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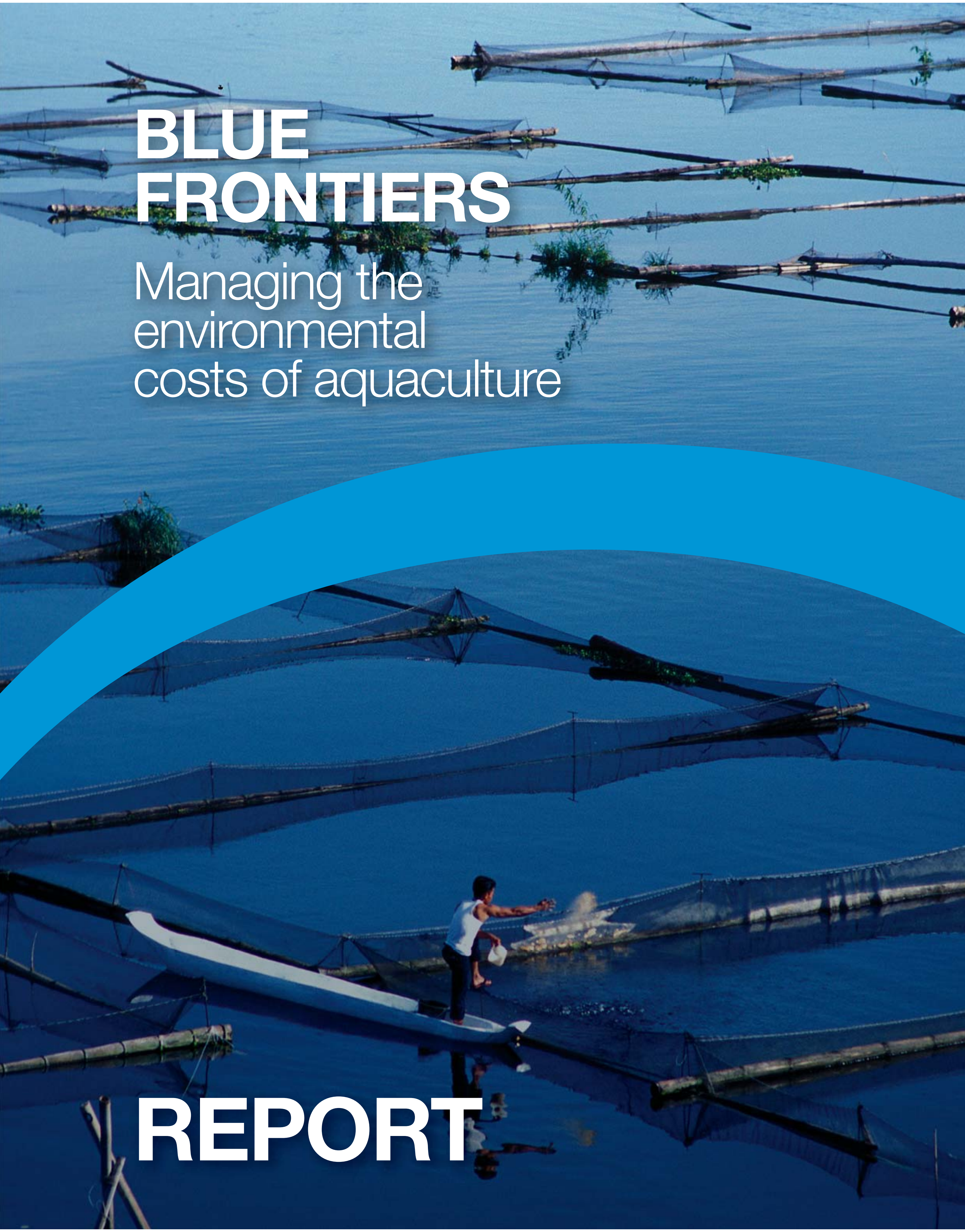

BLUE FRONTIERS

Managing the environmental costs of aquaculture

REPORT

Blue Frontiers

Managing the environmental costs of aquaculture

Authors

Stephen J. Hall,

Anne Delaporte,

Michael J. Phillips,

Malcolm Beveridge,

Mark O'Keefe.

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Mindanao, Philippines. Fish Farming on Lake Sebu

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About this Report

There is a pressing need to elevate the debate on the future of aquaculture and to place this in the context of other animal food production systems, including wild capture fisheries. Between 1970 and 2008 aquaculture production grew at an annual average rate of 8.4% and remains among the fastest growing food production sectors in the world. But with global demand for aquatic food products continuing apace, there are worries about the development trajectory of aquaculture. Of particular concern for Conservation International and many others is whether and how further growth can be met in ways that do not erode biodiversity or place unacceptable demands on ecological services. In this context, the potential for aquaculture to reduce pressure on wild capture fisheries by meeting global demand for aquatic food products is also important.

Directed towards helping inform and stimulate policy debate, this report provides a global review and analysis of these issues for both coastal and freshwater aquaculture. Such debate is needed to help ensure that the current and future potential benefits of the burgeoning aquaculture sector are captured and the associated costs minimized.

The report begins with an overview of the current status of world aquaculture. It then goes on to describe an approach for estimating the current combined biophysical resource demands of aquaculture for producer countries and regions. Following a comparison of these results with those available for other animal food production sectors the report then examines the consequences of likely future trends in production on the environmental impacts of aquaculture. Finally, the policy implications of the report's findings are discussed along with the research agenda that should be pursued to meet the challenge of sustainable food production.

Acknowledgements

This report has benefited greatly from critiques by several colleagues. We are especially grateful to Professor Max Troell, Mr Patrik Henriksson and Dr Patrick Dugan and colleagues at the World Bank and Conservation International for their insightful comments. We would also like to thank Professor Trond Bjorndal for help with part of the text.

