Aquaculture

Farming Aquatic Animals and Plants

Second edition

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WILEY-BLACKWELL
A John Wiley & Sons, Ltd., Publication

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Registered office: John Wiley & Sons, Ltd., The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial offices: 9600 Garsington Road, Oxford, OX4 2DQ, UK
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK
2121 State Avenue, Ames, Iowa 50014-8300, USA

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Library of Congress Cataloging-in-Publication Data
Aquaculture : farming aquatic animals and plants / edited by John S. Lucas Paul C. Southgate. – 2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN-13: 978-1-4051-8858-6 (pbk. : alk. paper)
ISBN-10: 1-4051-8858-8
1. Aquaculture. 2. Algae culture. I. Lucas, John S., 1940– II. Southgate, Paul C.
SH135.A6735 2011
639.8–dc23
2011022687

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

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Set in 9.5/12 pt Times by Toppan Best-set Premedia Limited

1 2012

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Preface to the Second Edition

The rapid growth of aquaculture continues at a faster rate than predicted a decade ago. Total global production by 2007 had increased by two-thirds over the production reported in the first edition of this book. This has been possible because of new technical developments, rapid expansion of some new and existing industries, and diversification in the species utilised by aquaculture. These exciting developments provide the basis for this second edition, which includes a major revision of production statistics and chapter contents, seven new chapters and a more diverse international authorship and coverage. There are contributors from 12 countries, and aquaculture in many more countries is considered. With the increasing importance of China as the major source of aquaculture products, there is greater consideration of aquaculture in that country. There are three new Chinese authors contributing to this edition. Sadly, Professor C. K. Tseng, who contributed Macroalgae in the first edition, is now deceased. He is considered to be the 'father of Chinese mariculture' for his great achievements in marine science and outstanding leadership in that country over many years.

We express our sincere gratitude to the authors for their commitment in contributing chapters and, in some cases, for their understanding and patience. We also express our gratitude to our wives, Helen and Dawn, for their contributions and support. We trust that you will find this new edition both helpful and stimulating.

John S. Lucas
Paul C. Southgate
June 2011

Preface to the First Edition

This textbook seeks to convey to its readers the contributors' enthusiasm for aquaculture and their accumulated knowledge. The contributors are recognised internationally in their fields. While it is not possible to comprehensively cover the ranges of aquaculture theory, practices and cultured organisms in one textbook, it is our earnest hope that this text will give readers a broad understanding of these topics.

The first part of the text introduces aquaculture with a series of 'theory and practice' topics, ranging from traditional topics such as ponds and pumps to contemporary environmental issues, nutrition physiology and genetic engineering. The second part of the text consists of chapters dealing with specific organisms, or groups of organisms, which illustrate the variety of culture methods used in aquaculture. It also provides examples of biological and other factors that make these organisms suitable for culture. The aquatic animals and plants treated in the text are but a small proportion of the hundreds of commercially cultured species; however, they constitute the most significant commercial components of world aquaculture production. They include the four major groups of cultured organisms – fish, crustaceans, bivalve molluscs and seaweeds; the three broad categories of aquatic environments – fresh, brackish and seawater; and the broad latitudinal zones – temperate, subtropical and tropical regions.

We express our sincere gratitude to the authors for their commitment in contributing chapters and, in some cases, for their understanding. Mr Michael New, President, European Aquaculture Society, Past-President, World Aquaculture Society, kindly assisted by reviewing Chapters 1 and 23. We also wish to express our gratitude to our wives, Helen and Dawn, for their substantial contributions.

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April 2003

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1
Introduction

John S. Lucas

1.1 WHAT IS AQUACULTURE?

Give a person a fish and you feed them for a day; teach them how to grow fish and you feed them and their descendants for their lifetimes.

(somewhat modified from a Chinese proverb)

Aquaculture continues to develop rapidly, especially through its growth in Asia. World aquaculture production is increasing much more rapidly than animal husbandry and capture fisheries, the other two sources of animal protein for the world's population. There is widespread recognition that seafood production from capture fisheries is at or near its peak, and that aquaculture will become increasingly important as a source of seafood production, and ultimately the main source. There is widespread public interest in aquaculture. This is the context in which this textbook is written and we trust that it will convey some of the excitement of the rapidly developing discipline of aquaculture.

