (Bromley and Sykes, 1985) and winter flounder (Lee and Litvak, 1996).

The question often arises as to what formulation should be used when a new aquaculture species is being reared for which the nutritional requirements are yet to be established. 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 diet and also require substantial levels of vitamins and minerals. Any good salmonid feed seems to work well during the early stages of rearing other species, though the minerals can be eliminated from the rations fed to marine animals since they obtain their minerals from the water, as we have seen. There will certainly be differences among non-salmonid species. Many require less protein than salmonids, while others have higher protein requirements. Research using a salmonid diet as a control will help the culture industry develop feed formulations that are species specific, a process that can take several years and remains to be completed for most species currently being successfully reared by commercial aquaculturists.

Once the animals are sufficiently large – actually, once their mouths are large enough to accept it – the feed particle size should be increased. Crumbles are particles intermediate between the finely ground feed (sometimes called fines) and pellets. Crumbles are produced by grinding pellets to the appropriate smaller sizes. Crumbles can be obtained in various sizes. Whole pellets are provided as soon as the animals are able to consume them.

In addition to changing particle sizes, 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 for larger fish. Specific feed formulas related to fish size are not common in the industry, but some have been developed, such as for channel catfish (Winfree and Stickney, 1984). Many culturists use salmonid feed until the animals are large enough to consume pellets, at which time they can be converted to formulations specific for fingerling and larger fish of the species being reared. Salmonid feeds are more expensive than feeds for many aquatic species of culture interest because of the high protein content. However, cost is not a major consideration when fine particles and crumbles are being fed, since the total amount of feed used is very small compared with the volume required during the period when the animals are consuming pellets.

Particle form

Microencapsulated feeds are not widely used in aquaculture, though it is possible to formulate such feeds for aquatic animals. The process involves dissolving the nutrients in liquid and forming very tiny ball-shaped particles with proteinaceous membranes surrounding the feed ingredients. These microparticles are similar to those widely used in slow-release pharmaceutical capsules. The particles can be as small as a few tens of microns in diameter. Techniques used in the microencapsulation process were discussed by Lee *et al.* (1996).

Microencapsulated diets have been used at least on an experimental basis as food for rotifers (Teshima *et al.*, 1981), molluscs (Chu *et al.*, 1987), marine shrimp (Jones, *et al.*, 1987; Kurmaly *et al.*, 1989) and marine fish (Yufera and Fernandez-Diaz, 1999; Yufera *et al.*, 2000). Microencapsulated diets have been developed for gilthead sea bream and several studies have investigated the use of microencapsulated diets in conjunction with the culture of penaeid shrimp.

Flake diets are in common use in the ornamental fish industry for feeding tropical fish. Flakes can also be used to feed young cultured fish, though they are not in widespread use at the present time. The very finely ground feed ingredients are made into a slurry with water. Then the mixture is passed between two heated rollers of a double drum dryer that rapidly dries the slurry and forms it into paper-thin sheets. The sheets are then broken up into smaller pieces for packaging and sale. Commercial products are usually a mixture of flakes of different colours (red, brown, yellow and green being the most common). The colours are conferred to the flakes by dyes or by the basic feed ingredients that impart colour to the flakes. Some fish take up the colours from the feed into their flesh (e.g. salmonids) or on the body surface (e.g. tropical fish such as guppies, swordtails and many others).

Historically, the three most common types of prepared feeds for aquaculture species have been moist feeds, semi-moist feeds and dry feeds. Moist feeds were developed and used primarily in salmon hatcheries in the USA, and most of those hatcheries have been associated with state and federal enhancement stocking programmes. The same kind of feed is widely used in Japan where it is prepared daily to feed such species as red sea bream in cages. Moist (sometimes called wet) feeds are produced from the processed carcasses (frames) of commercially captured fish or from the whole bodies of so-called trash fish to which dry ingredients have been added. Dry ingredients may include fish meal, vitamins, minerals and other items. After mixing, the material will still have a high water content. It can be made into soft pellets by passing the mixture through a meat grinder.

While it is probably 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 fed. Because of their high water content, moist pellets that are not going to be used within a day or two after manufacture should be frozen to keep them from deteriorating.

Semi-moist pellets have the consistency of ground beef and resemble that product, except they may be any number of colours, depending on the ingredients used. They contain a large percentage of preservatives to retard the development of microorganisms that can cause the feed to deteriorate. The feed is often placed in vacuum-packed plastic bags to further protect the feed from degradation. Such feeds are expensive to produce, so their primary use is in conjunction with young animals. To my knowledge, they are not currently in use as growout feed in conjunction with commercial aquaculture ventures because of the prohibitively high cost.

Dry feeds are the most popular. As previously mentioned, dry prepared feeds are manufactured in pellet form. 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. The methods of manufacturing such feeds are described later in this chapter.

Nutritional value

All aquaculture feeds are not equal in terms of the uses they will be put to. Research feeds may be formulated to determine the requirement for a particular nutrient in a ration that may contain highly purified ingredients or ingredients that are commonly available as commodities in the marketplace. Such feeds have been classified as purified, semi-purified or practical.

Purified diets are rarely used in aquaculture research. The simple fact is that such diets are extremely expensive to prepare. A purified diet will contain all the essential nutrients in a chemically simple form, except for the one that is being investigated in the study. That one will be deleted or put in several formulations that cover a range of levels with the intention of determining the minimal level required by the animal. A truly purified diet would contain individual amino acids, fat in the form of free fatty acids, 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. Such diets will usually produce relatively poor growth, since animals perform better on diets that contain more complex ingredients than they do on highly purified ingredients.

Many researchers have indicated that they used purified diets in their studies, but most have actually used semi-purified rations. 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 unpurified form. A few examples of what this means would be as follows.

1. Evaluation of an amino acid requirement:
  a. Each diet contains all but one essential amino acid in purified form, except for the control diet which contains all the essential amino acids.
  b. The carbohydrate may be in the form of starch.
  c. The lipid may be in the form of fish oil or some type of vegetable oil.
  d. A vitamin and mineral package is added.

2. Evaluation of a carbohydrate requirement:
  a. A protein source such as casein (milk protein) is used.
  b. A range of carbohydrates is used. Among them may be simple sugars or more complex carbohydrates such as disaccharides or starch.
  c. The lipid may be in the form of fish oil or some type of vegetable oil.
  d. A vitamin and mineral package is added.

3. Evaluation of a lipid requirement:
  a. A protein source such as casein (milk protein) is used.
  b. The carbohydrate may be in the form of starch.
  c. The lipid is included as a range of such ingredients as free fatty acids, triglycerides or ethyl esters of the fatty acids of interest.
  d. A vitamin and mineral package is added.

4. Evaluation of a mineral or vitamin requirement:
  a. A protein source such as casein (milk protein) is used.
  b. The carbohydrate may be in the form of starch.
  c. The lipid may be in the form of fish oil or some type of vegetable oil.
  d. Vitamin or mineral packages that eliminate one vitamin or mineral or provide the vitamin or mineral being tested at various levels.

Aquatic animal nutritionists often use semi-purified formulations to determine nutritional requirements. In most cases, a practical diet formulation is used as a control in such studies.

Commercial feeds are those formulated with readily available commodities, many of which are locally available and may not be found in the marketplace in most locations around the world, or if they are available, are present because they have been imported. Use of imported commodities adds significantly to the cost of feed. Also, humans and terrestrial livestock often take precedence over aquatic animals when it comes to utilizing imported feedstuffs.

If there is a considerable amount of natural productivity in the culture system or the stocking rate is low, so much of the food the animals consume comes from natural productivity, even if that productivity is low, and the aquaculturist may provide additional nutrition in the form of a supplemental feed. Supplemental feeds usually contain a lower protein and energy level than those required by the animals. Such feeds may also lack vitamins and minerals other than those present in the feed ingredients.

When natural productivity is low or absent, and in virtually all cases where stocking densities are high, complete feeds are 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 animals, each having slightly different nutritional requirements, though closely related species usually have quite similar requirements.

Feed Ingredients and Additives

The most common sources of protein in aquaculture feeds are fish meal and a variety of plant meals. Many of the aquaculture species being reared today are carnivores that require at least some animal protein in their diet, with fish meal being the most common source of protein. Vegetable protein sources tend to be deficient in one or more required amino acids required by carnivores (see Chapter 7 for more detail). Herbivorous species and some omnivores are able to perform very well on diets devoid of animal protein or containing only minute amounts. Tilapia and channel catfish are examples.

The most common fish meals are obtained from anchoveta, menhaden and herring. The world's largest fishery for fish that are used in fish meal is the anchoveta fishery off the coast of Peru. The meal produced from that fishery is used around the world in livestock and aquaculture feeds. Because the fishery declines or nearly collapses in El Niño years, and so much of the world's fish meal supply comes from that fishery, the price of fish meal in the marketplace can fluctuate significantly during periods when the Peruvian fishery fails. Because of that and the fact that fish meal is one of the most expensive ingredients in aquaculture feeds, other sources of protein that will work as well or nearly as well as fish meal have been sought. Some that have worked well include meat and bone meal (from cattle) and poultry by-product meal (primarily from the chicken industry). Because of BSE (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 prohibited. Feather meal (from poultry feathers) was once commonly found in aquaculture feeds, but its nutritional value was found to be poor.

Among the common plant protein sources in fish feed are soybean meal, groundnut meal, maize meal and cottonseed meal. Wheat, maize and various other grains have also been extensively employed. Rice bran is commonly fed in tropical nations, though its nutritional value is low. The only benefit is that rice bran is plentiful in countries where rice is a staple in the human diet. Because the cost of protein is high and many of the most desirable forms that work well in aquaculture feeds are not locally available, particularly in developing nations, aquaculturists have looked at a wide variety of alternatives to the protein sources mentioned thus far. A partial list of those protein sources and references to the details is presented in Table 6.1.

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, though usually below those required for proper nutrition of the aquaculture species to which the feedstuffs are fed.

It is common practice to add various additional nutrients to feed formulations, because mixtures of fish meal and vegetable protein sources are deficient in certain nutrients. Lipids of various kinds are often added, sometimes at very high levels. Vegetable oils are commonly employed, though many species do not perform as well on those types of fats as they do on fish oil. Supplemental vitamins and minerals are also added to complete aquaculture feeds.

Table 6.1. Examples of alternative protein sources that have been evaluated for use as or incorporated in aquaculture animal feeds. (Citations can be found in the References section of Chapter 6.)