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Acronyms and abbreviations

ARD	Agriculture and Rural Development
CED	Cumulative energy demand
CML	Institute of Environmental Sciences
EU	European Union
FAO	Food and Agriculture Organization
FCR	Feed Conversion Ratio
GM	Genetically Modified
ICES	International Council for the Exploration of the Sea
IFPRI	International Food policy Research Institute
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for the Conservation of Nature
LCA	Life Cycle Analysis
N	Nitrogen
NGO	Non-Governmental organization
OECD	Organisation for Economic Co-operation and Development
OIE	World Organization for Animal Health (formely Office International des Epizooties)
P	Phosphorus
RAS	Recirculation Aquaculture Systems
TSP	Triple Super Phosphate
USFDA	U.S Food and Drug Administration
WWF	World Wide Fund for Nature

Units of measure

ha	hectare
Gj	Giga joule
kg	kilogram
Mj	mega joule
m^3	cubic meter
t	metric ton (1000 kg)
US$	U.S dollar
yr	year

PHOTO CREDIT: He Qing Yunnan

EXECUTIVE SUMMARY

Executive Summary

Aquaculture is among the fastest growing food production sectors in the world and this trend is set to continue. However, with increasing production comes increasing environmental impact. For aquaculture to remain sustainable this future growth must be met in ways that do not erode natural biodiversity or place unacceptable demands on ecological services.

This study is a review and analysis of global aquaculture production across the major species and production systems. It compares the aggregate biophysical resource demands of each system and their cumulative environmental impacts. The study then compares these results with those from other animal food production systems before examining the consequences of likely future trends. Finally, the policy implications of the report's findings are discussed along with the research agenda that should be pursued to meet the challenges involved in producing food sustainably.

Worldwide, aquaculture production has grown at an average annual rate of 8.4% since 1970 and reached 65.8 million tonnes in 2008. The growth in farmed fish supply has significantly outpaced growth in world population. China supplies 61.5% of global aquaculture production; a further 29.5% comes from the rest of Asia, 3.6% from Europe, 2.2% from South America, 1.5% from North America, 1.4% from Africa and 0.3% from Oceania. Production in China and the rest of Asia is predominantly freshwater, from other continents predominantly coastal. The annual average growth rate in aquaculture between 2003 and 2005 in North America and Europe is slow (1.4–1.6%); it is rapid in China, Asia and South America (6, 11.2, 7.8% respectively) and explosive in Africa (16.2%), albeit from a very low baseline.

Carp dominates production in both China and the rest of Asia. In contrast, for Europe and South America it is salmonids; African aquaculture production is almost exclusively of finfish, primarily tilapias. For Oceania, shrimps and prawns dominate while in North America production is more even across the species groups. Aquaculture has growing significance as a supplier of fish; between 2003 and 2008 the proportion of aquaculture in total fish production (i.e. for food and industrial purposes) increased from 34 % to 42%. The proportion of food fish supplied by aquaculture in 2008 was 47%. Supply from aquaculture is now dominant for seaweeds, carps and salmonids.

The rapid growth of aquaculture witnessed over the last forty years has raised questions concerning its environmental sustainability. To answer those questions satisfactorily requires quantitative analyses. This study, based on 2008 data, compares the global and regional demands of aquaculture for a range of biophysical resources across the dominant suite of species and production systems in use today. The units of analysis were the elements of a six dimensional matrix comprising 13 species groups, 18 countries, 3 production intensities, 4 production systems, 2 habitats and 5 feed types. This gave 75 positive matrix elements that accounted for 82% of estimated total world aquaculture production in that year.

The assessment method chosen to analyse the data was Life Cycle Analysis (LCA). This method required estimates of both the biophysical resource inputs to and outputs from each of the 75 species-production systems identified. The input resources estimated were the amount of land, water, feed, fertilizers and energy required on-farm. The outputs (emissions) considered were nitrogen, phosphorus and carbon dioxide. From these data the LCA produced estimates of the impact of these species-production systems for each of six impact categories: eutrophication, acidification, climate change, cumulative energy demand, land occupation and biotic depletion (use of fish for fishmeal and fish oil). Boundaries were set to exclude environmental costs associated with building infrastructure, seed production, packaging and processing of produce, transport and other factors.

Overall, and unsurprisingly, the data from the 75 species-production systems reviewed showed a positive relationship between overall production levels and impact. The levels of impact were then compared across production system, species group and country.

Inland pond culture is the predominant production system and it contributes the greatest impact across all the six impact categories, with demand for wild fish (biotic depletion) also notable for marine cage and pen culture. Similarly carps, as a species group, dominate overall impacts reflecting the fact that carp production is greater than that of other species groups. Eel production stands out as highly environmentally demanding, largely due to high energy consumption, and salmonid, and shrimp and prawn production are notable for their demand for wild fish. Bivalves and seaweeds place low demands on the environment and actually reduce eutrophication.

A comparison of environmental efficiencies across countries gave a variable picture. For example, for the salmon producing nations of north Europe, Canada and Chile, the impact from eutrophication was moderate and biotic depletion high, but they were more efficient than China and Asia across the other four environmental impacts. Perhaps more interestingly however, were the differences in efficiencies within species-production categories between countries suggesting scope for improving environmental performance. For shrimp and prawn culture, for example, China is much less efficient, in relative terms, than other producer countries when considering impact on acidification, climate change and energy demand.

A look at the drivers of impact, i.e. those attributes of the production system that contribute most to environmental impact, showed that the aquaculture production system itself contributed most to eutrophication, but impacts on climate change and acidification were dependent on the nature of the national energy supply; a factor outside the control of the local operator.

