Edited by
John S. Lucas, Paul C. Southgate and Craig S. Tucker

Aquaculture

FARMING AQUATIC ANIMALS AND PLANTS

THIRD EDITION

WILEY Blackwell

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Farming Aquatic Animals and Plants

Third Edition

Edited by

John S. Lucas
Adjunct Professor in School of Biological Sciences
University of Queensland
Brisbane, Australia

Paul C. Southgate
Professor in Tropical Aquaculture
Faculty of Science, Health, Education and Engineering
University of the Sunshine Coast
Maroochydore, Australia

Craig S. Tucker
Research Leader, Warmwater Aquaculture Research Unit
United States Department of Agriculture
Stoneville, Mississippi, USA

WILEY Blackwell

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Contents

List of Contributors

Md Shah Alam
Center for Marine Science
University of North Carolina Wilmington
USA

Andrew Barnes
School of Biological Science
University of Queensland
Australia

Ram C. Bhujel
School of Environment, Resources and Development
Asian Institute of Technology
Thailand

Michael Borowitzka
Algae R & D Centre (Tasmanian Branch)
Murdoch University
Australia

Brian Bosworth
Warmwater Aquaculture Research Unit
United States Department of Agriculture
USA

Claude E. Boyd
School of Fisheries, Aquaculture and Aquatic Sciences
Auburn University
USA

Allan Bremner
University of the Sunshine Coast
Australia

Randall Brummett
Environment and Natural Resources Department
World Bank
USA

Kenneth D. Cain
Department of Fish and Wildlife Sciences
University of Idaho
USA

Patrick M. Carroll
Center for Marine Science
University of North Carolina Wilmington
USA

Peter Cook
Center of Excellence in Natural Resource Management
University of Western Australia
Australia

Lou D'Abramo
Department of Biology
University of Alabama at Birmingham
USA

Harry V. Daniels
Department of Applied Ecology
North Carolina State University
USA

Sena De Silva
School of Life and Environmental Sciences
Deakin University
Australia

Rex Dunham
School of Fisheries, Aquaculture and Aquatic Sciences
Auburn University
USA

John Hargreaves
Aquaculture Assessments, LLC
San Antonio, USA

Jeffrey M. Hinshaw
Department of Applied Ecology
North Carolina State University
USA

Kate S. Hutson
Centre for Sustainable Tropical Fisheries and Aquaculture
James Cook University
Australia

Darryl Jory
Shrimp Production and Business Development
Florida, USA

John S. Lucas
School of Biological Sciences
University of Queensland
Australia

Aaron A. McNevin
Aquaculture
World Wildlife Fund
USA

Thane A. Militz
Faculty of Science, Health, Education and Engineering
University of the Sunshine Coast
Australia

Leigh Owens
College of Public Health, Medical & Vet Sciences
James Cook University
Australia

Nicholas A. Paul
Faculty of Science, Health, Education and Engineering
University of the Sunshine Coast
Australia

Igor Pirozzi
Port Stephens Fisheries Institute
New South Wales Department of Primary Industries
Australia

John Purser
Fisheries and Aquaculture Centre
University of Tasmania
Australia

Qingjun Shao
College of Animal Sciences
Zhejiang University
China

Victor Suresh
United Research (Singapore) Pte. Ltd.
Singapore

Paul C. Southgate
Faculty of Science, Health, Education and Engineering
University of the Sunshine Coast
Australia

Clem Tisdell
School of Economics
University of Queensland
Australia

Les Torrans
Warmwater Aquaculture Research Unit
United States Department of Agriculture
USA

Craig S. Tucker
Warmwater Aquaculture Research Unit
United States Department of Agriculture
USA

Qidong Wang
Institute of Hydrobiology
Chinese Academy of Sciences
China

Wade O. Watanabe
Center for Marine Science
University of North Carolina at Wilmington
USA

Chaoshu Zeng
Centre for Sustainable Tropical Fisheries and Aquaculture
James Cook University
Australia

Preface to the Third Edition

When the first edition of this book was published almost 15 years ago, annual production from aquaculture was around 43 million tonne. But the past two decades have seen unprecedented growth that has greatly exceeded predictions, and annual aquaculture production in 2016 was about 106 million tonne valued at about USD 243 billion. Factors supporting this rapid expansion of the aquaculture sector include increased production from existing industries through improved culture methods and technological advances, expansion of aquaculture into new areas, and an increase in the number of species that are utilised for aquaculture production. These developments are described in this revised and extended third Edition that includes a major revision of production statistics and trends, discussion of technical developments, and revised and extended coverage provided by broader international authorship. This edition brings together 35 internationally recognised contributors, including a number of new contributors, and it includes expansion of the editorial team. We trust that this new edition will be both helpful and inspirational to those who share our enthusiasm for aquaculture, and its important role in supporting food security, livelihoods and economic development around the world.