The term 'seafood' is used inclusively in this textbook, i.e. for all animal and plant products from aquatic environments, including freshwater, brackish and marine environments[1]. The term 'shellfish', according to common usage, describes aquatic invertebrates with a 'shell'. In this way, bivalve and gastropod molluscs, decapod crustaceans and sea urchins are combined, while recognising the extreme diversity of morphology and biology within this grouping. The two groups that overwhelmingly constitute shellfish are the bivalves (oysters, mussels, clams, etc.) and decapod crustaceans (shrimp, crayfish, crabs, etc.). The other major group of aquatic animal that is cultured is fish, also known as finfish. 'Fish farming' is used in the sense of aquaculture of fish, crustaceans, molluscs, etc., but not plants.

There are many different forms of aquaculture and, at the outset of this book, it is important to establish what aquaculture is, what it isn't and what distinguishes it from capture fisheries.

> The definition of aquaculture is understood to mean the farming of aquatic organisms, including fish, molluscs, crustaceans and aquatic plants. Farming implies some form of *intervention* in the rearing process to enhance production, such as regular stocking, feeding and protection from predators. Farming also implies individual or corporate *ownership* of stock being cultivated.
>
> *(FAO, 2006)*

> For statistical purposes, aquatic organisms that are harvested by an individual or corporate body that has owned them throughout their rearing period contribute to *aquaculture* while aquatic organisms that are exploitable by the public as a common property resource, with or without appropriate licences, are the harvest of *fisheries*.
>
> *(FAO, 2006)*

The two essential factors that together distinguish aquaculture from capture fisheries are:

- *intervention* to enhance the stock;
- *ownership* of the stock.

[1] With the exception of the final chapter, Chapter 26 The Next 20 Years, which focuses on edible products ('Food fish') and food security. The terms used in Chapter 26 are defined in its Introduction.

Aquaculture: Farming Aquatic Animals and Plants, Second Edition. Edited by John S. Lucas, Paul C. Southgate.

Thus, a structure to which fish are attracted and caught (e.g. a fish-aggregating device (FAD) floating in the open ocean) may be owned, but this does not confer ownership of the stock of attracted fish. Furthermore, the FAD facilitates capture, but does not enhance the fish stock that is being captured. This is capture fisheries production. Hatchery production of juvenile salmon is aquaculture: they are owned by the hatchery and may be sold as fingerling fish. Their ultimate capture, after being released into rivers to which they eventually return to breed, is a fishery. The released fingerlings enhance the stock, but they become a common property resource. The same situation applies where hatchery-reared fish fingerlings are sold to fishing clubs and local government bodies to be stocked into lakes and dams to improve recreational fishing.

Hydroponics, the cultivation of terrestrial plants with their roots in dilute nutrient solutions instead of soil, isn't aquaculture. Hydroponics is an alternative method for growing terrestrial plants.

Activities constituting aquaculture production, according to FAO (2006), are:

- hatchery rearing of fry, spat, postlarvae, etc.;
- stocking of ponds, cages, tanks, raceways and temporary barrages (e.g. dams) with wild-caught or hatchery-produced juveniles to be reared to market size;
- culture in private tidal ponds (e.g. Indonesian 'tambaks');
- rearing molluscs to market size from hatchery-produced spat, transferred natural spatfall or transferred part-grown animals;
- stocked fish culture in paddy fields;
- harvesting planted or suspended seaweed;
- valliculture (culture in coastal lagoons).