Alternative Protein(s)	Reference(s)
Blood meal and cattle rumen contents	Reece *et al*. (1975)
Brewer's dried yeast	Li and Gatlin (2003)
Cabbage	Rajadevan and Schramm (1989)
Canola (rapeseed)	Davies *et al.* (1990), Kissil *et al.* (1997)
Cassava flour	Hung and Cacot (2002)
Clitoria ternatea leaf (common Indian weed)	Raj (1989)
Coffee pulp	Bayne *et al.* (1976)
Date pits	El-Sayed *et al.* (2002)
Dried poultry waste	Stickney *et al*. (1977)
Egg-waste protein	Davis *et al*. (1976)
Fermented fish silage	Wassef *et al.* (2002)
Goat blood meal	Saha and Ray (1998)
Kikuyu grass	Rajadevan and Schramm (1989)
Lepidium meyenii (maca)	Alvarez *et al.* (2002), Flores and Palacios (2002), Palacios *et al.* (2003)
Lupinus luteus (lupin meal)	Robaina *et al.* (1995), Sudaryono *et al.* (1999), Glencross *et al.* (2002), Millamena (2002)
Macadamia presscake	Balogun and Fegbenro (1995)
Maize gluten protein	Mente *et al.* (2002)
Maggot meal	Ajani *et al.* (2002)
Mauritia flexuosa (aguaje)	Palacios *et al.* (2003)
Malt protein flour	Akiyama *et al.* (1995), Yamamoto *et al.* (1994, 1996)
Meal worms	Ng *et al.* (2001)
Myrciaria dubia (camu-camu)	Palacios *et al.* (2003)
Palm kernel meal	Ipinjolu *et al*. (1989), Ng *et al.* (2002)
Panagrellus redivivus (free-living nematodes)	Reyes *et al.* (2002)
Paper-processing sludge	Orme and Lemm (1973)

continued

Table 6.1. *(continued)*

Alternative Protein(s)	Reference(s)
Pisum sativum (feed peas)	Davis *et al.* (2002), He *et al.* (2002)
Poultry litter	Saha and Ray (1998)
Processed grass clippings	Bender *et al.* (1989)
Sesbania aculeate (Sesbania meal)	Hossain *et al.* (2001, 2002)
Silkworm pupae meal	Habib *et al.* (1994)
Tomato meal	Hoffman *et al.* (1997)
Various aquatic plants such as hornwort, duckweed and water hyacinth	Wee (1991)
Water hyacinth (fresh and composted)	El-Sayed (2002)
Water hyacinth meal	Habib and Roy (1994)

A number of other items may be added to prepared feed formulations. Important among them are some type of binder to help retard dissolution of feed pellets when the pellets are put in the water. As a rule of thumb, a feed pellet should remain intact in water for at least 10 minutes to provide the animals with an opportunity to find and eat the food. That does not mean some soluble nutrients will not leach from the feed even though the pellet has not dissolved. Water-soluble vitamins, in particular, 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 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, gelatin and guar gum. In most cases binders are a form of starch, though that is not always the case.

Antioxidants are often added to feed formulations to protect some of the ingredients from degradation, or a nutrient may be overfortified to prevent loss during processing. Vitamin C, for example, is heat labile. If added as ascorbic acid, it needs to be put in the feed at several times the required amount, as a significant percentage can be lost during the pelleting process when the vitamin is exposed to heat. Over the last few years, protected forms of vitamin C that are heat resistant have been effectively used. Those forms include ascorbic acid sulphate, ascorbyl monophosphate and ascorbyl polyphosphate.

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. This may involve a small amount of material such as shrimp meal, krill meal or some other ingredient that imparts an odour that is attractive to the culture species. 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, inosine, lysine, proline and serine have all been shown to attract certain aquatic species as have a number of other chemicals.

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. Some sources of carotenoids are 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 (George *et al.*, 2001).

As we have seen, good management of the culture system can help reduce stress, and 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 fish are vitamins C and E, β-1,3 glucan and levamisole (Montero *et al.*, 1999; Sahoo and Mukherjee, 1999).

Feed Manufacture

Commercially prepared feeds are manufactured in feed mills that keep a variety of commodities on hand. While some fixed formulations of aquaculture diets are used – formulas that remain constant from one batch to another – it is common practice to allow substitutions, particularly in the case of certain vegetable ingredients, to accommodate changes in the cost of these ingredients. For example, it may be less expensive to use cottonseed meal as an ingredient one day and groundnut meal another as the market price fluctuates. This is known as least cost formulation. It is important that any ingredient that is used as a substitute should still lead to a final product that meets the nutritional requirements of the species that will receive the feed.

The various ingredients arriving at the feed mill may or may not have received some preprocessing between being harvested and delivered to the feed manufacturer. Cotton is sent to cotton gins where the seeds are removed, so that only the cottonseeds or cottonseed meal are shipped to the feed mill. Soybeans may have the oil removed at a soybean 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. Wheat is processed into a number of fractions, some of which (e.g. wheat middlings and wheat germ) are often found in aquatic animal feeds.

Feed mills generally purchase premixed vitamin and mineral packages, though some of those ingredients may be added at the time the formulation is put together. Lipid may be mixed into the diet or can be sprayed on after the pellets have been manufactured.

The ingredients are finely ground and placed in large mixers where they are blended together. They can then be made into pellets by passing them through either a pressure pellet mill or an extruder. Alternatively, micro-encapsulated, flake, moist and semi-moist feeds can be manufactured.

Pressure pelleting

The standard for aquaculture diets for many years was the pressure pellet. To make pressue pellets, the feed mixture is fed into the machine from a hopper at controlled speed and passed through a die, which is a short, cylindrical metal object with a large number of uniform-sized holes drilled through its hollow centre to the outside edge. The feed enters the die (which is spinning within a chamber) through the centre opening, and pressure forces the material laterally through the holes where the material is put under pressure. Coupled in many cases with steam to heat the material and add some moisture, along with the incorporation of a binding agent among the feed ingredients, the pressure causes the particles to bind tightly together as they move through the die. The length of the holes in the die are in 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. As the strands of material exit the die, a knife cuts them into pellets of the appropriate length. Once the pellets leave the mill, they are dried, often using forced air. They are then either bagged, usually in bags that each contain about 23 kg (Fig. 6.1), or they can be stored in bulk for delivery to feed bins (Fig. 2.6).

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

Fig. 6.1. Sacks of feed pellets. Sacks of this type are used for both pressure pellets and extruded rations.

allow the culture animals to consume them. Some species, such as shrimp, feed by gnawing on food pellets as they can ingest only very small particles. As a result, it takes shrimp a long period of time to consume a pellet, so if pressure pellets are used those pellets need to contain a considerable amount of binder to ensure that they remain intact until consumed.

Extrusion

A wide variety of extruded products can be found in the market today. When I was young, a cereal company in the USA advertised that its cereals were ‘shot from guns.’ In fact, most breakfast cereals, along with spaghetti and noodles, are among the many products that are made in the same way – through extrusion. An extruder is a machine with a long barrel (therefore, the reference to being shot from guns) that has a single hole through it that is actually, in most cases, smaller than the pellet that is produced. The shape of the hole translates into the shape of the product. It may be round, square, star-shaped, etc. For aquaculture pellets, the hole in the barrel is round.

The mixture of feed ingredients, prepared as described above, is pushed through the extruder barrel under a pressure much higher than is the case in pressure pelleting. An extruder barrel is much longer than the width of a die used for pressure pelleting, can be heated along its length (sometimes with varying temperatures at different points along the barrel) and places much more pressure on the feed ingredients. When the material exits the extruder barrel it is cut into pellets.

Some species grow well on feeds that contain high levels of lipids. There is a limit to the amount of fat that can be used in the ingredient mix and still produce a high-quality feed pellet, so lipids can be sprayed onto the pellets after production. About 5% additional fat can be added through the spraying process. Extruded pellets, like pressure pellets, may require drying following production.

If the ingredients have a relatively high level of starch and the temperature and pressure are sufficiently high, the starches will expand as the material leaves the extruder barrel and it will trap air in the process. This produces floating pellets. 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.

Floating pellets are preferred by perhaps the majority of aquaculturists who grow animals that will feed at the surface. The reason is that the farmer can observe the animals (fish, virtually without exception) feeding. This is important in that the farmers can feed *ad libitum*; that is, they can feed until the fish are satiated. If the farmer cannot see the fish feeding, calculated amounts of feed will need to be offered as discussed below. Further, if the fish have been stressed or are experiencing 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 used, but can also begin looking for the cause of the problem so it can be remedied.

As is the case with pressure-pelleted feed, extruded feed can be purchased in bulk or in bags. Storage should be the same as for pressure pellets as described in the next section.

Storage and Presentation

Bags of prepared feed need to be stored in a cool dry place, particularly if it is not going to be used within several days to a few weeks after purchase. The problem associated with mould formation in improperly stored feed has already been mentioned. There are also problems associated with bugs getting into the feed. Some of them will burrow through the bags to gain access. Mice and rats can also get into feed, so it should be stored in a secure location. Bagged feed should be used within 90 days of purchase. Stock rotation is important. This 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. 2.6. During the growing season, deliveries of bulk feed are made on the basis of every few days to perhaps 2 weeks, so heat is not as much of a problem if the feed is stored for a relatively short time. Moisture should not be a problem in feed bins unless there is a leak in the bin.

By presentation, I am 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 fairly simple to understand. The culturist feeding prepared feed to small animals in confinement can merely pour the feed into the tanks or raceways that contain the animals. In small ponds, feed can be thrown in from scoops or buckets.

Mechanical feeding involves the use of demand feeders, automatic feeders, or feed blowers mounted on boats or pulled along the pond bank by trucks or tractors (Fig. 6.2 shows a tractor pulling a feed blower). Demand feeders are those that the animals activate as a result 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.

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 is a footplate of some type that trips the device so feed is dropped into the water. Thus, the individual fish can obtain feed whenever they want it. Once a fish or two activate such a device, others quickly learn to do so as well. A typical demand feeder is shown in Fig. 6.3.

Automatic feeders are those that deliver feed in batches at certain times of day or continuously drop small amounts of feed. Automatic feeders are used, for the most part, in conjunction with feeding postlarval and fry fish in the hatchery or in tanks or raceways (often in conjunction with research) when larger animals are being reared. A small automatic feeder is shown in Fig. 6.4. It was in use to feed fish in small tanks. Fig. 6.5 shows a continuous automatic feeder mounted on the edge of a circular tank. The same type of feeder, with its top lifted to show the belt on which the feed is placed, is shown in Fig. 6.6.

Fig. 6.2. A tractor pulling a feed blower.

Fig. 6.3. A typical demand feeder over a raceway. Note the rod extending into the water.