Sensitivity analyses were run to determine the robustness of the findings, and comparisons were made with other LCA studies. Although most variations tested gave results that differed little from the model in use, some notable deviations occurred. Most of these were related to assumptions associated with on-farm energy use and feed supply indicating that improved data in these areas are required.

There is a growing demand for animal source foods, driven partly by population growth but mainly by rising standards of living and prosperity in developing countries. The study continues with a comparison of the environmental impacts of aquaculture with those from other animal food production sectors. This is important because without a balanced picture of the environmental impacts of producing animal source foods through different systems, it is not possible for governments or consumers to understand the true costs of production.

The comparative analysis draws heavily on studies of the environmental impact of livestock produced by the FAO and considers four key aspects: conversion efficiencies, environmental emissions (nitrogen, phosphorus and carbon dioxide), land use and water use.

Fish convert a greater proportion of the food they eat into body mass than livestock and therefore the environmental demands per unit biomass or protein produced are lower. The production of 1 kg of finfish protein requires less than 13.5 kg of grain compared to 61.1 kg of grain for beef protein and 38 kg for pork protein. However, although farmed fish may convert food more efficiently than livestock there are important issues with respect to carnivorous fish species, which place heavy demands on the fishmeal and fish oil industry—the use of capture fisheries for animal feeds. Unfortunately, simply substituting a vegetable-based food for fishmeal is often not possible at present.

Extensive livestock production places heavy demands on land use through deforestation and land degradation. However, land use demands per unit of protein production appear broadly similar across other animal food production systems. Intensive livestock production is noteworthy, however, for the high levels of nitrogen, phosphorus, carbon dioxide and methane produced. Comparatively, aquaculture systems perform well with respect to the emissions produced from beef and pork production. Livestock rearing, especially in intensive systems, also places heavier demands on the use of fresh water.

There are, however, a number of issues concerning the calculations which make true comparisons difficult and there are insufficient data to properly compare the different intensities and methods of animal production, so the results must be viewed as 'broad-brush'. Certainly there are some efficiencies associated with farming a product that is cold blooded and feeds near the bottom of the food chain but much depends on the species, production system and management used. And there are trade-offs between extensive systems that place higher demands on land use, and ecological services such as water, fuel, nutrient cycling, and intensive systems that require higher levels of fossil fuels, feed, and produce more effluent.

In the fourth section the authors briefly review the drivers of demand and environmental constraints to aquaculture production, along with published predictions of future trends for the aquaculture sector. Driven largely by increasing wealth and urbanization, published estimates suggest production will reach between 65 and 85 million tonnes by 2020 and between 79 and 110 million tonnes by 2030. As an illustration of the potential environmental impact of this growth, in the absence of significant innovations and improvements in management and technology, a production level of 100 million tonnes by 2030 (excluding seaweeds) will lead to environmental demands that will be between 2 and 2.5 times greater than 2008 levels for all the impact categories studied.

A number of key conclusions and recommendations arise from the analysis, and point the way towards improved productivity for aquaculture with reduced environmental impact. These include the following points.

- As the degree of environmental impact is largely determined by the level of production, with carp production from inland ponds in China and Asia creating the largest environmental footprint, this is an important field where research needs to be undertaken to develop measures to reduce overall environmental impact.
- The variety in impact measured by the same species-production system operating in different countries suggests strongly that the potential to improve performance exists, such as through regional learning networks for both policies and technologies. Much of the aquaculture industry in developing countries provides opportunities for improved efficiencies.
- Feed constraints are key to aquaculture development. Reducing the dependency on fishmeal and fish oil will require new innovations in technologies and management but the payoffs may be spectacular both in terms of profitability, food and nutrition security and reduced environmental impact.
- Analysis shows that reductions can be made to the sector's impact on both climate change and acidification by improving energy efficiency throughout the production and value chains. The use of water and energy audits and better practices should lead to reduced resource demands.
- It is apparent from this study that aquaculture has, from an ecological efficiency and environmental impact perspective, clear benefits over other forms of animal source food production for human consumption. In view of this, where resources are stretched, the relative benefits of policies that promote fish farming over other forms of livestock production should be considered.

- The growing need for aquaculture to contribute to food security, especially in African and Asian countries will require governments to actively support growth of the sector and stimulate private sector investment.
- Aquaculture affects climate change and climate change will affect aquaculture. To minimise the potential for climate change, energy consumption should be kept as low as possible and new aquaculture enterprises should not be located in regions that are already high in sequestered carbon such as mangroves, seagrass or forest areas.
- There are measures that policy makers can take which include providing support to innovative and technological developments, ensuring a suitable regulatory framework that captures environmental costs within aquaculture processes, building capacity for monitoring and compliance, and encouraging research on the supply and demand for fish and fish products.

This study is the first to provide a global picture of the demands fish farming makes on environmental resources using Life Cycle Analysis. It illustrates the opportunities and challenges that lie ahead for aquaculture. The key messages for policy makers, NGOs, entrepreneurs and researchers are that there must be a wider exchange of knowledge and technology, with policies and action to promote sustainability and investment in research to fill the knowledge gaps. These efforts can lead to a more ecologically sustainable industry—an important goal, given the likely rapid growth in aquaculture production. They will also help ensure that aquaculture contributes fully to meeting our future needs for fish.

1. AQUACULTURE TODAY

PHOTO CREDIT: The WorldFish Center

1. Aquaculture Today: Production and Production Trends

Aquaculture production in context

For several decades aquaculture has been the fastest growing food production sector in the world. Five year averages for global production increases in major food commodities rank aquaculture number one for every period since 1974. Worldwide, aquaculture production has grown at an average annual rate of 8.4%, since 1970 (Table 1.1). With poultry showing the next largest rate of increase over this period at 5%, aquaculture's dynamism stands out clearly.