1.2 ORIGINS OF AQUACULTURE AND AGRICULTURE

There were a number of independent origins of small-scale agriculture and a substantial variety of crops were domesticated for farming. Small-scale agriculture appears to have first developed about 10 000 years BC in the Fertile Crescent of south-west Asia, corresponding roughly to the modern-day region of Syria, Israel and Iraq, as human populations changed from hunting–gathering to cultivating crops that included wheat, barley, lentils, chickpeas, etc. (Fig. 1.1). Farming of cereals and other crops spread to adjacent regions. Subsequently, the farming of cereal crops arose independently on other major landmasses. Rice cultivation began in Asia about 7000 years ago. Sorghum and millet cultivation, and maize cultivation, developed somewhat later in Africa and America, respectively. These changes from hunting–gathering to farming cereal crops caused profound changes in lifestyle, from a nomadic to a settled existence. They resulted in greatly increased productivity from the land for human consumption and increased human populations per unit land area as a consequence. Whether quality of life improved in the early farming communities is debatable: diet became less varied and conditions became more favourable for disease.

The origins of aquaculture are much later. Culture of common carp (*Cyprinus carpio*) was developed thousands of years later in China, where the carp is a native species (Fig. 1.2). The first aquaculture text is attributed to a Chinese politician, Fan Lei, and is dated about 500 BC (Ling, 1977). Fan Lei attributed the source of his wealth to his fish ponds: so his fish culture was more than a hobby. However, in Africa, America and Australia, aquaculture was not practised until it was introduced in recent centuries.

The late origin of aquaculture compared with agriculture and its failure to develop in some continents is partly because humans are terrestrial inhabitants. We cannot readily appreciate the parameters of aquatic environments and there are environmental factors that may profoundly affect aquatic organisms, such as:

- very low solubility of O_2 in water;
- high solubility of CO_2 in water;
- pH;
- salinity;
- buffering capacity;
- dissolved nutrients;
- toxic nitrogenous waste molecules;
- turbidity;
- heavy metals and other toxic molecules in solution;
- phyto- and zooplankton concentrations;
- current velocity.

These can only be rigorously measured with modern instrumentation.

Many of the diseases that afflict aquatic organisms are quite unfamiliar to us. Furthermore, virtually all the animals used in aquaculture are poikilotherms (their body temperature is variable and strongly influenced by environmental temperature) ('cold blooded'). Their metabolic rates, and all functions depending on metabolic rate, are profoundly influenced by environmental temperature in ways that we do not experience as 'warm-blooded' mammals.

The difficulties of appreciating the influences of these environmental factors still apply today, causing aquacul-