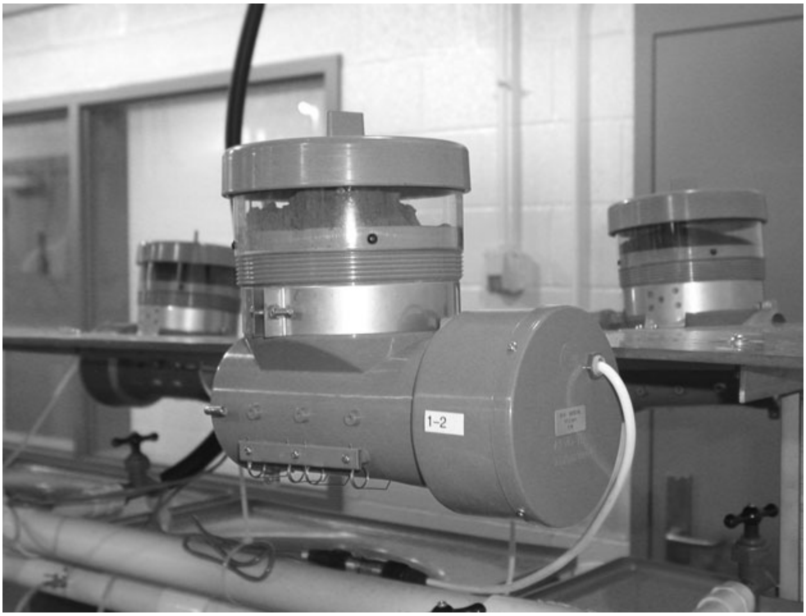

Fig. 6.4. An automatic batch feeder.

Fig. 6.5. An automatic continuous feeder.

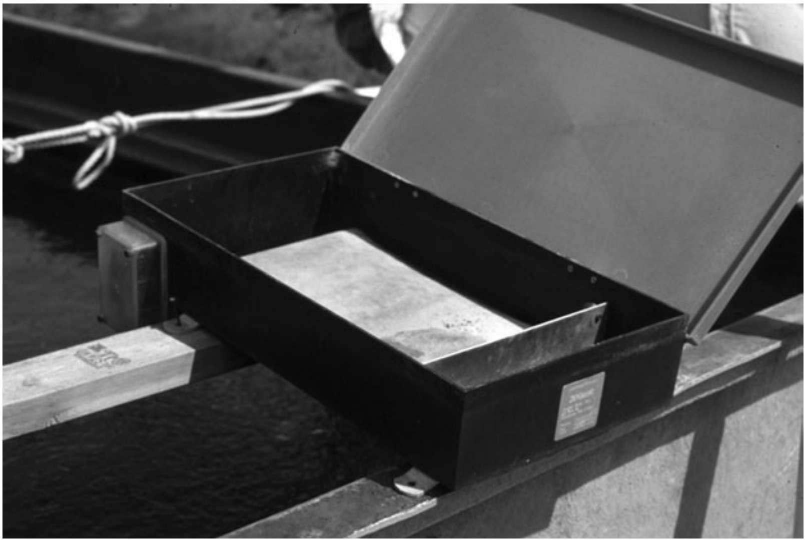

Fig. 6.6. An automatic continuous feeder showing the interior.

The belt on the continuous feeder moves very slowly so that finely ground or crumble feed can be delivered to small culture animals.

Feeding Practices

Proper feeding involves providing food of the appropriate formulation at the right time or times of day, in the proper amounts and 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 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 fish such as channel catfish may not be fed at all or will be fed only a very small amount daily, every other day, every third day or only on relatively warm days.

In general, juvenile aquaculture animals will consume about 3 to 4% of their body weight daily in prepared feed. There are exceptions to that, of course. Some species have very high metabolic rates and require much higher feeding rates. An example is mahi-mahi (dolphin). Others may have low metabolic rates and require less food. Then, of course, there are situations where some of the food is from natural sources (plankton, benthic organisms, etc.), so the amount of prepared feed that is required will be less than 3 to 4%.

It is common practice to feed postlarval and fry animals far in excess of what they can possibly consume. Culturists may, for example, feed fry fish as much as 50% of their biomass daily. This 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 chamber 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 insignificant since the total weight of the fish is so 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 to help preserve water quality. In ponds, the excess feed helps fertilize the system.

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! Those larger stages of aquaculture species on a production facility receive large amounts of feed each day when they are fed at the proper level. Feeding more than what the animals will consume is wasteful, expensive and may lead to impaired water quality due to the increased biochemical oxygen demand imposed on the system by decomposing feed.

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 until the final growout feeding rate is reached. Early fingerling fish are typically fed 5% to 10% of body weight daily and that level is gradually reduced until the 3% to 4% rate is reached. Broodstock, which are growing very slowly, if at all, are commonly fed about 1% per day, though a higher feeding rate may be used when the gonads are developing prior to spawning.

Feed particle size should be increased as the size of the animals allows them to take larger particles. Once the animals are able to accept full-size feed pellets, those pellets will be fed thereafter in many cases. Larger pellets, if desired, can be produced by using larger dies in pressure pellet mills or a larger extruder barrel aperture.

Postlarvae, fry and very small juveniles may be fed several times daily, or even continuously using automatic feeders. Carnivorous species prone to cannibalism are typically fed at high frequency or continuously to reduce the rate of cannibalism. Many carnivores do not exhibit cannibalistic behaviour, particularly if there is not much size variability in the cultured population.

Once the fish are on the 3% to 4% daily ration, they are usually fed once or twice a day, unless they are provided with demand feeders. Feed is typically offered before mid-morning and in the late afternoon prior to dusk. Feeding during the warmest part of the day is avoided because the water may be so warm that feeding activity is reduced. Similarly, feeding very early in the morning is avoided since the oxygen level may be low at that time. The afternoon feeding typically occurs just prior to the end of the normal workday for the employees on the farm.

The time of day relative to the light–dark cycle can have an influence on fish growth rates. Spieler (2001) reported that at least 25 studies involving 14 species had been conducted to investigate that relationship. In most instances, differential growth was observed depending on when during the circadian cycle the fish were fed.

As mentioned above, when floating extruded feed is used, the farmer has the advantage of being able to observe the fish feeding. To feed *ad libitum* with floating feed, the farmer offers an amount of feed that is approximately what was consumed the day before and allows several minutes for the animals to consume the ration. If they continue to surface in search of food once no more pellets are visible, an additional relatively small amount of food is offered. The process is continued until feeding activity virtually ceases. The process is more time consuming than putting all of a ration that has been calculated from sampling (described below) into the culture chambers at one time, but it more accurately assures that the fish are not being overfed or underfed.

Salmon net pens (and perhaps those used with other species) are often fed with automatic feeding systems. One example used by salmon culturists involves a central feed storage facility (one I saw was a barge that held the stored feed) and distribution equipment. Feed is distributed through plastic hoses from the central facility to each net pen on a schedule that allows each net pen to be fed several times daily. The pellets are blown through the hoses by air pressure. Sinking pellets can be used because the net pens are wide and deep so the fish have ample opportunity to feed before the pellets fall through the bottom or are carried laterally out of the enclosure by currents. Small feedings several times a day help ensure that the fish have ample opportunities to eat. Since the pellets sink, it is difficult for the aquaculturist to observe feeding activity. Divers, or an observer who monitors feeding activity via a video camera, can overcome that deficiency.

Determining Feeding Rate

For culturists who sample the animals periodically to adjust the feeding rate, it is necessary to know 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 (such as those used in research laboratories). Capturing all the animals in hatchery culture chambers as well as in large raceways and tanks is also possible, but how does one count and weigh them in such an expeditious manner so that the stress placed on the population is not severe? The problem is compounded further in conjunction with animals reared in large cages, net pens and ponds. One method to avoid stress is to use subsamples from the population. All the animals in a tank, for example, regardless of size, can be captured and weighed as a group. A subsample can then be collected, counted and weighed. By knowing the weight of the total population and that of a known number of fish from the subsample, a good estimate of the number of animals in the population can be determined. With very small animals, the amount of water displaced by the total population and subsample is often used rather than the actual weights. For example, if 100 fish fry displace 5 ml of water and the entire population displaces 500 ml of water, the equation would be: $100/5 = x/500$, so $5x = 50{,}000$ and $x = 10{,}000$ fish in the population. When using the water displacement technique with very small animals, the sample size should probably be at least 100 or even several hundred individuals if a reasonable estimate is to be obtained, because each animal displaces a miniscule amount of water.

For fingerlings and larger animals in large culture chambers, it is necessary to have a good estimate of the total number that were initially stocked. Thereafter, when feeding rate is to be adjusted (typically at two-week intervals) a subsample of at least 30 individuals taken at random and weighed should be sufficient to provide a good estimate of average weight. The total weight is determined by dividing the total weight of the subsample by the number of animals in the subsample and multiplying the average weight by the number of animals thought to be present in the culture unit.

The problem comes in actually knowing how many animals are in the culture unit. Culturists rarely individually count the numbers of animals stocked. Rather, they are also stocked by taking a subsample and determining the average weight, then determining how many, by weight, of the animals should be placed in the culture chamber. This implies that all the animals to be stocked need to be weighed, which is actually true. To do that, the culturist has a couple of choices. A group of animals can be netted and placed on a scale, weighed and then stocked. Additional groups are weighed and stocked until the weight of fish equalling the numbers that are to be stocked into the culture chamber is reached. To keep the animals from being out of water for an extended period of time, nets full of fish are poured into containers of water that have been tared. That means that the container, partially filled with water, is placed on the scale and the scale is zeroed. Then the netted animals are added so that the increase in weight represents only the weight of the animals that have been placed in the water. There is an error involved since there is always going to be some water transferred with the animals in the net. This should be insignificant if the animals are relatively large (e.g. fingerling fish) and the net is allowed to drain for a few seconds before the animals are transferred.

An alternative used with small animals is the water displacement method previously described. In this instance, where the culturist is not trying to determine the number of fish that have already been stocked, but is instead interested in stocking a particular number of fish in a culture chamber, the process is still very much the same. For example, if 100 fry increase the water level by 5 ml, and the farmer wants to stock 10,000 fish fry in a culture chamber, the conversion would be: $100/5 = 10{,}000/x$, so $x = 500$ ml of water displacement to equal 10,000 fish.

While knowing with a high degree of accuracy the number of animals initially stocked in a particular culture unit is an issue, the major problem associated with estimating feeding rate is that the culturist usually does 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. Those lost to cannibalism or bird predation and dead animals that do not float where they can be observed will not be counted in most instances. The culturist can use an estimated mortality rate as an adjustment factor when adjusting feeding rates, but that can introduce a considerable error factor because it is, at best, a guess.

For our purposes, let us assume that the culturist has accurately determined the number of animals in the system at stocking and that the number of mortalities over time have been accurately determined. Given that caveat, how does one calculate a new feeding rate. In many cases, new feeding rates are calculated no more often than weekly, and most commonly they would not be calculated more often than at two-week intervals.

As an example of how you would go about calculating a new feeding level, 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 want to feed them 4% of their body weight daily until the next adjustment in the feeding rate which will be 2 weeks later. Note that because the fish will presumably be growing from day to day, the actual feeding rate will be less than 4% after the first day, and will decline slightly each day thereafter until the new adjustment is made. How much feed are you putting in the pond each day?