This rate of production growth has ensured that, as a global average, farmed fish supply has outpaced population growth. From a per capita value of 0.7 kg in 1970, global supply of farmed fish rose to 7.8 kg in 2006. The estimated average per capita fish consumption for wild and farmed combined was 16.8 kg in 2006, indicating that about 47% of fish for human consumption was supplied by aquaculture at that time. Given the unlikely prospect of increased yields from wild capture fisheries, this value will increase as aquaculture production grows.

Table 1.1: Food production statistics for major commodities. (Source: FAOStat and FishStat)

	Average annual production increase (1970–2008)	**Average annual production increase (2004–2008)**	**2008 Production (tonnes x 1000)**
Plant Food Commodities			
Cereals	2.1%	3.9%	2,525,107
Pulses	1.1%	0.6%	60,929
Roots and Tubers	0.9%	0.9%	729,583
Vegetables and Melons	3.4%	1.7%	916,102
Animal Food Commodities			
Beef and Buffalo	1.3%	1.6%	65,722
Eggs	3.2%	2.2%	65,586
Milk	1.5%	2.4%	693,707
Poultry	5.0%	3.9%	91,699
Sheep and Goats	1.8%	2.4%	13,174
Fish	8.4%	6.2%	52,568

Fish is also pre-eminent as an internationally traded animal source food. Representing about 10% of total exports of agricultural products by value, seafood exports from wild fisheries and aquaculture in 2008 had a combined value of US$102 billion (FAO, 2010), an 83% increase from 2000. The share of exports from developing countries is close to 50% by value and 60% by volume. Of internationally traded agricultural commodities seafood export value is exceeded only by fruits and vegetables (Table 1.2). The European Union is the world's largest seafood importer, followed by the United States and Japan.

Table 1.2: The export value of selected agricultural commodities in 2007. (Source: FAOStat and FAO TradeStat 2007)

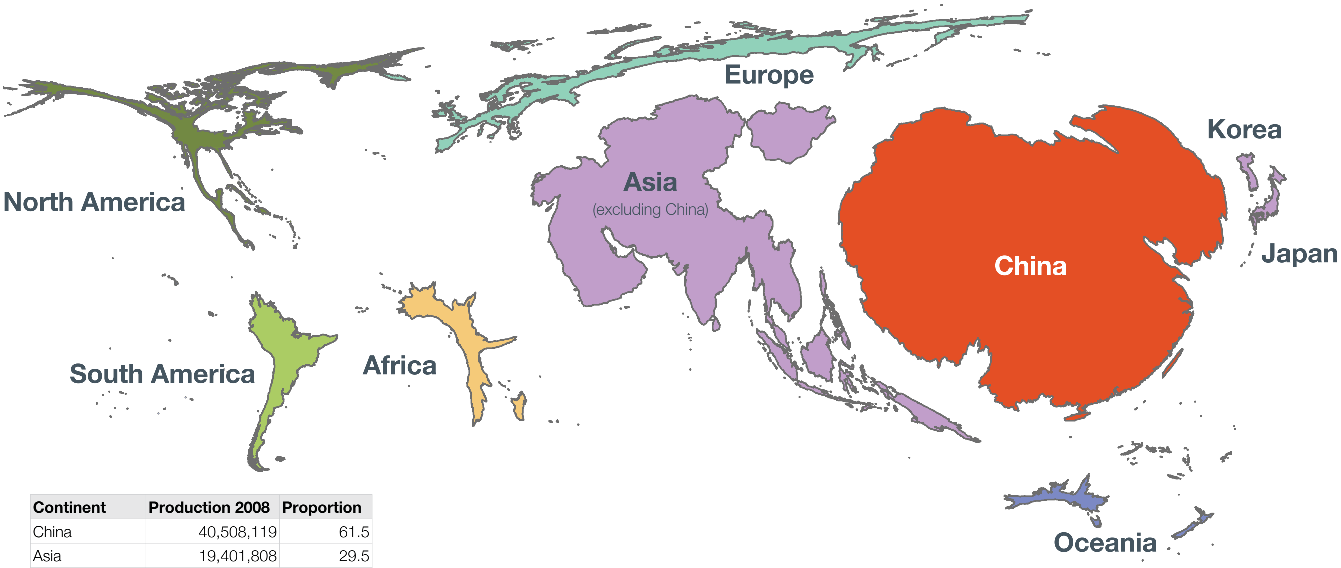
	Trade Value US$ billions 2007
Plant Commodities	
Fruit and Vegetables	150.89
Wheat	36.40
Tobacco	29.06
Sugar	18.58
Coffee	17.67
Rice	13.48
Pulses	4.82
Animal commodities	
Fish	92.80
Pigs	30.21
Cattle	28.99
Poultry	22.10
Sheep and Goats	4.35

Unfortunately national trade statistics do not distinguish between aquaculture and wild capture as the source of imports. It is, therefore, difficult to draw firm conclusions at a global level about the proportion of total international fish trade volume that aquaculture provides. A 2006 estimate for China, however, was that 39% by volume and 49% by value of the country's aquaculture production was exported (Fang, 2007). A high level of international trade in aquaculture products is important because it offers a potentially powerful entry point for harmonizing and improving environmental standards of production.Several recent reviews of global aquaculture production are readily available (e.g., Muir et al., 2009; Bostock et al., 2010), and the FAO provides biannual updates in its Status of Fisheries and Aquaculture series (FAO, 2009b). We have built on these to offer a concise global overview of current aquaculture production that helps put into context the analyses and results that follow. It also serves to introduce the reader to the data categorization approach we used for analyses described later in the report.