April 2018

John S. Lucas
Paul C. Southgate
Craig S. Tucker

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 report 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.

June 2011

John S. Lucas
Paul C. Southgate

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, nutritional 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.

April 2003

John S. Lucas
Paul C. Southgate

Acknowledgments

We first acknowledge the contribution of Prof. T.K Tseng, now deceased, who contributed to the Seaweed components of the first and second editions of this book, and whose legacy is reflected in this edition. Helen Lucas and Dawn Southgate assisted with editorial, administrative and support activities required for completion of this book and Dr. Kate Hutson assisted with editorial input to chapters other than her own. Many people have assisted the editors and authors of chapters with photographs, translations, information and opinions, and we express our sincere gratitude for their contributions. Finally, we express our sincere gratitude to all authors for their commitment, patience and enthusiasm for this project.

1

Introduction

John S. Lucas

CHAPTER MENU

1.1 What is and What isn't Aquaculture?

> *Give a person a fish and you feed them for a day;*
> *Teach a person how to fish and you feed them for their life-time;*
> *Teach a person how to grow fish and you feed them and their neighbours for their life-times.*
> (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 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'[1] is used inclusively in this textbook, i.e., for all animal and plant products from aquatic environments, including freshwater, brackish, and marine and hypersaline environments. The term 'shellfish', according to common usage, is used to describe 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[1], crayfish, crabs, etc.). The other major group of aquatic animals that is cultured is the fishes, also known as finfish. 'Fish farming' is used in the sense of aquaculture of fishes, 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

1 'Shrimp' is used throughout this book for species of the family Penaeidae (known as 'prawns' in some countries). It doesn't include species of the family Palaemonidae.

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

individual or corporate *ownership* of stock being cultivated.'

For statistical purposes:

- aquatic organisms that are harvested by an individual or corporate body that has owned them throughout their rearing period are classed as aquaculture products.
- aquatic organisms that are exploitable by the public as a common property resource, with or without appropriate licences, are the harvest of *fisheries*.

According to the FAO definition[2], the two essential factors that together distinguish aquaculture from capture fisheries are:

- *Intervention* to enhance the stock.
- *Ownership* of the stock.

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 fishes 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 fishing. The released fingerlings enhance the stock, but they become a common property resource. The same applies where hatchery-reared fish fingerlings are sold to fishing clubs and local government bodies to stock lakes and dams to improve recreational fishing.

Hydroponics and aeroponics, the cultivation of terrestrial plants with their roots in dilute nutrient solutions aren't aquaculture. These are alternative methods for growing terrestrial plants.

Activities constituting aquaculture production, according to FAO[3] 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).

2 ftp://ftp.fao.org/docrep/fao/011/i0400t/i0400t.pdf

3 ftp://ftp.fao.org/docrep/fao/011/i0400t/i0400t.pdf

1.2 Origins of Aquaculture and Agriculture

The New Stone Age (Neolithic Age ca. 8,000–4,000 BC) was distinguished by the invention of farming. There were at least seven independent origins of farming during this Age: in China, New Guinea, Mexico, West Africa, the Andes, the Amazon basin and the Middle East (Figure 1.1). Wheat, rice, maize, barley and millet, which are still the major cereal crops, and the major root crops, potatoes and cassava, were all domesticated at various of these geographical locations during this period. Similarly, the husbandry of pigs, cattle, chickens, sheep, goats and horses, which are still major farm animals, was developed during the Neolithic Age. The origins of the plants and live-stock that we farm go back a long way.

These changes from hunting–gathering to agriculture and animal husbandry 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. There were, however, disadvantages. The heavy dependence on a crop could lead to nutritional deficiencies and, if the crop failed, to starvation. Close proximity to other humans, domestic animals and opportunistic vermin led to the transmission of diseases. The hunter-gatherer probably tended to be healthier, wih a more varied diet and less exposure to diseases.