10,000 fish/ha × 5 ha = 50,000 fish
50,000 fish × 200 g/fish = 10,000,000 g = 10,000 kg of fish
10,000 kg × 0.04 = 400 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 to 500 g on average. Assume that the feed cost is US$0.40/kg.

US$0.40/kg × 400 kg/day = US$160/day.

Now you can begin to realize why feed costs can amount to such a high percentage of the variable costs of production.

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 fish × 210 g/fish = 10,500,000 g = 10,500 kg
10,500 kg × 0.04 = 420 kg of feed/day
420 kg × US$0.40 = US$168/day

The fish are growing and so is your cost of feeding them. Over the previous 14 days you have spent US$2240. This 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 Conversion

Looking back at the growth of your fish over the two-week period when they increased from an average weight of 200 g/fish to 210 g/fish, 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 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 that are growing slowly are not being underfed, they may not be consuming the feed and may be suffering from a disease problem, or perhaps the feed is not as nutritionally complete as you thought. 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 efficiently utilized by the animals. Realizing that only the protein in the feed is used for somatic growth, the goal of the nutritionist is to convert as much of the protein provided in the feed to tissue in the culture species as possible. Some protein is always going to be utilized as an energy source and will be burned for metabolic activity, but if lipid and carbohydrate can be the primary energy sources in the diet, protein can be more effectively used.

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 conversion efficiency (FCE). There seems to be some controversy among aquatic animal nutritionists as to which is the proper parameter to measure, though as you will see, one can be derived from the other. That being the case, I have elected not to select one term over the other. The formulas for the two are:

$$\text{FCR} = \text{dry weight of feed consumed/wet weight of gain} \tag{6.1}$$

$$\text{FCE} = 1/\text{FCR} \times 100 \tag{6.2}$$

FCE is expressed as a percentage, whereas FCR is a ratio that does not have any units.

If we look at a very efficient terrestrial animal, the chicken, we can get some idea of what a good FCR should look like. Chickens will have a FCR of about 2.0; that is, for every 2 kg of dry feed consumed there will be 1 kg of wet weight gain. The FCE for that FCR is 1/2 × 100 = 50%. Thus, 50% of the feed consumed goes to growth.

Now let us look at how the pond fish 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 of feeding was 10,500 – 10,000 kg or 500 kg. The total amount of feed offered was 420 – 400 kg/day × 14 days = 20 kg/day × 14 = 280 kg. Thus, the FCR is calculated as follows:

FCR = 500 kg fed/280 kg gain = 1.78
FCE = 1/1.78 × 100 = 56%

Given that what is considered a good FCR for most aquatic organisms is from 1.5 to 2.0, the value calculated above is not bad and is probably typical for tilapia. But, a step has been omitted. Recall that the FCR and FCE 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 a typical feed pellet contains something like 9 to 10% moisture. Let us recalculate the FCR and FCE using a moisture content in the feed of 9% to see if it makes a difference.

500 kg of feed × 0.09 moisture = 45 kg of moisture
500 – 45 = 455 kg of dry feed
FCR = 455 kg fed/280 kg gain = 1.63
FCE = 1/1.63 × 100 = 61.3%

Thus, by taking the water into consideration, the FCR and FCE improve, though only slightly.

In many laboratory experiments, FCR for some species has been < 1.0 meaning that the FCE 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 kg of feed offered because the animals may be supplementing their diets with natural food. In the laboratory, this is less likely to occur. The answer lies in the fact that in determining FCR and FCE, we look at dry weight of the feed compared to wet weight gain. A finfish, for example, may be 70% water, so a considerable amount of the observed weight gain is in the form of water. Thus, FCRs of 0.7 to 0.8 can easily occur, though in commercial culture, the figures previously provided (1.5–2.0) are considered to be reasonable, if not very good. When a farmer calculates FCRs of 3 (equating to 33.3 FCE), the animals can be considered to be significantly underperforming – at least in the case of most 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 FCEs because of their high rates of metabolism. For those species, feed costs may be a considerably higher percentage of total variable expenses, though if the final products bring premium prices, such as would be the case for sushi-grade tuna, the added expense would be recovered at the time of sale.

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7 Basics of Nutrition

Energy and Growth

Living organisms require energy to grow. Energy can come from a variety of sources. Plants utilize light as their source of energy, while animals depend upon food energy which is found in proteins, lipids and carbohydrates. Some organisms obtain their energy from other chemicals, but none of those are cogent to this discussion. In this chapter only aquatic animal nutrition, which is based upon food energy, is discussed.

The energy contained in the food aquaculture animals consume is measured in calories, which for our purposes involve the large calorie or kilocalorie (kcal). One kcal is defined as the amount of heat required to raise the temperature of 1 kg of water through 1°C. A small calorie is 1/1000 of a kcal. Aquaculture feeds need not only 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 needs to be evaluated individually.

As previously mentioned, one goal of the aquaculture nutritionist is to balance the diet's energy sources such that the protein is used primarily for growth, while lipids and carbohydrates are burned for various routine metabolic processes. White *et al*. (1964) 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 approximately twice the energy per gram as proteins and carbohydrates.

Not all of that food energy is actually available for growth and metabolism. The 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. 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 can be measured through a method known as bomb calorimetry from samples of the food and faeces. If one knows the amount of energy in the feed and faeces, the difference is the digestible energy value.

This is not the end of the story, however. There are a couple of other losses of energy after digestion that need to be taken into account before the energy that can be used for growth and metabolism (metabolic energy) can be determined. These additional losses are energy excreted via the gills and contained in the urine. Researchers often assume values of metabolizable energy for protein, carbohydrate and lipid average 4, 4 and 9 kcal/g, respectively.

The amount of energy burned by an organism at rest is a measure of its basal metabolic rate. When an aquatic animal swims (or moves about in some other fashion), is involved in reproductive activity or digests its food, etc. 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 the food. On the contrary, as in humans, active behaviour (exercise, if you will) is required for maintenance of proper physiological functioning.

Nutritionists are not only concerned that the species being cultured obtain the proper level of energy in their diets and the proper level of protein, they are also concerned about the ratio of protein to energy, or the P:E ratio (some nutritionists use energy:protein or E:P ratio instead of P:E ratio). A number of studies on P:E ratio optima in aquaculture species were summarized by Stickney (1994), and many studies looking at optimum P:E ratios or how various P:E ratios affect performance under various conditions have been published in the meantime. Some examples are: Woods *et al.* (1995), Britz and Hecht (1997), Dias *et al.* (1998), Keembiyehetty and Wilson (1998), Jantrarotai *et al.* (1998), Lin *et al.* (1998), Lupatsch *et al.* (1998), McGoogan and Gatlin (1998), Bautista-Teruel and Millamena (1999), Chuntapa *et al.* (1999), Cruz-Suarez *et al.* (2001), Tibbetts *et al.* (2001), Hafez (2002) and Gomez-Montes *et al.* (2003).

While many aquatic animals continue to grow throughout their lives, growth does level off 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. Postlarval and fry fish may double in size every few days, while young fingerlings may double every month or so and older submarketable animals grow at a rate that requires several weeks or months between doublings. These rates of growth apply to rapidly growing species. Some, particularly coldwater species, tend to grow more slowly. In general, the aquaculturist would like to be able to rear the species being cultured from egg to market within one year. For many species that can be done and it may even be possible to obtain two or more crops per year. In the tropics, for example, shrimp farmers can often get three crops per year by having postlarvae 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 years or more are required to rear the animals to market size, it may be difficult to obtain a profit unless the species brings a premium price.

Many species are harvested before they reach maturity, though we have already seen that there are exceptions, such as certain tilapia species that will become mature and begin to spawn well before reaching a size that is accepted in many markets. For such things 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 to 500 g range. Larger sizes of fish dominate some markets, and that is not necessarily a function of species. Similarly, some markets will accept fish of quite small size. For some species, different sectors of the market may desire different sizes of product.

Proteins

Proteins comprise the muscles and other connective tissues in an animal. They are also important as enzymes, which are responsible for catalyzing thousands of biochemical reactions. The estimated protein requirements of some aquaculture species are presented in Table 7.1. Note that in cases where two or more studies to determine the optimum protein level have been conducted, the results may not be in agreement. Differences in culture conditions, dietary protein sources, protein:energy ratio, feeding rate, number of feedings per day, initial animal size, stocking density and the response being evaluated (growth, food conversion efficiency, protein conversion efficiency or some other physiological parameter) are among the factors that tend to confound the

Table 7.1. Published protein requirements of some aquaculture species.

Species	Published Requirements	References
Abalone	Optimum dietary protein = 27%	Bautista-Teruel and Millamena (1999)
	Optimum dietary protein = 34%	Britz and Hecht (1997)
	Optimum dietary protein = 44%	Britz and Hecht (1997)
Shrimp, Black tiger	Optimum dietary protein = 35–46%	Guillaume (1997)
Blue	Optimum dietary protein = 44%	Colvin and Brand (1977)
Freshwater	Optimum dietary protein = 13–25%	Gomez *et al.* (1988)
Indian white	Optimum dietary protein = 40–43%	Guillaume (1997)
	Optimum dietary protein = 40%	Ali (2001)
Kuruma	Optimum dietary protein >40–60%	Guillaume (1997)
Pacific white	Optimum protein 1.8–3.8 g/kg body weight for juveniles and 1.5–2.1 g/kg body weight for sub-adults	Kureshy and Davis (2002)

Bass, European sea	Optimum performance with 40% protein	Dias *et al.* (1998)
	Optimum protein = 40% of diet	Hidalgo and Alliot (1988)
Striped	Optimum protein = 52% of diet	Berger and Halver (1987)
Carp, Bighead	Optimum protein for fry = 30% of diet	Santiago and Reyes (1991)
Common	40% protein diet improved by addition of arginine	Francis and Ramanathan (1995)
	Optimum protein = 35–50% of diet	Ogino (1980)
Grass	Optimum protein = 41–43% of diet	Dabrowski (1977)
Silver	Optimum protein = 37–42% of diet	Singh (1990)
Catfish, Channel	Optimum protein = 32–35% of diet	Garling and Wilson (1976)
Hybrid African (fry)	Protein requirement <50% of diet	Adebayo and Alasoadura (2001)
Hybrid African (2–4 g)	Maximum growth at 40% protein	Jantrarotai *et al.* (1998)
Indian	Protein requirement = 37–40% of diet	Singh (1994)
	Optimum protein = 30% of diet	Chatiyanwongse and Chuapoehuk (1982)
Charr, Arctic	Dietary protein requirement 37–42%	Gurure (1998)
Eel, Japanese	Optimum protein = 36–42% of diet	Nose and Arai (1972)
Flounder, Japanese (larval)	Optimum dietary protein >60% of diet	Bai *et al.* (2001)
Japanese (juvenile)	Optimum dietary protein >46.4% but <51.2% of diet	Kim *et al.* (2002)
Milkfish	Optimum dietary protein for fry = 40% of diet	Lim *et al.* (1979)
Mullet, Striped	Growth best at 28% protein	Lin *et al.* (1998)
Sea bream, Gilthead	Best growth and food conversion on ration with 500 g protein per kg of diet	Santinha *et al.* (1996)
Red	Optimum protein = 55% of diet	Yone (1976)
Tilapia, Blue	Optimum protein for fry = 56% of diet; for fingerlings, 34%	Winfree and Stickney (1981)
Mozambique	Optimum protein for fry = 40% of diet	Jauncey (1982)

continued

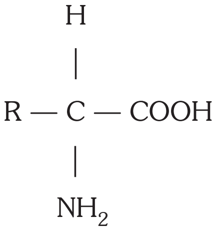
Table 7.1. (*continued*)

Species	Published Requirements	References
Nile	Optimum protein = 25% of diet	Wang *et al.* (1985)
Trout, rainbow	Optimum protein = 35–50% of diet	Ogino (1980)
	Requirement to meet indispensable amino acid requirement = 24%	Kim (1997)

results of such experiments. Perhaps the most important contribution of such studies is that they provide feed formulators with a target protein level or range that should lead to acceptable performance.