Using FAO data[1] , our starting point is the overall global picture (Figure 1.1). This figure summarizes how the world's total aquaculture production of 65.8 million tonnes in 2008 was distributed across continents by adjusting continental areas to reflect production volume. Following convention, we have treated China separately from the rest of Asia—a decision that is clearly appropriate given its pre-eminence as a producer.

With 61.5% of global production (40,508,119 tonnes) China deserves special attention. The further 29.5% of global production (19,401,808 tonnes) supplied by the rest of Asia places the continent as a whole in an overwhelmingly dominant position. By contrast, production in Europe with 3.6% (2,341,646 tonnes), South America with 2.2% (1,461,061 tonnes), North America with 1.5% (965,792 tonnes), Africa with 1.4% (952,133 tonnes) and Oceania with 0.3% (176,181 tonnes) is trivial in overall terms.

1 All data are from FAO FishStat unless otherwise stated.



Continent	Production 2008	Proportion
China	40,508,119	61.5
Asia	19,401,808	29.5
Europe	2,341,646	3.6
South America	1,461,061	2.2
North America	965,792	1.5
Africa	952,133	1.4
Oceania	176,181	0.3

Figure 1.1: World aquaculture production by continent in 2008 (China treated separately). Land areas are adjusted proportionally to reflect production volumes.

But, despite the overall dominance of Asia, aquaculture is an important economic activity on most continents and its importance is growing almost everywhere. To illustrate how production is distributed within regions Figure 1.2 lists the countries that account for at least 90% of production on each continent. Production is spread most widely among countries in Europe and Asia with over 90% of production accounted for by 11 and 9 countries, respectively. In contrast, most African and South American production is accounted for by only three countries on each continent.

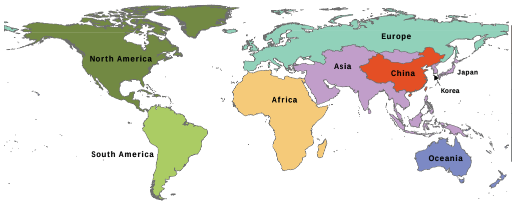
Figure 1.2 also shows how production is distributed in each country between coastal[2] and freshwater systems. Overall, 60% of global production occurs in freshwater. China and the rest of Asia contribute most to this average value, producing over 59 and 64% in freshwater, respectively. In contrast, coastal production dominates in South America, Europe and Oceania with respective values of 78, 80 and 98% from coastal areas. Production in North America is almost evenly split between coastal and freshwater habitats, while FAO reports there is a 60:40 split between coastal and freshwater in Africa. This picture is dominated by production from Egypt, which accounts for 73% of total aquaculture production on the continent. Data for Egypt are somewhat misleading, however, because although the FAO classifies the majority of production as coming from brackishwater, almost all of this is from very low salinity ponds in the Nile Delta.

[2] For this analysis we combined data classified in the FAOStat database for brackishwater and marine production into a single coastal production category.

Region	Production 2008 (T)	FW:C
USA	500,114	
Mexico	151,065	
Canada	144,099	
Honduras	47,080	
Cuba	33,039	
N. America	**965,791**	

Region	Production 2008 (T)	FW:C
Chile	849,159	
Brazil	290,186	
Ecuador	172,120	
S.America	**1,445,392**	

Region	Production 2008 (T)	FW:C
Norway	843,730	
Spain	249,062	
France	237,833	
Italy	181,469	
UK	179,187	
Russia	115,420	
Greece	114,888	
Ireland	57,210	
Netherlands	46,622	
Faroe Islands	45,929	
Germany	43,977	
Europe	**2,341,339**	



Region	Production 2008 (T)	FW:C
Egypt	693,815	
Nigeria	143,207	
Uganda	52,250	
Africa	**942,044**	

Region	Production 2008 (T)	FW:C
India	3,478,692	
Vietnam	2,461,700	
Indonesia	1,709,783	
Thailand	1,374,024	
Bangladesh	1,005,542	
Japan	748,474	
Philippines	741,142	
Myanmar	674,776	
Korea, Republic of	477,389	
Asia	**13,677,725**	

Region	Production 2008 (T)	FW:C
China	35,233,199	
Taiwan	323,982	
Hong Kong	4,754	
China	**35,561,935**	

Region	Production 2008 (T)	FW:C
New Zealand	112,358	
Australia	57,152	
Oceania	**174,115**	

Figure 1.2: Summary of 2007 aquaculture production by region.

To summarize the distribution of production with respect to species we have constructed treemaps that show the relative proportion of production by continent for each of 12 species groups (excluding seaweed, Figure 1.3). These maps show how carp dominates production in both China and the rest of Asia. In contrast, for Europe and South America salmonids dominate and account for more than 70% of worldwide salmonid production (capture and culture). African aquaculture production is almost exclusively of finfish, of which tilapias are the most important. For Oceania, shrimps and prawns dominate while in North America the pattern of production is somewhat more evenly distributed among species with shrimps and prawns, catfish, bivalves and salmonids accounting for the majority.

Rates of change in production (indicated by color in Figure 1.3) show several patterns. The first is that China and Asia continue to grow apace. Overall growth rates were 30% and 56% over five years, respectively. Growth in Oceania at 37% and South America at 39% is also high. The continent with the highest growth rate over the period, however, was Africa at 81%. Admittedly, this growth was from a very low baseline, but these “blue shoots” provide an indication that Africa may be poised for further dramatic production increases. In contrast, growth patterns in Europe and North America were the lowest at 8% and 7%, respectively.

The second is the explosive growth of catfish culture in Asia (307%) and Africa (496%) during the period. Albeit from a low base, these figures show how quickly a sub-sector can develop. While not so spectacular, growth for many other species groups is also high. In Asia, for example, tilapia production increased by 121%, carp production by 67% and shrimps and prawns by 53% over the five year period. Similarly large growth rates for several species groups can be found on all continents.