The origin of aquaculture came some thousands of years after the Neolithic Age when culture of common carps (*Cyprinus carpio*) was developed in China where the carp is a native species (Figure 1.2). There is a long history of aquaculture in China (section 1.6). Common carps may have been farmed as early as 2000–1000 BC.[4] The first aquaculture text is attributed to a Chinese politician, Fan Lei, and is dated about 500 BC. Fan Lei attributed the source of his wealth to his fish ponds: so his fish culture was more than a hobby. However, on three continents, 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. There are some environmental factors that may profoundly affect aquatic organisms, such as:

- the very low content of O_2 in water (<1%) compared with air (21%);
- high solubility of CO_2 in water;

4 http://www.fao.org/docrep/field/009/ag158e/AG158E02.htm (viewed January 2017).

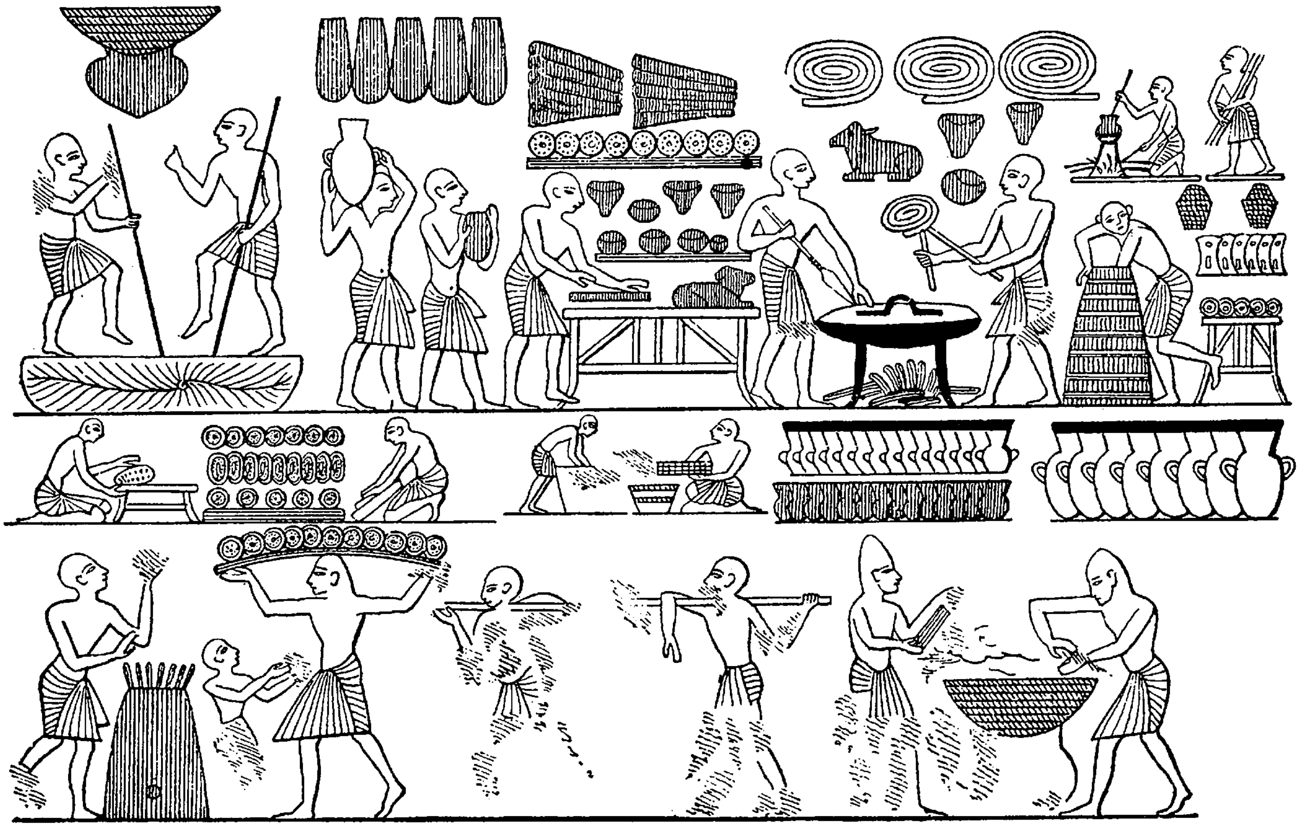


Figure 1.1 The court bakery of Ramses III. From the tomb of Ramses III in the Valley of the Kings, twentieth dynasty. (The Oxford Encyclopaedia of Ancient Egypt.) (Courtesy of Wikimedia Commons).