Amino acids combine in long chains to make up the thousands and thousands of different proteins that are found in the body of the animal. Each amino acid is comprised of carbon, hydrogen, oxygen and nitrogen. Three of them also contain sulphur. These are methionine, cystine and cysteine. While an individual protein molecule may contain thousands of amino acids in its formula there are only about 20 different amino acids that have been identified.

The basic structure for an amino acid is as follows:



$$\begin{array}{c} \text{H} \\ | \\ \text{R}-\text{C}-\text{COOH} \\ | \\ \text{NH}_2 \end{array} \qquad (8.1)$$

where R can be as simple as a hydrogen atom (glycine) or much more complicated, including benzene rings.

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). These are known as non-essential amino acids. Essential amino acids are those that need to be provided in the diet. Among them are a sulphur-bearing amino acid.

There are ten essential amino acids. They are:

- Arginine
- Histidine
- Isoleucine
- Leucine
- Lysine
- Methionine
- Phenylalanine
- Threonine
- Tryptophan
- Valine

It is important to provide all the essential amino acids at the proper level in the feed 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. Fish meal tends to meet the essential amino acid requirements of aquaculture species, which is one reason that fish meal is so often used as an ingredient in prepared feeds. Other animal proteins that provide proper levels of essential amino acids are meat and bone meal and poultry by-product meal. Shrimp head meal and krill have also found their way into at least some aquaculture feeds. Plant proteins are usually deficient in one or more essential amino acids. Lysine and methionine are two that seem to be present at inadequate levels in the plant proteins most commonly found in prepared feeds used in aquaculture.

Some plant proteins contain antinutritional factors such as protease inhibitors, phytates, glucosinolates, saponins, tannins, alkaloids and gossypols (Francis *et al.*, 2001). Regular cottonseed meal has glands in it that contain the yellow pigment gossypol which has been shown to depress growth in channel catfish if cottonseed meal is used at a level higher than 17.4% of the diet (Dorsa *et al.*, 1982). Salmonids appear to be able to tolerate somewhat higher levels of dietary cottonseed meal. (Wolf, 1952; Fowler, 1980). A glandless cottonseed meal has been developed in which the level of free gossypol is significantly lower than in glanded meal. If that type of cottonseed meal is used, higher levels than 17.4% can be fed to channel catfish without causing reduced growth.

Soybean meal is widely used in aquaculture feeds, but it too contains an antinutritional component in the form of a trypsin enzyme inhibitor that can limit fish growth. Depressed growth from trypsin inhibitor has been seen in carp (Viola *et al.*, 1983), channel catfish (Wilson and Poe, 1985) and tilapia (Wee and Shu, 1989). Proper heating of soybeans will reduce or eliminate the problem. Shimeno *et al.* (1997) found that inclusion of full-fat soybean meal in a diet used with yellowtail, improved growth of the fish when the diet was extruded or otherwise heated.

Lipids

Lipids are the fraction of the tissue of a plant or animal that can be extracted in such solvents as ether, chloroform and benzene. Several types of lipids occur in tissues. Included are fatty acids, triglycerides, phospholipids, glycolipids, aliphatic alcohols, waxes, terpenes and steroids. Fatty acids have the following chemical structure:

$$\text{R–COOH} \qquad (8.2)$$

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:

$$CH_3CH_2CH = CHCH_2CH = CHCH_2CH = CH(CH_2)_7COOH \qquad (8.3)$$

If a fatty acid contains no double bonds, it is called saturated. Fatty acids with two or more double bonds are called polyunsaturated. Linolenic acid is an example of a polyunsaturated fatty acid.

Depending on the species, animals may require certain types of polyunsaturated fatty acids (PUFA) that are found in three families that have been called omega fatty acids. You may have heard of the purported health benefits from omega-3 (ω3, also known as n-3) fatty acids. Linolenic acid (formula 8.3) is the smallest molecular weight fatty acid in that family. Other families of PUFA are the oleic acid (ω9 or n-9) and linoleic (ω6 or n-6) families, with the lowest molecular weight fatty acids in the ω9 and ω6 families being oleic and linoleic acids.

A shorthand notation has been developed for PUFA in the three families. For example, linolenic acid is presented as 18:3ω3 or 18:3n-3. 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. Biochemical conversions from one fatty acid to another within a PUFA family can often be made within the organism, but the fatty acids in one family cannot be used by animals to make those in another family.

Many terrestrial animals have a requirement for ω6 family PUFA, while the requirement in aquatic animals tends to be for PUFA in the ω3 and sometimes in both the ω3 and ω6 families. For marine species, eicosapentaenoic acid or EPA (20:5ω3) and docosahexaenoic acid or DHA (22:6ω3) are often required. These two fatty acids are often referred to as highly unsaturated fatty acids (HUFA). PUFA (including HUFA) are required for development and proper functioning of cell membranes.

Freshwater fish seem to be able to convert 18:3nω3 to HUFA better than marine fish (Yone, 1982), so HUFA are commonly supplied in marine aquaculture diets. Good sources are, as you might imagine, fish oils. Other marine oils are also sources of HUFA. Marine fish and anadromous salmonids appear to have a dietary requirement for ω3 fatty acids, while non-anadromous freshwater fish and at least some invertebrates appear to require both ω3 and ω6 fatty acids.

A recent study by Cheng *et al.* (2003b) found no significant differences in performance or body composition in Pacific white shrimp fed diets containing fish oil (high in ω3 HUFA) as compared with those fed diets containing soybean oil or poultry fat (high in ω6 PUFA). The authors concluded that the latter two lipids were appropriate replacements for fish oil in the diet of that species. D'Abramo (1997) reviewed the lipid requirements of crustaceans with respect to triglycerides and fatty acids.

Several reviews of fish lipid requirements have been written, though none appear to have been prepared recently and the available ones are not comprehensive: that is, they focus on finfish, and often on a particular group of finfish. An example is a paper by Stickney and Hardy (1989).

While many people currently monitor their cholesterol level and attempt to keep it as low as possible through controlling their diets and in many cases taking medications, at least some species of shrimp appear to require supplemental cholesterol in their diet. Teshima (1997) concluded that shrimp have a sterol requirement that can generally be met by including 0.5% dietary cholesterol. On the other hand, Thongrod and Boonyaratpalin (1998) indicated that banana shrimp did not perform better on diets containing 1% to 2% cholesterol compared with those fed a diet containing no cholesterol, but suggested that the species may require from 1% to 2% lecithin in their diet. D'Abramo (1998) concluded that a combination of dietary plant sterols was as effective as cholesterol in meeting the 0.6% requirement for total sterols in juvenile freshwater shrimp. Phosphatidylcholine, a precursor of cholesterol, can be used to satisfy the cholesterol requirement of marine shrimp (Chen and Jenn, 1991).

Over time, the PUFA in feed can oxidize and form peroxides. The result can be rancid feed that may be harmful to the fish that consume it or at least retard their growth (Ketola *et al.*, 1989). Adding antioxidants to the feed formulation will help protect the lipids from oxidation. Ethoxyquin and vitamin E are antioxidants that have been used in this manner.

Carbohydrates

Carbohydrates are rather 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, such as sucrose (glucose + fructose), maltose (glucose + glucose) and lactose (glucose + galactose) are called disaccharides. Carbohydrates with high molecular weights and made up of long chains of simple sugars are called polysaccharides. Examples are starches, cellulose and hemicellulose.

Carbohydrates are not stored in the bodies of animals to any large extent. The major place where carbohydrate can be found is in the liver in the form of glycogen, but that accounts for a very small fraction of the weight of an aquatic organism. 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, carbohydrate can be burned 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.

Some aquatic animals utilize carbohydrate 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. Trout do not digest carbohydrate well and can develop toxic levels of liver glycogen when fed diets too high in carbohydrates, while channel catfish and tilapia perform well on diets high in carbohydrates. Turning to crustaceans, freshwater shrimp grow poorly when the diet is supplemented with glucose but exhibit good growth on diets with high levels of starch (Gomez and Nakagawa, 1990). More specifically, black tiger shrimp perform more poorly on diets supplemented with glucose than on diets containing more complex carbohydrates (Alava and Pascual, 1987). Ali (2001) reported that dietary carbohydrate at levels up to 33% improved growth and spared protein in rations fed to Indian white shrimp. Disaccharides and starches were better utilized by that species than were 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 harbour intestinal flora that do manufacture the enzyme. Stickney and Shumway (1974) examined the intestinal tracts of a wide variety of marine and estuarine fish, along with 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 food those fish consumed and not to an endogenous source of the enzyme. Channel catfish that had been held indoors and fed prepared feed their entire lives were found to have a low level of cellulase activity, though there was no cellulase activity found in the 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 organism that fell into the culture tanks was the source of the enzyme.

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 primary 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. 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 tend to serve as coenzymes in biochemical reactions. Scientists believe that all the vitamins that are required by animals have been chemically identified. 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 their chemical structures.

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 submersion of feed pellets can lead to over 70% loss of that vitamin (De Muylder and Hillion, 2002). 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 to 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. Since those signs are fairly universal they were not included in the tables.

Just because a fish shows one or more of the signs listed in Tables 7.2 and 7.3, it 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.

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, citrus fruit (rich in vitamin C) and legumes. Synthetic vitamin packages are often added to fish feed formulations to ensure that the proper level of each vitamin is provided. It is very important to have a complete vitamin package in complete feeds, whereas supplemental feeds may not contain added vitamins.

Table 7.2. Signs associated with excess or insufficient dietary fat-soluble vitamin levels in fishes (Halver, 1989).