Another feature of these production growth data is that the only regions where production changes were positive for all species groups cultured were China and Oceania. In contrast, the rest of Asia saw declines for bivalves and the “other finfish” category, Europe for bivalve and carps and North America for catfish, carps and salmonids. Declines in Africa and South America were restricted to groups that contribute relatively little to the total continental production.

There are also significant differences in the relative importance of various species groups for wild capture and farmed fish production. Table 1.3 shows that between 2003 and 2008 the proportion of aquaculture in total fish production (i.e., for food and industrial purposes) increased from 34% to 42%. Supply from aquaculture is now dominant for seaweeds (99.5%) carps (89.9%) and salmonids (72.8%). At around 50% of total supply, cultured tilapia, catfish, mollusks, crabs and lobsters are now reaching prominence. This is especially true of tilapia and catfish where aquaculture production has increased dramatically against a backdrop of almost stagnation in wild capture. As a result, the share of production of farmed catfish and tilapia rose by 19.3 and 18.4%, respectively.

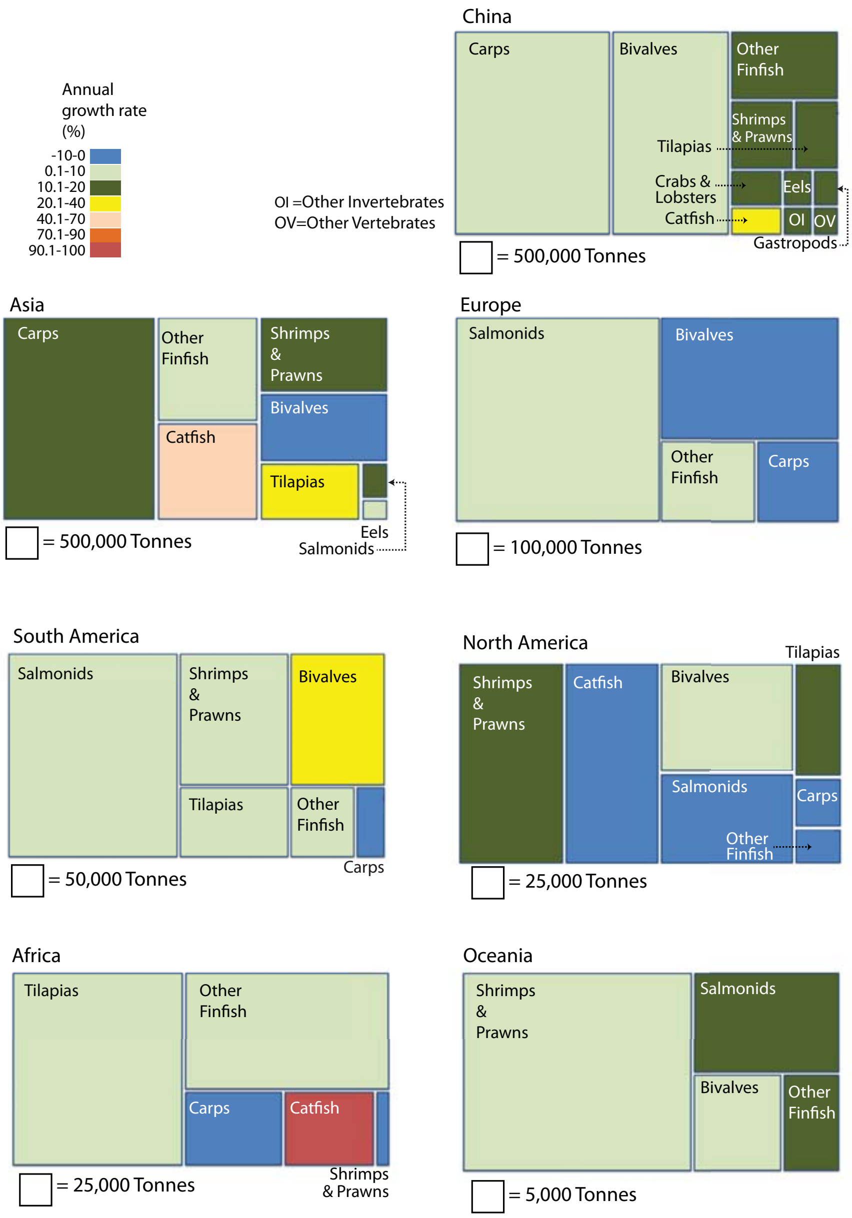


Figure 1.3: Treemaps summarizing 2008 production by species group for each continent (excluding seaweed). The area for each species in a map is proportional to the tonnage produced (Note differing scale for each map). The color of each block indicates the rate of increase between 2003 and 2008.

Table 1.3: The relative importance of aquaculture in global fish production per species group. (Source: FAO FishStat)

	Capture production (Mt)		Aquaculture production (Mt)		Proportion of total production from aquaculture (%)		
Species Group	**2003**	**2008**	**2003**	**2008**	**2003**	**2008**	**Difference**
Carps	2.02	2.21	15.04	19.72	88.2	89.9	1.8
Catfish	2.33	2.77	1.03	2.78	30.8	50.1	19.3
Tilapias	3.95	3.14	1.59	2.80	28.6	47.1	18.4
Eels	0.65	0.62	0.32	0.48	32.9	43.4	10.5
Salmonids	1.16	0.84	1.85	2.26	61.5	72.8	11.3
Other Finfish	50.81	51.79	4.40	5.79	8.0	10.0	2.1
Bivalves	18.43	19.72	11.06	12.65	37.5	39.1	1.6
Gastropods	0.30	0.32	0.21	0.37	41.4	53.7	12.3
Crabs and Lobsters	0.93	0.78	0.49	0.76	34.4	49.4	15.0
Shrimps and Prawns	8.85	8.47	2.59	4.35	22.7	33.9	11.3
Other Invertebrates	1.14	1.18	0.12	0.31	9.7	20.5	10.8
Seaweeds	0.34	0.07	9.02	13.24	96.3	99.5	3.1
TOTAL	**91.31**	**92.3**	**47.9**	**65.81**	**34.4**	**41.6**	**7.2**

Conclusion

This brief overview highlights several key features of the aquaculture sector: high overall growth in production, rapid emergence of species that meet market demand (e.g., striped catfish (*Pangasianodon hypophthalmus)* from Vietnam), growing significance as a supplier of food fish, and dominance by China. But growth in production has not come without environmental cost. In the next section we examine how these costs compare across the sector.