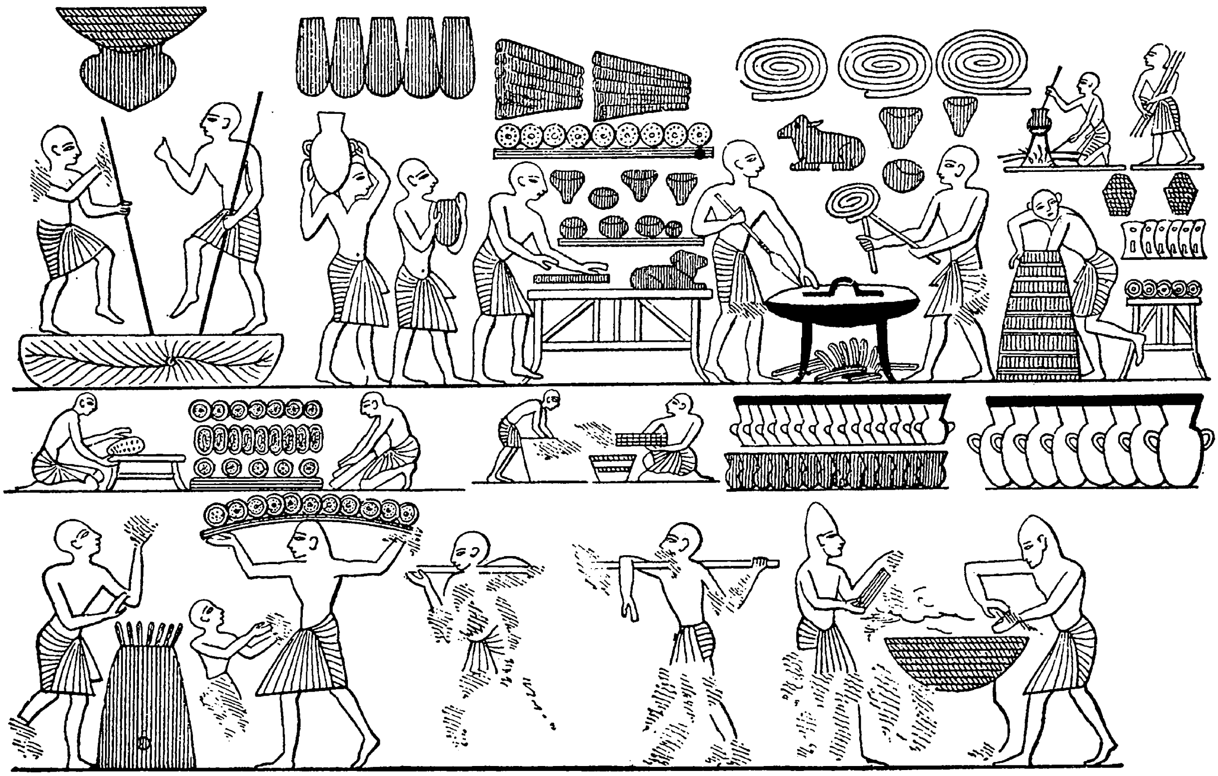

Fig. 1.1 The court bakery of Ramses III. From the tomb of Ramses III in the Valley of the Kings, twentieth dynasty. (*The Oxford encyclopedia of ancient Egypt*, copyright expired.)

Fig. 1.2 The common carp (*Cyprinus carpio*). (Photograph by Piet Spaans.)

ture programmes to have a relatively longer development period than other forms of food production. 'Even when tested technologies are adopted, the construction of physical facilities (particularly pond farms), solution of site-specific problems, the building up of the productivity of the system and, above all, attainment of skills by workers take considerable time' (Pillay, 1990). In agriculture we are much more readily able to appreciate the parameters influencing the success or otherwise of the output, and we have a very long history of attaining the skills needed.

A further major consequence of the late origin of aquaculture is that there has been relatively little genetic selection for many species and this is compared with the highly selected plants and animals of agriculture. Modern agriculture is based on organisms that are vastly different from their wild ancestors, and in many cases their wild ancestors no longer exist. This selection for desirable traits took place steadily and without any scientific basis over thousands of years of domestication. It was more intense last century with scientific breeding programmes. Modern agriculture would be totally uneconomic and the current world population would starve without these domesticated and genetically selected agricultural plants and animals. Much of aquaculture, by contrast, is based on plants and animals that are still 'wild'. There are, however, species that have been subject to strong selection, hybridisation, and molecular and genomic techniques (Chapter 7), such as:

- common carp;
- Atlantic salmon;
- rainbow trout;
- tilapia species;
- channel catfish.

Their breeding is based on broodstock that differ substantially from their ancestors in their genetics. Many other aquaculture species are based on wild broodstock obtained from natural populations. In some cases the life cycle has not yet been 'closed', i.e. the species has not been reared to sexual maturity and then spawned on a regular basis under culture conditions. Until the life cycle is closed, there is minimal potential for selective breeding.

1.3 AQUACULTURE AND CAPTURE FISHERIES PRODUCTION

Fishing activities, whether they are spearing individual fish, collecting shellfish from a rocky shore or coral reef, using a cast net, or capturing schools of fish with huge nets from factory trawlers that ply the world's oceans, are all hunting–gathering regardless of the degree of technology. As capture fisheries production currently exceeds aquaculture production, hunting–gathering activities remain the principal source of seafood. These fisheries suffer problems that are fundamental to hunting–gathering:

- variable recruitment and consequent unpredictability of stock size;
- difficulties in assessing stock size and its capacity for exploitation;
- difficulty in regulating exploitation to match the stock size;
- relatively low productivity.