Figure 1.2 The common carp (*Cyprinus carpio*). *Source:* Photograph by Piet Spaans. Reproduced under the terms of the Creative Commons Attribution License, CC-BY-SA 4.0.

- pH;
- salinity;
- buffering capacity;
- dissolved nutrients;
- toxic nitrogenous waste molecules;
- turbidity;
- heavy metals and other toxic molecules in solution;
- phyto- and zooplankton concentrations; and
- current velocity.

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 (Figure 1.3).

The difficulties of appreciating and controlling the influences of these environmental factors still apply today, causing aquaculture programmes to have a relatively longer development period than other forms of food production. Even where there is well-established technology for an organism there will still be site-specific issues and progressive achievement of optimum husbandry. In agriculture we are much more readily able to appreciate the parameters influencing the success or

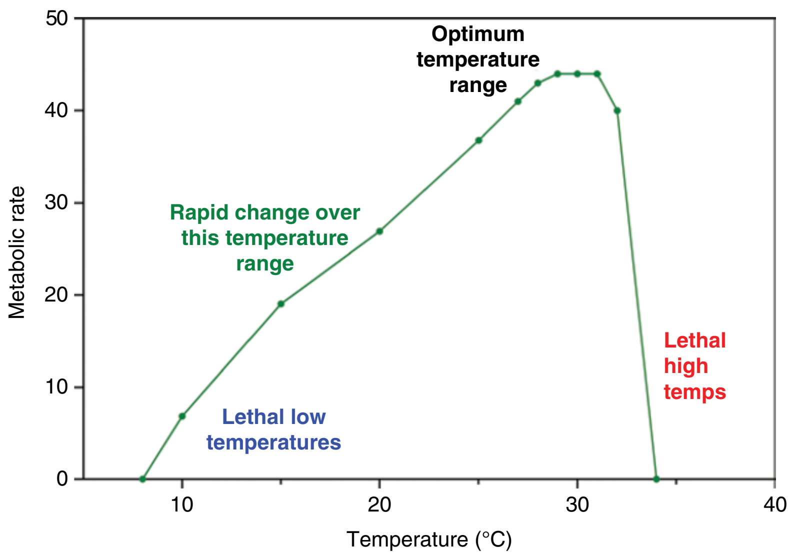


Figure 1.3 Metabolic rate over a temperature range in a poikilothem. Metabolic rate will be reflected in the rate of the animals's oxygen consumption. Reproduced with permission from John Lucas.

otherwise of the output, and there is 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, however, 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 some species that have been subject to strong selection, hybridization, and molecular and genomic techniques (Chapter 7), such as:

- common carps;
- Atlantic salmon;
- rainbow trout;
- tilapias; and
- 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 the shore, casting a net, fishing from a boat or the factory ships that ply the world's oceans, are all tradional hunter–gatherer activities regardless of the degree of technology. Until recently, capture fisheries production exceeded aquaculture production: hunter–gathering was the major source of seafood. These fisheries suffer problems that are fundamental to hunter–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; and
- 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 direct human consumption or consumption through use in fishmeal is ca. 2.5 kg/ha/yr of ocean surface. Furthermore, this huge but finite amount of harvest is within the scope of our current