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
E	Hypervitaminosis	Lethargy, dark coloration
	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 water-soluble vitamin deficiency levels in fishes (Halver, 1989).

Vitamin	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

The potency of vitamins can be expressed in any of four ways: (i) International Units (IU), in which vitamin activity is 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 mg/kg of feed. Most of the vitamin packages 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 IU or USP units.

The vitamin requirements for only a few aquaculture animals have been determined in any detail. Good data exist for trout, salmon, carp and channel catfish. 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 with differences at various life stages.

Since some vitamins are degraded by heat, moisture and 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 that are commonly added to prepared feeds to help protect the vitamins are

Table 7.4. Range of vitamin requirements for finfish (trout, salmon, carp, channel catfish) and shrimp. (Sources: National Research Council, 1983; Satoh *et al.*, 1987; Wilson and Poe, 1988; Halver, 1989; Stickney *et al.*, 1984; Roem *et al.*, 1990a, b, 1991; Poston, 1991; Rumsey, 1991; Chen and Hwang, 1992; Shiau and Suen, 1992; D'Abramo, 1998; Boonyaratpalin, 1998.)

Vitamin and Units	Range of Amount in Diet	
	Finfish	Shrimp
A (IU)	1000–2000	Not Available
D (IU)	500–2400	Not Available
E (mg/kg)	30–100	Not Available
K (mg/kg)	10 or Required	Not Available
Thiamin (mg/kg)	1–15	120
Riboflavin (mg/kg)	7–30	22.3 g
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 or Required	Not Available
Biotin (mg/kg)	1–1.5 or Required	Not Available
Cyanocobalamin (mg/kg)	0.015–0.02, Required or Not Available	Not Available
Ascorbic acid (mg/kg)	30–150	100–8000
Inositol (mg/kg)	200–400, Required or Not Available	2000
Choline (mg/kg)	0–8000	600

lecithin (phosphatidylcholine), ethoxyquin, BHA (butylated hydroxyanisol), BHT (butylated hydroxytoluene) and vitamin E. To maintain the required level of vitamin C in the 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 highly heat stable. Shiau and Hsu (2002) reported that either the ascorbic acid or monophosphate form of vitamin C can spare the need for vitamin E in hybrid tilapia diets.

Culture conditions can influence apparent vitamin requirements. Some species – notably penaeid shrimp and tilapia – are able to graze on microflora that grow on the walls of culture chambers. These microflora may contain nutrients that are missing in an experimental feed to the degree that a deficiency cannot be produced. Roem *et al.* (1990c) were unable to obtain deficiency signs in blue tilapia fed diets deficient in pantothenic acid in a recirculating system. It was concluded that the fish were obtaining the vitamin from bacteria within the system. When the study was repeated in a flow-through system in which ambient sunlight promoted the growth of algae in the culture tanks, the results were the same. The algae were being grazed from the aquarium walls by the fish which were getting the vitamin through that source. In the third repetition of the work, a flow-through system was used in which extraneous microflora appeared to be eliminated and artificial light was used in a windowless room to avoid algal growth. The result was that the requirement for pantothenic acid was established (Roem *et al.*, 1991). It is probably not necessary to add pantothenic acid to tilapia feed in most water systems as conditions will commonly exist where one of the natural sources will be present and able to supply the required level of the vitamin.

Minerals

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. The opposite is true of freshwater species where the proper level of minerals must be consumed in the feed to meet the animals' requirements for proper tissue development and to support various life processes. Included in the places and activities where minerals are essential are skeletal tissue, 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
- Sodium
- Sulphur

As much as 80% of the inorganic material of a finfish is contributed by the seven major minerals (about 10% of the dry weight of a fish is comprised of inorganic material).

The trace elements include:

- Cobalt
- Copper

- Fluorine
- Iodine
- Iron
- Manganese
- Molybdenum
- Selenium
- Zinc

They are called trace elements since they are required in very small amounts. If present to excess, they can be toxic.

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 packages based on trout requirements are commonly used in conjunction with species for which detailed mineral requirement information is not available. The same is true of vitamin packages, in fact. Mineral as well as vitamin premixes that work well in trout feed seem to perform well when used in feed manufactured for other species of finfish 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 trout, channel catfish and common carp.

Table 7.5. Mineral requirements of representative aquaculture species (based on a review by Davis and Gatlin 1996). Ranges are indicative of the results of two or more studies in most cases.

Mineral	Species	Recommended level (mg/100 g diet)	Comments
Calcium	Kuruma shrimp	1.0–2.0	One study indicated calcium is dispensable
	Pacific white shrimp	Dispensable	
	Blue tilapia	0.17–0.7	In calcium-free fresh water
	Channel catfish	0.45–1.5	One study indicated calcium is dispensable; actual level depends on water hardness
	Common carp	Dispensable	
	Rainbow trout	Dispensable	
	Red sea bream	Dispensable	
Chloride	Rainbow trout	Dispensable	
	Red drum	2.0	As sodium chloride
Copper	Channel catfish	1.5–5.0	
	Common carp	3.0	
	Rainbow trout	3.0–3.5	

continued

Table 7.5. *(continued)*

Mineral	Species	Recommended level (mg/100 g diet)	Comments
Iodine	Chinook salmon	0.6–1.1	
Iron	Channel catfish	30	
	Common carp	199	
	Red sea bream	150–199	
Magnesium	Kuruma shrimp	0.3	One study reported that magnesium is dispensable
	Blue tilapia	0.023	
	Channel catfish	0.04	
	Common carp	0.06	
	Mozambique tilapia	Dispensable	
	Nile tilapia	0.059–0.077	
	Rainbow trout	0.05–0.07	
	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	
	Pacific white shrimp	≤0.34–2.0	
	Atlantic salmon	0.6	
	Blue tilapia	0.5	
	Channel catfish	0.33–0.80	
	Common carp	0.6–0.7	
	Hybrid striped bass	0.5	
	Rainbow trout	0.7–0.8	
	Red drum	0.86	
	Red sea bream	0.68	
Potassium	Kuruma shrimp	0.9–1.0	
	Red sea bream	Dispensable	

	Channel catfish	0.26	
	Chinook salmon	0.6–1.2	
Selenium	Channel catfish	0.25	In the presence of adequate vitamin E
	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 chemical substance called phytate (a form of phytic acid) that is present in various grains contains phosphorus but does not seem to be a good source of that element, because of poor digestibility, unless the enzyme phytase is added to the feed. One concern is that much of the dietary phytate enters receiving waters in the effluent from aquaculture facilities and can lead to eutrophication. A considerable amount of research on this issue has been conducted in the last few years. Hardy (1998) reviewed the topic. Peisker and Herzog-Moeller (2002) indicated that growth of rainbow trout fed pellets treated with phytase improved significantly as compared with fish fed untreated feed. Adding microbial phytase to rainbow trout diets comprised primarily of soybean meal and distiller's dried grain (Cheng *et al.*, 2003c) or soy protein concentrate (Cheng *et al.*, 2003a) has also been shown to improve fish growth.

Harmful Substances and Off-flavours

The issue with gossypol in cottonseed meal was discussed above and potential mould problems with improperly stored feed or feed stored too long have also been described. Another mould issue also deserves mention. Aflatoxin is a toxic metabolite of a mutant blue-green mould, *Aspergillus flavus*, that sometimes occurs as a contaminant of oilseed meals. This substance is known to cause hepatomas (liver tumours) in trout, liver lesions in tilapia and histopathology of the hepatopancreas in shrimp. The toxicity of aflatoxin to fish varies from species to species. The topic was reviewed by Lovell (1991) and Manning (2001). Mould growth with concomitant production of aflatoxin may be induced through improper feed storage. Moist feed is particularly susceptible to development of aflatoxin-producing mould.

Toxic algal blooms can occur in both freshwater and marine environments and have been known to cause mass mortalities in wild as well as in cultured fish. Toxins may also accumulate in the flesh of aquatic organisms and lead to sickness or death when the affected animals are ingested by higher animals, including humans. The extensive literature on the topic of harmful algal blooms was reviewed by Landsberg (2002).

More common than direct toxicity is off-flavours in cultured animals. The problem has been associated with various chemicals, including geosmin and 2-methylisoborneal, produced by blue-green algae (cyanobacteria). Off-flavour is typically reported as an earthy, musty odour or a muddy taste. The topic has been reviewed in detail by Tucker (2000).

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 can be metabolized by fish. Placing affected fish in uncontaminated water for a period of time will resolve the problem. Diongi *et al.* (2000) found that depuration 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-methylisoborneal with various chemicals. Of those evaluated by Schrader *et al.* (1998), the only effective one that was environmentally and toxicologically safe was sodium carbonate. Copper sulphate has been used to control algal growth, but toxic levels of copper and the impact on waters receiving aquaculture effluents are concerns. Kelly *et al.* (2003) reported that adding such hydrophobic substances as paraffin and maize oil significantly reduced the levels of 2-methylisoborneal and geosmin in laboratory studies. Application of the technique to commercial culture situations apparently remains to be demonstrated.

Most of the 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 product. Even a small percentage of off-flavoured fish is deemed unacceptable because any customer who purchases an off-flavour catfish is 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 and smelling it (sometimes the odour can be detected in raw flesh). The tail is then microwaved to cook it and is then tasted. The test is often conducted at least three times before the fish are processed: several days before a pond is harvested (the farmer takes a fish from the pond to the processing plant), three or so days before harvest, and when the shipment arrives at the plant or before the fish are captured but on the day of harvest. If the fish fail any of the tests, they 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 fish 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 that an off-flavour is detected.

Off-flavour can be eliminated, as previously mentioned – by a process known as depuration – within a few days if the fish are placed in water, such as from a well, that is free of the algae that cause the problem. Most farmers do not have suitable facilities to depurate their fish so they have to wait for the algal bloom in the pond to die off and keep testing the fish until the animals can be processed. In one visit I 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 considerably higher.

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8 Finishing Up

Introduction

As one wise individual said about the work of an aquaculturist, 'You're not finished 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 of sufficiently high quality that it is readily accepted by consumers, and in many cases, that it can compete effectively with wild-caught counterparts taken in the commercial fisheries. The culturist needs not only to maintain a high-quality growing environment for the plants and animals being reared, there must also be care taken during harvesting, processing, packaging and storage of the product. Some of those 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 even process and market the product directly, thereby by-passing 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 product.

Harvesting

Harvesting may involve all the animals in one or more culture units or as has been discussed with respect to channel catfish, there may be intermittent harvesting of marketable fish with restocking with fingerlings. This technique is also called partial harvesting. Live harvesting and shipping is conducted with some species. This technique involves harvesting in a way that does not damage the fish, or at least keeps damage to a minimum, and is followed by hauling the fish to the processor alive in trucks designed for that purpose (Figs 8.1 and 8.2). The size of the vehicle used naturally depends on the amount of fish being harvested and distance to the processing plant. If the plant is nearby, making several runs with smaller vehicles during the harvesting is an option as is the use of two or more trucks if one will not do the job. For very small harvests, delivery of fingerlings and moving fish around a facility, a tank on the back of a pickup truck provides yet another option.