The natural productivity of the world's water masses, fresh, brackish and marine, is huge, but finite; and a finite amount of plant and animal products can be harvested by fishing. For instance, the mean harvest from oceans that can be obtained for human consumption or processed for use in fish meal is ca. 2.5 kg per hectare of ocean surface per year. Furthermore, this huge but finite amount of harvest is within our current fishing capacity. Many of the world's major capture fisheries range from being heavily exploited to heavily overexploited, and production from capture fisheries has reached a plateau of ca.90 million t/year[2], around which it now fluctuates annually (Fig. 1.3). Global capture fisheries production increased to 93 million tonnes in 1994 and since then has fluctuated between 89 and 97 million t/year, with an overall mean increase of <1% per year.

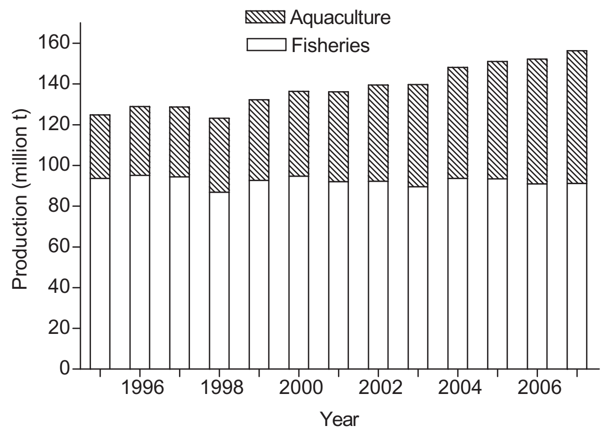

Fig. 1.3 Global production of capture fisheries and aquaculture per year from 1995 to 2007.

There are two further factors in capture fisheries production. About one-third of capture fisheries production is used to make fish meal, i.e. dried fish products, based on sardines, anchovy, fish wastes, etc. Fish meal is used as a source of animal protein and lipids in feeds in agricultural animal husbandry, e.g. pig feeds, but it is also extensively used in feeds for aquaculture (section 9.10). Thus, the effective annual production from global capture fisheries for direct human consumption is in the order of 60 million t/year. The other 30 million tonnes subsequently finds its way into the human diet by indirect processes.

A further factor that does not appear in FAO fisheries statistics is the substantial proportion of capture fisheries that is bycatch (non-target catch) and discards (e.g. under commercial size). A high proportion of these die. Alverson *et al.* (1994) estimated a mean of 27 million t/year of bycatch and discards from global commercial fisheries. They considered this conservative as it didn't include data on some invertebrate fisheries, and recreational and subsistence fisheries. Bycatch and discards vary according to

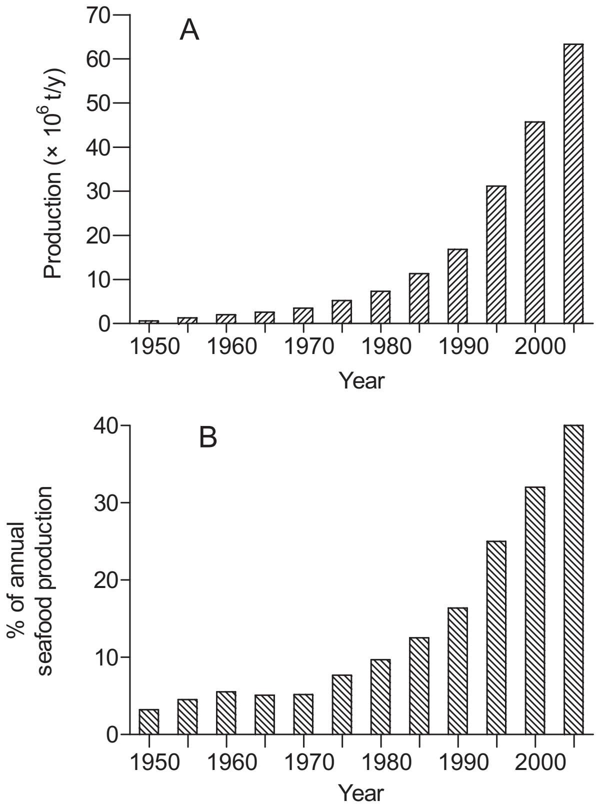

Fig. 1.4 A. Global production of aquaculture per year from 1950 to 2007. **B.** Aquaculture production as a percentage of global seafood production per year.