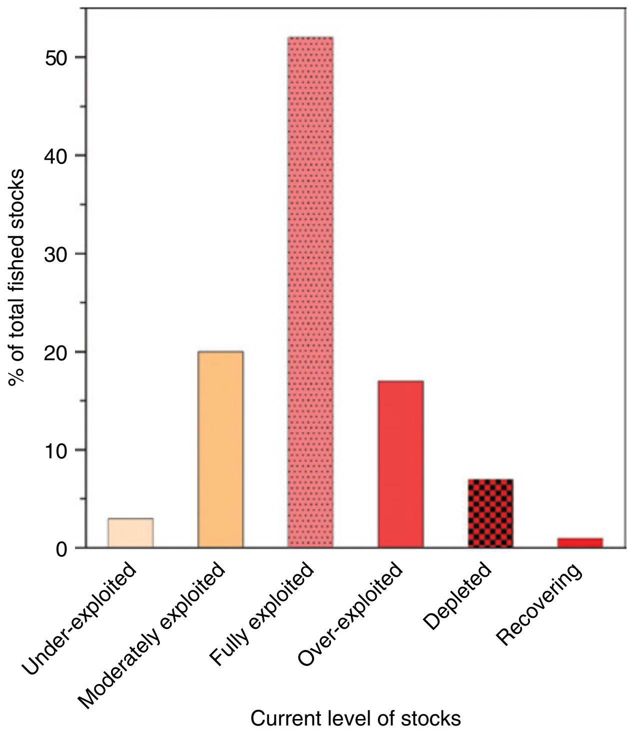
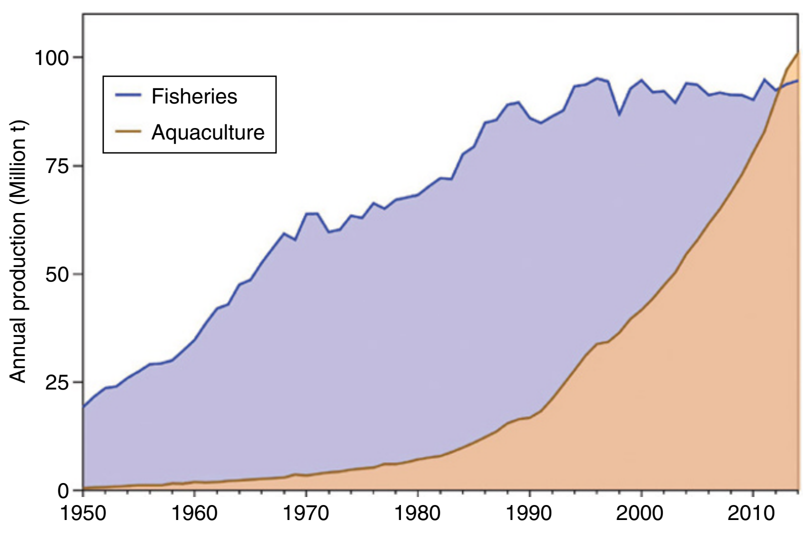


Figure 1.4 Percent status levels of 600 marine fisheries stocks based on the assessment of FAO. Data from http://www.fao.org/newsroom/common/ecg/1000505/en/stocks.pdf. *Source:* Reproduced with permission from John Lucas.

Figure 1.5 Global production of aquaculture and capture fisheries per year from 1995 to 2015. Data from http://www.fao.org/fishery/statistics/global-aquaculture-production/query/en. *Source:* Reproduced with permission from John Lucas.



fishing capacity. Based on the FAO assessment of 600 marine fisheries, 77% are fully or over-exploited, i.e., without capacity for increased harvest. This figure includes 17% of fisheries that are overexploited, 7% that are depleted and 1% recovering from depletion (Figure 1.4). This situation is reflected in the FAO data for annual capture fisheries production. Global capture fisheries production increased to 93 million t/yr (t = tonne)[5] in about 1994 and since then has fluctuated between 89 and 97 million t/yr without any trend (Figure 1.5).[6]

There are two further factors in capture fisheries production. About one-quarter of capture fisheries production is used to make fishmeal, i.e., dried fish products, based on sardines and anchovies (Figures 5.10, 27.4), and fish wastes. Fishmeal is used as a source of n-3 fatty acids in feeds for agricultural animal husbandry, e.g., pig feeds, but it is also extensively used in feeds for aquaculture. Thus, the effective annual production from global capture fisheries for direct human consumption is in the order of 70 million t/yr. The other 20–30 million t subsequently finds its way into the human diet by indirect processes involving substantial losses from the feed to incorporate it into a diet for human consumption (see later).

A further factor that doesn't appear in FAO fisheries statistics is the substantial proportion of capture fisheries that consists of:

- bycatch = non-target species; and
- discards = individuals of the target species that don't fit the commercial criteria.

There are no precise data, but these amount to a substantial component of total fisheries' catch and high proportions die through the handling. Bycatch and discards

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5 The International System of Units (ISU) is used in this book, usually with the appropriate abbreviation. The unit 'tonne' (=1,000 kg) is abbreviated to 't'. The unit 'ton' (= 2,000 or = 2240 pounds) is not used.
6 The data on world aquaculture and fisheries production are from the FAO websites http://www.fao.org/fishery/statistics/global-aquaculture-production/query/en
http://www.fao.org/fishery/statistics/global-capture-production/query/en
or from downloaded FAO FishStatJ software, which has identical data.