2. IMPACTS

PHOTO CREDIT: The WorldFish Center

2. Aquaculture production: Biophysical demands and ecological impacts

The rapid growth of aquaculture described in the previous section raises questions concerning the environmental sustainability of future industry growth. Central to these concerns is the demand aquaculture places on biophysical resources. Unsustainable consumption of these resources will ultimately undermine the productivity of the sector and bring it into competition for resources with other sectors (Gowing et al., 2006; Primavera, 2006).

Balanced against these concerns is the fact that farming aquatic animals that feed low in the food chain can be an ecologically efficient means of producing animal proteins. Some forms of aquaculture can also help mitigate environmental impacts. For example seaweed and mollusk farming are known to mitigate the effects of eutrophication (Troell et al., 1999; Neori et al., 2004; Nellemann et al., 2009).

To better understand the effects of aquaculture on the environment and its demands on biophysical resources, we need quantitative analyses. These are needed at several scales, from detailed studies for production of a particular species through to larger scale studies across regions and species-production systems. This study focuses on the larger scale, comparing and contrasting the global and regional environmental demands of aquaculture for a range of biophysical resources across the dominant suite of species and production systems in use today. It then goes on to examine their ecological impacts. This section describes our approach for achieving this.

Preliminary data analysis

We have based our assessment of environmental demands on the 2008 estimates of aquaculture production summarized in Section 1. To produce a manageable data set for analysis, however, some data reduction and aggregation of the full disaggregated data set was necessary. This was achieved using the following steps. First, we identified those species, excluding seaweeds, which cumulatively accounted for 90% of total world production. This list comprised 71 species. Extracting records for these species revealed that 29 countries contributed to this total. Using this data set, each of the individual species was then allocated to one of twelve separate species groups. Production for a given species by a given country was then further categorized into one of four separate production systems, resulting in 16 species group—production system combinations (Table 2.1). For each production system we made a further distinction between production in inland (freshwater) and coastal (marine and brackishwater) habitat, recognizing that some production systems are used in both (Table 2.1).

Table 2.1: The generic species group—production systems used to assess environmental demands. The subscript c denotes a coastal system and i denotes an inland (freshwater) system. ci indicates that the system occurs in both inland and coastal systems. (Note: Although carps are also cultured in cages and pens, this accounts for a small proportion of production and has, therefore, been omitted).

Species Group	Bottom Culture	Off-Bottom Culture	Cages & Pens	Ponds
Bivalves	✓c	✓c		✓ci
Carps				✓i
Catfish				✓i
Crabs and Lobsters			✓c	✓c
Eels				✓i
Gastropods		✓ci		
Other Finfish			✓ci	✓ci
Other Invertebrates				✓ci
Other Vertebrates				✓i
Salmonids			✓c	
Shrimps and Prawns				✓ci
Tilapias				✓ci

From the resulting data set we then extracted the species-country production records that cumulatively accounted for 90% of the production for each species group. To this we added the records accounting for 90% of seaweed production, all of which we classified as off-bottom marine culture.

In total, these combined records accounted for just over 82% of total world aquaculture production in 2008 and reduced the number of countries in our data set to 18. Further data reduction was then achieved by summing production within each unique species group, country, production system and habitat combination.

For the relevant production systems (e.g., coastal pond culture) we also considered the intensity of production for each species group—country combination in our data set. This is important because intensity of production determines the amount and type of feed and fertilizer regime required and the consequent level of emissions (Table 2.2).

Table 2.2: The production intensity categories used in this analysis. (After de Silva and Hasan, 2007).

Production Intensity	Description
Extensive	Systems requiring large areas of earthen ponds or water area; primarily for species in the finfish, mollusk, seaweeds, and shrimps and prawns species groups. Extensive production relies on natural productivity, but in ponds it is often supplemented by locally available crop wastes and other material. Little or no processed feed is used.
Semi-intensive	Primarily freshwater but also some coastal earthen pond systems in which natural productivity is augmented with fertilizers and farm made or industrially produced feeds. The majority of Asian finfish aquaculture is produced in freshwater, semi-intensive earthen pond culture systems.
Intensive	Some highly productive pond systems (e.g., shrimp, striped catfish), finfish cage culture and some high value species, such as eels in China. Intensive systems are mostly supplied with complete industrially produced pellet feeds that meet all of the nutritional requirements of the culture species.

To assign intensities to the data records we examined the available literature and consulted experts on species production methods within each species group within a country. For countries where species within a species group were produced at more than one intensity we duplicated the data record and adjusted production values for each record to reflect the proportion produced under each production intensity.

Finally, we considered the types of feed used for each species group, country, production system, habitat and intensity combination. Drawing on Neori et al. (2004) and de Silva and Hasan (2007) we distinguished five primary feed categories (Table 2.3). We then examined the literature and combined this with expert opinion where necessary (6% of records) to estimate the dominant feed type for each data record.