Fig. 8.1. A medium-size live-hauling truck.

Fig. 8.2. A large live-hauling truck.

In many cases, harvested fish and shellfish are harvested and immediately placed on ice for shipping. In those cases, shipping can also be by trucks fitted with large insulated containers, such as the one shown in Fig. 8.3.

Harvesting extensive culture systems

Proper pond design as discussed in Chapter 2 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 have an all-weather road on two sides (which should be opposite one another), are all 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 have some type of snags associated with them which inhibit easy harvesting of the crop. Trapping, gill netting or some other form of harvest will have to be used in such situations.

Having a drain in each culture pond is also important so the water can be removed by gravity. In some cases, such as with shrimp harvesting, it is even possible to place a net over the end of the drain pipe to capture the shrimp as they are flushed out of the pond during draining. It is certainly possible to pump water out of a pond, but that involves the use of an electric, petrol or diesel pump which means additional expense to the producer that can be

Fig. 8.3. A truck with large tanks that can be used for hauling fish or shellfish on ice to the processor.

avoided through installation of a gravity drain; a once-only expense and not a recurring one.

While partial harvesting may allow the culturist to maintain a pond in production for up to several years, eventually complete draining will be necessary, so having drains in ponds that are operated using the partial harvesting technique is still important. Eventually, pond levees will erode 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, drained and reworked. Reworking involves reshaping the levees and allowing the bottom to dry so that the organic matter becomes oxidized. 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. 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 morning before daytime heating of the water 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 begins depends upon the size of the pond and the size of the drain or drains, 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 overnight before the seine crew arrives, only to find many dead fish and the remaining live ones flopping around in the mud.

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. The seine needs to be deep enough so 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 workers to follow the seine through the pond and stand on the lead line to help keep it on the bottom. The float or head line of a seine typically consists of a rope to which floats made from cork, plastic, Styrofoam® or some other buoyant material are attached at intervals of several centimetres. The lead line is typically a nylon rope with lead weights spaced at intervals of a few centimetres. 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, bundled together to make a larger rope of 3 to 4 cm diameter that, when water soaked, tends to hold the bottom well without collecting balls of mud.

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 in the middle into which the fish are gathered.

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 sizes. When partially harvesting, it may be sufficient to pull the seine through the pond only once or twice to achieve the desired result; that is, to collect the majority of the harvestable-size fish.

During total harvest, smaller mesh seines are used as the object is to collect as many of the fish as possible, and ultimately to collect them all. Following the first seine haul the water level may be reduced and a second seine haul is made. The process is repeated until the pond is virtually empty. This 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 in the mud) will be trapped. Having a supply of new water at the harvest basin is also important during the final stages of harvesting as the small amount of water in the harvest basin will heat rapidly under full sunlight during warm weather, thereby severely stressing the fish. 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 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.

There have been several techniques employed in getting the crop from the seine to the hauling vehicle. Baskets may be hand carried up the levees and handed up to workers who put the animals in the live hauling tank or box of ice. This 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 pond to the hauling truck. I have seen conveyer systems used to bring fish from the pond bottom to the top of the pond bank as well.

One device that is a real labour saver is the fish pump. Fish pumps basically suck the fish out of the seine bag or harvest basin and transfer them to the hauling truck or to a sorting area. Various designs have been developed, with the major standard feature being that they are gentle enough that the animals are not damaged when going through the pump.

Since there are so many different size ponds and producers around the world who have different capacities with regard to mechanical assistance and with respect to seining and hauling the catch to market, the descriptions above tend to relate best to fairly sophisticated and large-scale culture operations. Modifications to suit local conditions in small-scale and subsistence operations need to be made. In some cases, the catch is carried in reed baskets to the local market by hand 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 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 force the culture animals into a fairly small volume of water from which they can be removed with dip nets or fish pumps. The amount of crowding can be increased as animals are removed so that the concentration within the crowder remains high. A crowder in a raceway may be a metal frame with vertical bars placed at intervals close enough that marketable animals cannot escape. Alternatively, frames with screens attached may be used. The crowder is pushed from the upper (inflow) end of the raceway toward the lower (drain) end, forcing the fish or invertebrates to move toward 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 that the animals are eventually crowded between the devices. In deep tanks, the water level may need to be reduced before the animals are crowded.

One trout hatchery I visited used a fish pump to remove the fish from the raceways. The fish then travelled through a pipe to a sorting machine that separated them into size classes after which they were taken, by means of pipes through which the individual size groups passed, directly into the processing plant that was located not far from the culture raceways.

If the harvested animals are loaded onto a truck within a building, the aisles between culture chambers need to be sufficiently wide (and the ceiling 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. Using experienced architects and engineers when designing facilities 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 one that is constructed on pilings for harvesting. If the cages are moored away from the platform they can be towed to it for harvesting. Having a winch and gantry on the platform so the cage can be partially lifted and tilted during harvest will come in very 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. Lifting cages from the water when they are full of fish is generally not practical because cages are not designed to accommodate the weight and would probably rupture. If the cage were to rupture during harvest, most or all of the crop contained within that cage would be lost along with the money involved in rearing the animals to harvest size.

Large marine cages, some of which now measure 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 a net within a net 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 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 are used to transport the fish back to land where they are transferred to trucks, or the boats may sail directly to a shoreside processing plant. Sedation with isoeugenol (Aqui-S™) has been used in conjunction with salmon harvests from net pens to reduce stress. The technique has also been evaluated with respect to harvesting catfish (Bosworth *et al.*, 2002).

Submarketable individuals captured from raceways, tanks, cages or net pens can be transferred back into the culture chamber from which they were captured. A more common technique would be to place the animals in a different culture chamber for further growout. If submarketable 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.

Specialized harvesting methods

Harvesting sessile marine animals such as oysters and mussels requires harvesting techniques different from those used for motile species. Oysters reared on the bottom can be harvested manually by picking up intertidal oysters at low tide or by tonging (collecting oysters using specially designed tongs) or dredging for subtidal animals. Some states have regulations on harvesting oysters that have even been applied to aquacultured animals. Florida, USA, has long restricted oyster harvesting 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 harvests from aquaculture facilities on Sundays. In other states, fish raised on private property are deemed property of the state, not the individual land owner. Over the past several 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 long lines suspended from rafts are manually harvested through mechanical devices which are used to raise heavy strings of animals to the surface. Mechanical oyster harvesters to collect the animals from the bottom have been developed (Collier and McLaughlin, 1983). Mussels are grown on the bottom, on poles and on long lines. Harvesting technique is based on how the mussels are grown, but generally mirror the methods used for oysters. Scallops are sometimes grown in lantern nets (a type of basket) attached to long lines. Scuba divers are commonly used for harvesting benthic animals such as abalone.

Clams can be dredged or grown in trays, in which case they are manually harvested. One technique is to plant young clams in the intertidal zone under netting, which helps keep predators from attacking the animals. 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 designed to collect the clams. 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, crawfish are harvested using baited traps such as the one shown in Fig. 5.9. The trapping season is up to several months long, since it involves first the recapture of the adults that were stocked for reproductive purposes, and second, capture of the young-of-the-year crawfish that recruit to harvest size. The traps are run at least once a day using a shallow draught small boat with an outboard motor. Specially designed motors are used in Louisiana, USA, that can be operated in the very shallow waters of the crawfish ponds. As the boat approaches a trap, it 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 is then rebaited for use. Often trapping is conducted by one person in the boat, though having two people can expedite the process.

Factors that can affect the efficiency of trapping include the amount of natural food (forage) present, water quality, crawfish density, climate, trap design, the bait being used and trap density (Romaire, 1989). While only one trap design has been shown in this book (Fig. 5.9), a large number of designs are currently in use.

Traps are baited with dead fish or commercially manufactured baits, three types of which were evaluated by Rach and Bills (1987). 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 according to Burns and Avault (1990). Much of the harvest period occurs when the water temperature may actually be lower than 14°C.

Crawfish producers began producing soft-shell crawfish in 1985 (Culley and Doubinis-Gray, 1989) and there was a significant demand for the product during the first few years after it became available and commonplace. To produce soft-shell crawfish, immature animals are trapped and put in culture trays at high density where they are fed. The culturists were able to identify crawfish that are about to moult and would remove them from the population to avoid cannibalism. Once they moulted, the soft-shell crawfish 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 soft-shell production facilities that were once numerous in Louisiana. Only a few continue to operate. Imports also outcompeted frozen crawfish tails in the US market by being less expensive than the domestic product. The market for processed crawfish, mostly in the form of frozen tail meats, is dominated by imported product. The vast majority of the crawfish harvested in Louisiana are now sold live for crawfish boils.

Live-hauling

We have already seen that live-hauling can involve carrying harvested aquaculture animals to market in tanks of water mounted on trucks (Figs 8.1 and 8.2). Such trucks need to be equipped with aeration equipment. Trucks or pickup trucks typically employ agitators that consist of electric motors from which a paddle in a cage is suspended about half-way into the water. The cage is hardware cloth and protects the live fish from contacting the paddle when the motor is running. The caged paddle 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 sits on top of the hauling tank. The motors run off the truck battery. When activated, the paddles spin rapidly causing agitation of the water which leads to aeration and the maintenance of dissolved oxygen. Another method commonly used is bottled oxygen or compressed air fed to the water through airlines and airstones.

Large trucks may use any of the methods mentioned for pickup trucks, in addition to perhaps carrying a liquid oxygen tank or a generator that runs a blower or agitators. In many cases, at least two aeration methods are available on large trucks so there is a back-up in case one of the methods of aeration should fail. I once helped load several thousand channel catfish fingerlings on a small hauling truck for a trip of a few hundred kilometres from one government laboratory to another. During the trip, the driver frequently checked the agitator visually to determine that a wheel on top of the motor was spinning (thereby indicating that the motor was running). When the fish arrived at their destination, the driver discovered that most of them in one of the tank compartments were dead and that the dissolved oxygen level was below the critical level. The paddle on the agitator in that compartment had fallen off, so while the motor was running, the water was not being aerated.

Animals scheduled for hauling should not be fed for at least 24 h prior to being loaded so they can purge their intestinal tracts. This 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 used. 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 an acceptable anaesthetic for fish going to processors since it is a natural by-product of respiration.