the nature of fishery and other factors. Alverson *et al.* (1994) rated marine shrimp trawl fisheries wherever they occur as consistently being among the highest bycatch fisheries. In view of the increase in world fishery effort since 1994, it is reasonable to assume that this wastage amounts to about 30 million t/year, i.e. a third again on top of the 90 million t/year global fishery.

In contrast to capture fisheries, aquaculture production of animals and plants grew at a mean rate of 8.1% over the same period (Fig. 1.4A). The increase in global aquatic animal and plant supply in recent decades has come largely from aquaculture. In 2007, aquaculture contributed 42% of total global seafood production (Fig. 1.4B) and it will continue to increase in relative importance. It is clear that further increases in supply from aquatic environments will come largely from aquaculture. Unlike capture fisheries, aquaculture is not limited by the natural productivity of the world's water masses. It is therefore not surprising that aquaculture production has been increasing and will inevitably overtake global capture fisheries production. In view of the fact that the percent contribution of aquaculture to global seafood supply seems to be increasing exponentially (Fig. 1.4B), this may happen sooner rather than later.

Aquatic plants (very predominantly seaweeds) contribute substantially to aquaculture and capture fisheries production, especially to the former (section 13.2.1). Aquatic plant productions from aquaculture and capture fisheries were ca. 14.9 million and 1.1 million tonnes, respectively, in 2007 (FAO Fishstat Plus, 2009)[2]. The relative proportions by weight and value of fish, molluscs, crustaceans and plants from aquaculture in 2007 are shown in Fig. 1.5. Fish constitute about half the weight and value of aquaculture production. Plants and shellfish each constitute about 20% of the weight. There are, however, major changes between relative weights and relative values of plants and shellfish. Molluscs decline in relative value. Plants decline even more in relative value and together molluscs and plants constitute a bit less than a quarter of the value of aquaculture production. Crustaceans (mainly marine shrimp) show a very large increase in value to almost a quarter of the value. Fish remain at about half the value of aquaculture production. This has significant implications for countries such as China.

Food security for the world's population, especially in poorer countries, is a major factor constraining international organisations such as the FAO (Chapter 26). To put aquaculture and fisheries production into the perspective of providing animal protein for the world's current population: global production of slaughtered meat from livestock (pork, beef, chicken and lamb) is in the order of 250 million t/year compared with about 60 million t/year from capture fisheries (for direct human consumption) and 52 million tonnes from aquaculture (excluding aquatic plants). This 110 million tonnes from aquaculture and fisheries is pre-slaughtered weight, and slaughtered weight (after removal of viscera, heads and shells) is probably around 50–60%. This value is not easy to estimate as it varies markedly with the kind of animal and country of consumption. Consequently, seafood makes up about 20% of all animal protein production per year. Aquaculture is a modest 7% of all animal protein production/year based on these calculations. With fisheries production/year almost

[2]Unless otherwise stated, all production and value data given for aquaculture and capture fisheries in this textbook are derived from the FAO online site Fishstat Plus 2009. The software may be downloaded and installed from http://www.fao.org/fishery/statistics/software/en.