Table 1.1 Global aquaculture production over 20 years from 1993 and 2013 by developing and developed countries. Data for China are also shown separately.*

	Aquaculture production		
	1994	2014	Mean
	(10^6 t)	(10^6 t)	% increase/yr
World	27.8	101.1	6.7
Least developed countries	0.8	4.0	8.4
% of world total	*2.9*	*4.0*	
Developing countries	24.3	93.3	7.0
% of world total	*87.4*	*92.2*	
Developed countries	3.5	4.8	1.6%
% of world total	*12.6*	*4.7*	
China	17.5	59.2	6.3%
% of world total	*62.9*	*58.1*	

Data from mailto:mailto:jorgen.bjorkli@balsfjord.kommune.no]
* http://www.fao.org/fishery/statistics/global-aquaculture-production/query/en

In the second edition of this textbook it was predicted on page 5 that:

> '*...aquaculture production ... 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 this may happen sooner than later.*'
> https://www.wiley.com/enus/Aquaculture%3A+Farming+Aquatic+Animals+and+Plants%2C+2nd+Edition-p-9781405188586

This prediction was fulfilled in a surprisingly brief time when aquaculture contributed >50% of global seafood production in 2015 (Figure 1.5). Furthermore, it will continue to increase in relative importance and be the source of increased food supply from aquatic environments. Unlike capture fisheries, aquaculture is not limited by the natural productivity of the world's water masses.

Aquatic plants (very predominantly seaweeds) contribute substantially to aquaculture production. Aquatic plant productions from aquaculture and capture

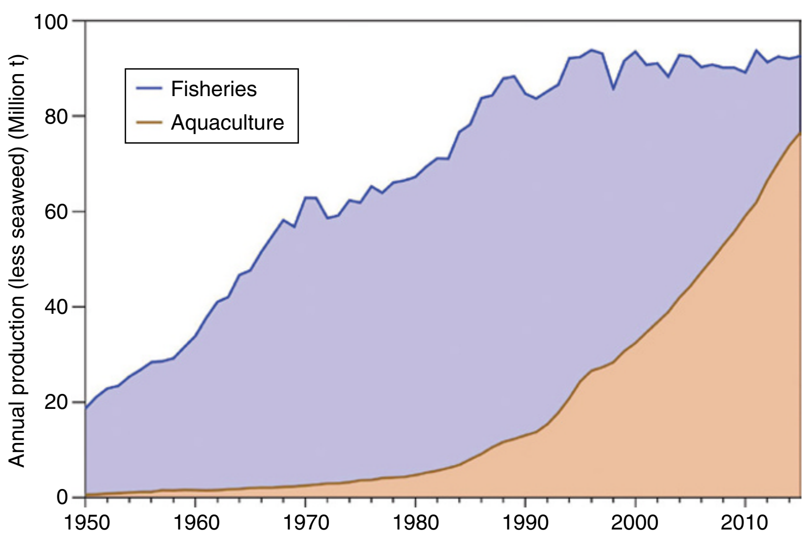

Figure 1.6 Global production of aquaculture and capture fisheries, excluding aquatic plants (mainly seaweeds) from 1995 to 2015. Data from http://www.fao.org/fishery/statistics/global-aquaculture-production/query/en
Note that > 20 million t of capture fisheries products are used for fishmeal, etc., and not directly for human consumption. *Source:* Reproduced with permission from John Lucas.

vary according to the nature of fishery and some trawl fisheries are among those with the highest levels of bycatch. Thus, it is not unreasonable to assume that this wastage amounts to at least 10% on top of the 90 million t/yr global fishery: about 10 million t/yr.

In contrast to capture fisheries, aquaculture production of animals and plants grew at a mean rate of 6.7% over the same period (Figure 1.5) (Table 1.1). All the increase in global seafood production in the past two decades has come from aquaculture.

fisheries were ca. 29.3 million t and 1.09 million t wet weight, respectively, in 2015 (Figure 1.6) (FAO).[7] It may seem from these production numbers that aquaculture is still considerably behind fisheries as a source of seafood for human consumption and aquaculture still needs to increase substantially before it reaches capture fisheries

7 http://www.fao.org/fishery/statistics/global-aquaculture-production/query/en