Anaesthetics that have been effectively used on fish include quinaldine, tricaine methanesulfonate (MS-222), benzocaine, AQUI-S™, FINQUEL™, Tricaine-S™, etomidate, metomidate, 2-phenoxyethanol, clove oil and the previously mentioned carbon dioxide. The concentrations of the chemicals needed for effective anaesthesia will vary with the species involved, water temperature and other factors. Quinaldine has come into disfavour because of potential toxicity to people. MS-222 is effective but quite expensive and can cause significant reduction in pH (Allen and Harman, 1970). Clove oil has been shown to anaesthetize at least one species of penaeid shrimp (Soltani *et al.*, 2002), but is apparently not effective on freshwater shrimp, nor are MS-222 or 2-phenoxyethanol (Coyle *et al.*, 2003). MS-222 is the only anaesthetic currently approved for use with aquaculture fish in the USA, though efforts are underway to gain approval for use of AQUI-S™, which is currently approved as a food flavouring substance (Bowker *et al.*, 2002).

Carbon dioxide anaesthesia can be produced by adding CO_2 gas or carbonic acid to water.

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 and hauling stress the fish experience. There does not appear to have been a great deal of research focused directly on the question of optimum density during live hauling, but a recent study by Gomes *et al.* (2003) evaluated that situation with respect to tambaqui. They found that the best density over 10 h of hauling among four densities they evaluated was 78 kg/m. At that density there was no mortality 23 h post-hauling.

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 by shipping such items out of water and they can be delivered anywhere in the world within 24 h. Traditionally, trout eggs have been shipped packed in wet Spanish moss. Baseball-size packages of oyster spat (several million in number) 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.

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 fish 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 line is placed in the bag, the top of the bag is wrapped around the air line, and oxygen is pumped into the bag to saturate the water and displace the air in the bag over the water with pure oxygen. The air tube is then extracted and the bag is sealed with a rubber band. The bag is then placed in an insulated box which 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 thing is to get the boxes delivered within 24 h, if possible.

Several years ago I was asked to send some tilapia fingerlings (3 to 4 cm in length on average) from Texas, USA to Canada. We boxed up a few hundred fish in bags that each contained about no more than 50 fish. The flight schedule called for delivery at the final destination within about 8 h after the boxes were first boarded on a plane. Several weeks passed after the fish were shipped before I heard back from the Canadians. They said 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 dissolved oxygen was virtually zero. Of about 400 fish in the shipment fewer than 10 failed to survive the trip. I do not recommend trying that with any other species. The tilapia probably would not have survived either, except the shipment was made during the winter and the cold weather helped reduce the metabolism of the fish while they sat on the tarmac. Fortunately, it was not cold enough to kill them.

Fee-fishing

Fee-fishing operations may be independent of other aquacultural activities or they may be integrated into the production of food animals for sale 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 for catfish and trout can be found in many regions, with the species available being dependent on climate. In Brazil, various local fish such as pacu, as well as exotics such as tilapia are found in fee-fishing operations (Fig. 8.4).

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, while in the latter the fish would be purchased from a grower. An intermediate activity would involve production ponds strictly for growing fish to be stocked in fee-fishing lakes on the same facility.

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. 8.5). Picnic tables and other amenities may also be provided. Anglers are expected to keep all the fish

Fig. 8.4. A sign in Brazil showing the types of fish available to fee-fishermen.

Fig. 8.5. Fee-fishing facilities can be aesthetically pleasing and provide other recreational opportunities for visitors.

caught and pay on the basis of the weight or number of fish they remove from the lakes. In some cases an entry fee may also be required.

The operator of a fee-fishing operation will stock the ponds with catchable fish and frequently replace the ones caught with new ones. The point is to make sure that each angler has a very large 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.

Since fee-fishing operations profit from the capture and removal of fish, it makes sense to keep the ponds well stocked and to limit feed so that the fish are hungry. A good fishing experience is not only good for profits; it also helps ensure that customers will return for additional enjoyment.

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 or not well maintained. 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.

Well-operated fee-fishing facilities offer an array of services to anglers. Bait is commonly sold and the facility may rent 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 made available. Public restrooms (often in the form of portable toilets) are a must, and refreshments should be made available through vending machines or at a sales stand.

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 landing 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 far distant from the aquaculture operation. The availability of local processing plants can be a determining factor as to whether to process on farm or ship the product to a processor. If the harvest is processed on the farm, having a well-developed market for the product is essential. This may be anything from shipping frozen product in trucks owned by the culturist to selling the product fresh or frozen from a market established on the farm, to everything in between.

In 1997, a new regulation in the USA requiring seafood processors to implement a HACCP (Hazard Analysis Critical Control Point) safety control system was implemented (Gall, 1998). Monitoring programmes and mandatory record keeping are part of the HACCP programme. Seafood safety inspections are also being 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 farmers 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. A crawfish processing plant would not, for example, typically also process catfish or oysters. 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 by using automated equipment, though efficient automated equipment is yet to be developed for some species. Imagine coming up with a machine to clean crabs, for example. Actually, such machines have been developed, though they do not tend to be very efficient, at least the ones I have seen. As a result, crab processing, as 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 bandsaw, 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. At each stage of processing a person holds the fish and applies it to the machine. Fully automated processing lines are not used.

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, be put through a filleting machine or be 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.

Marketing of seafood, including aquaculture products, requires year-round availability of the product in most cases. Seasonal availability of a product will make it impossible for chain restaurants to maintain a consistent menu. Grocery stores may accept seafood species on a seasonal basis, 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. Failure by the producer or processor to meet that commitment will lead to loss of a retail customer. The same holds true for restaurants. As an aside, some aquaculturists have their own restaurants on or adjacent to the farm where they feature the products they grow. In cases where the product is only available seasonally, the restaurant may be closed for part 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, in particular, like to select their dinner at a restaurant from among the live specimens on exhibition. In 1999, on a trip to China, I visited several restaurants in two major cities. In all cases, aquariums with a wide variety of seafood species were on display. One tilapia farmer I visited in Idaho, USA several years ago, was shipping a few thousand kilograms of tilapia live each week to Vancouver, Canada for display (and consumption) in local restaurants. Many other examples could be cited.

The primary objective of the farmer, producer, wholesaler (if any), grocery outlet and restaurant is to provide a high-quality product, so the consumer will have a positive experience when he or she eats the fish or shellfish. As previously mentioned, it is the responsibility of all those who grow or handle fisheries products to ensure that product quality is maintained. Once the animals leave the farm, control over the product devolves to someone else who takes on the responsibility for maintenance of its quality. The final point of sale, whether a fish market, grocery store or restaurant, is also a critical point in the process of maintaining quality. In any of 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 product first, because the longer the product stays in the meat case, refrigerator 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.

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 an extended period of time. 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.

Potential Aquaculture Moneymakers

My career has involved, in part, conducting aquaculture research and teaching students about aquaculture at college level. I admit to never having had to depend on an aquaculture crop for a livelihood. However, if I were to go into the business – and having observed commercial aquaculture for over 30 years – I think I would lean toward producing ornamental fish or invertebrates. The amount of space involved for production is relatively limited since the animals are small when harvested and marketed, and the price per piece in the marketplace can be quite high (which, one would hope, translates to a premium price for each piece to the producer as well). This is particularly true for marine fish and invertebrates. The problem with marine species is that successful culture has only been achieved for a few of them. This will change with time, so if I were involved in producing marine aquaculture species, I would (if I could afford it) develop a research programme as an add-on to my production facility, so I could develop culture techniques for new species.

Koi carp are also attractive as an alternative to foodfish. Koi can bring extremely high prices if fish with the most desirable colour patterns can be produced. The problem is getting high-quality broodstock from producers in Asia who do not want to give up their advantage in having control of those animals. Even relatively common-coloured koi bring fairly good prices, so production of them is an option to be considered.

For those who are interested in aquarium species and would like to make a living working with them, you might consider the aquarium maintenance business. You would have to live and/or work in a fairly large city to be successful. The business involves maintaining display aquariums in businesses, doctors' offices and other locations where you would be paid for the service. You 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, periodic replacement of the finfish (and invertebrates, if any) when mortalities occur and may even involve routine feeding.

A few people are making a living by being 'fish doctors.' Those people provide veterinary[1] services to clients who maintain highly priced fish such as koi. Those who are successful in the fish doctoring business are 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 successful.

If you are able to find a way to produce a pharmaceutical or neutraceutical product from an aquatic plant or animal species, you could potentially make a fortune. Be advised that I have been told that it takes screening of 5000 or so chemicals from aquatic species to find one that has any commercial

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[1] I am not implying that the person providing those services needs to be a veterinarian as you do not have to be licensed to treat aquaculture animal diseases. Having a veterinary degree would undoubtedly be useful, however, as it would help establish your credentials.

value. The costs of finding some chemical that will have some potential in treating a disease can be enormous 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 manner.

Many who go into commercial aquaculture do so because they want to provide nutritious high-quality food for people. This has been what the bulk of this book is about and I applaud those who embark on that aspect of aquaculture.

My Crystal Ball

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 against 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 foodfish (which if you recall, I defined as being inclusive of finfish and invertebrates that are cultured as human food). Aside from the preceding section and a few mentions of plant culture in this book, foodfish has been the focus and is the focus of the comments that follow.

There is no doubt in my mind that aquaculture will continue to grow on a global basis. The increasing human population and concomitant increasing demand for seafood in the face of level or declining wild captures requires increases in aquaculture production. The question is, from where will the products emanate? Currently, the growth areas are primarily in Asia and in parts of Latin America. Modest increases in production have occurred in Europe and North America, but the potential production in those areas is far greater than what has been achieved to date. Much of the lack of production is the result of opposition to aquaculture development and a strict regulatory environment that is often difficult to navigate as one goes in search of permits.

I follow what might be called ‘the aquaculture wars’ fairly closely by reading news releases that range from deriding aquaculture products as being sources of dangerous foods to claims for products that 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 development.

I, like most interested in aquaculture, am opposed to environmental degredation, but I believe that aquaculture can be developed in a manner that will not cause harm to the environment. What I would not like to see is pressure from the increasing human population being so great that environmental concerns from unlimited aquaculture development would be ignored or discarded.

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. As developing nations become more affluent, the amount of domestic demand for aquaculture species that had been produced almost exclusively for export will increasingly be consumed domestically. At some point, importing nations will not have sufficient production to meet existing demand. When that occurs, either alternative foods need to be provided or domestic aquaculture production will have to expand.

It is my view that when imports to developed nations decline, those nations will take up the challenge and will produce more aquaculture products for their internal consumption. The important point is that when that happens the domestic production should be accomplished without causing environmental damage. I 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 I am optimistic that aquaculture species can be produced with little or no environmental damage. The future will tell, and my 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.

At some point, the public in nations where aquaculture is under fire are going to have to make a decision. What they decide will have a significant influence on the future of aquaculture in many nations. My trust in human nature convinces me that the public will make the right decision: which is, in my view, to support aquaculture development with appropriate regulations to ensure that the environment, and thus the quality of life for all of us, is protected.

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