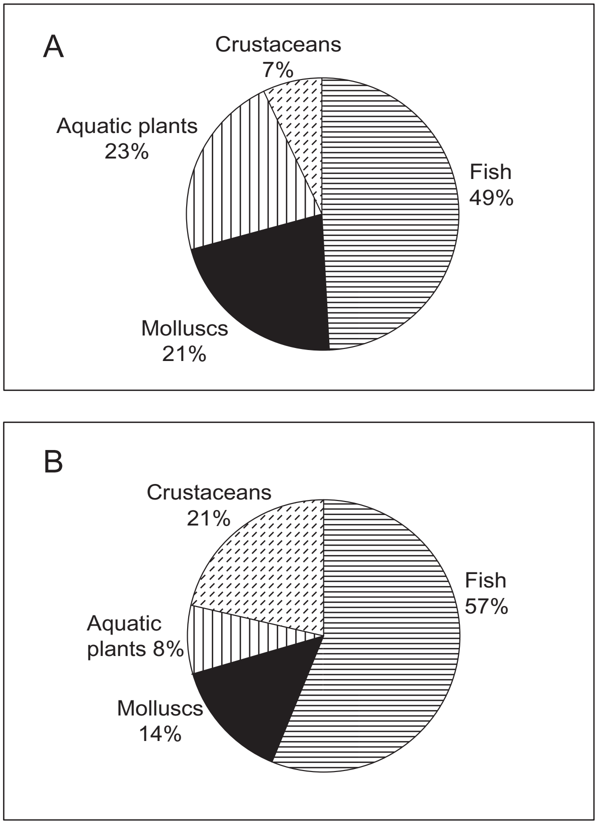

Fig. 1.5 Relative proportions of fish, molluscs, crustaceans and aquatic plants in global aquaculture production in 2007. **A**. By weight. **B**. By value.

static and unlikely to increase much, and, while livestock production is increasing at about 2% per year, aquaculture is increasing at 8% per year. This roughly estimated value (7%) of aquaculture's contribution to world animal protein production is an increase from 3.5% in 1993, estimated by New (1997).

1.4 THE 'BLUE REVOLUTION'

The rapid increase in aquaculture production in the 1990s led to suggestions that aquaculture was undergoing a 'Blue Revolution' that would transform the productivity of marine and other aquatic environments with new technology (e.g. Holmes, 1996; Entis, 1997) (Fig. 1.6). This envisaged a revolution in productivity similar to the 'Green Revolution' in agriculture during the decades following World War II. The Green Revolution occurred 'where concentrated research developed the basis for the agricultural practices in use today (e.g. mechanisation, heavy fertilisation, heavy pesticide use, irrigation, genetically improved stocks, advanced feed formulations)' (Hopkins, 1996).

The great, almost exponential, increase in the quantity of animal and plant aquaculture production in the two decades from 1987 to 2007 came mainly from increases in freshwater and marine aquaculture. There was a greater absolute increase in the marine environment in total aquaculture production, which includes considerable aquatic plant production (Fig. 1.7A). In terms of specifically animal production, however, and hence protein production directly for human consumption, the increase was substantially greater from freshwater aquaculture (Fig. 1.7B). The annual rate of production of aquatic animals in freshwater environments increased by 25 million tonnes over these two decades compared with an increase of 15 million tonnes in the rate of annual production in the marine environment. This clearly establishes freshwater as the major environment of aquatic animal production (Fig. 1.7). The large increase in seaweed production in the marine environment is important as a source of income, but it is of low value as an immediate source of protein for human consumption.

There is a further very important statistic about the growth in aquaculture production over recent decades: it was particularly driven by growth of the industry in China (Table 1.1). Furthermore, dividing between developing countries (FAO classification), which include China, and developed countries, 50 out of the 51 million t/year increased rate of global aquaculture production over the period 1987 to 2007 came from developing countries (Table 1.1). Aquaculture production in these countries increased at the remarkable rate of 9.0% per year over these two decades (Table 1.1). Compared with this, the 1.9% per year growth of aquaculture production in the developed countries was modest. The 'Blue Revolution' in aquaculture, like the 'Green Revolution' in agriculture, occurred primarily in developing countries. China alone showed an increase of about 35 million t/year over the period 1987 to 2007 at the even more remarkable rate of 10.1% per year (Table 1.1). It was the driving force of aquaculture expansion in the developing countries and the world. By 2007, China accounted for almost two-thirds of global aquaculture production (Table 1.1). In view of the fact that the growth in aquaculture production of aquatic animals in particular occurred predominately in freshwater systems, which are often anything but blue, it might be appropriate to call the huge increase in aquaculture the 'Brown Revolution'.