Assessment method

The objective of this study is to compare and contrast the global and regional demands of aquaculture for a range of biophysical resources across the entire suite of species and production systems in use today. Examples of the sorts of questions we wish to ask include:

- **How do countries or regions differ in their resource demands for aquaculture production?**
- **Which species groups or production systems are especially demanding, or efficient, and in what respect?**
- **Are there particular areas of the production process to which attention might most profitably be paid to reduce environmental demands?**

Table 2.3: The feed types used in this analysis. (After Neori et al., 2004 and de Silva and Hasan, 2007)

Feed Category	Description
Natural Feeds	Plant materials, mainly crop waste, used in combination with other material but with little or no processing. The feeds vary in nutrient quality.
Trash Feeds	Small or lower value fish used for aquaculture feeds and fed directly into aquaculture systems. This practice is common for marine fish cage production in Asia. Trash fish require no processing energy (except occasionally for chopping before feeding).
Mash Feeds	Mixed materials with some processing; processing is on farm and specific to farmers' requirements. These are 'farm-made' feeds and the major feed input for semi-intensive aquaculture.
Pellet Feeds	Feed pellets are manufactured in industrial feed plants and distributed through conventional market chains. The pellets are expected to completely fulfill all nutritional requirements of species. The pellets are mainly used in intensive aquaculture operations.
Extracted Food	Organic matter and nutrients for growth are assimilated from the environment through autotrophic processes or filter feeding. This category applies largely to bivalves, aquatic plants and some filter feeding fishes (e.g., silver carp).

With the data reduction described above our fundamental units of analysis are the elements of a sparse six dimensional matrix comprising: 13 species groups x 18 countries x 3 production intensities x 4 production systems x 2 habitats x 5 feed types. This resulted in 75 positive matrix elements, accounting for 82% of total world production in 2008 (Appendix). These 75 unique production elements form the basis of our assessment.

To facilitate meaningful comparisons of this sort, we require a method that can be applied in a standardized way across all units of analysis. Several approaches have been used previously to examine the sustainability of aquaculture and we were faced with a choice of the most appropriate method for this study. Table 2.4 summarizes the key features of several of these approaches.

Photo by Kam Suan Pheng
CHINA

Table 2.4: Summary of approaches to quantifying environmental impact. (Adapted from Bartley et al., 2007)

Method	Key attributes	Advantages	Disadvantages	Scientific rigor	Ease of application and communicability
Environmental Impact Assessment	Project-based Descriptive Site-specific	Public planning and transparent process Based on multiple criteria and can be used in sensitivity analysis Identifies hazards and impacts Allows redesign of project to reduce impacts	Does not quantify trade-offs or effects Does not provide a single performance indicator for comparisons Problems with how to interpret data	Variable (very high to low) Lots of uncertainty due to lack of data Often time-constrained due to development deadlines	Good Often figures prominently in decision-making
Risk Assessment or Analysis	Tool for understanding environmental processes	Contributes to better understanding of environmental flows and impacts Attempts to be quantitative but can also be qualitative Identifies hazards and impacts	Relies on qualitative judgments and estimates due to knowledge gaps Limited comparative use (some risks apply to some sectors, others not)	Variable at present Quantitative measures need to be developed (environmental indicators)	Good Formalized in legislation as decision-making tool
Material Flows Accounting, Mass Balance, Input/Output models	Examines input and output of key materials Accounts for biological flows associated with economic activities Applicable to systems at many scales	Quantifies levels of inputs and outputs Can produce comparable information over time and space Used to improve ecological efficiency Well-known tool with standard protocols	Does not reflect environmental effects Snapshot picture of flows at a specific point in time and place	High	Very good
Cost Benefit Analysis, including environmental costs	Uses valuation techniques for non-marketable goods to compare net results of activities of different sectors (e.g., contingent valuation, willingness to pay, hedonic pricing)	Can compare production systems Can be very inclusive of many types of information, including non-marketable goods Long history and familiarity with concept; decision-makers need and want to know this information Provides aggregate measures of the relative performance of various production systems	Environmental values hard to determine Ecological function changes hard to predict Often environment is not included Normally long term sustainability issues not addressed Discount rates are arbitrary and may be political Loses information during aggregation	High	Results easily communicated and understood Including valuation of environmental goods and services and non-marketable goods makes application difficult

Method	Key attributes	Advantages	Disadvantages	Scientific rigor	Ease of application and communicability
Ecological Footprint	Method to aggregate impacts into a single statistic to address eco-efficiency of human activities Converts all impacts to a measure of area needed to support a given activity	Provides a single indicator for comparison Can be applied to many levels and scales (e.g., a footprint for an individual to one for a national economy) Provides accumulative/aggregated effects	Does not include all flows Applications to food production systems are not obvious Method does not deal well with water Does not provide specific information about impacts or effects Does not address specific effects in specific environments Aggregated statistic treats all environments as homogenous and equal	Low	Easy to communicate, but statistic is often misused or can be misinterpreted Application is constrained by knowledge gaps on environmental differences among habitats
Life Cycle Analysis (LCA)	Examines a range of impacts of food production systems Product-oriented environmental impact assessment, with a cradle to grave perspective, multiple criteria analysis Quantifies potential contribution to global impacts	Allows hazards to be identified and prioritized Can build on previous work/data Can compare between products/processes/alternatives and different scenarios Basic method to develop eco-labeling criteria to support purchasing decisions for consumers Can provide policy-relevant insights	Large data requirements Some studies use different functional units Results address global impacts at expense of local impacts Some indicators may not be appropriate for specific cases Results are not directly applicable unless conducted for specific comparison Some standard impact categories may not be relevant to food product systems, thus need to develop new ones	High	Can “streamline LCA” for specific comparisons Communication on multiple criteria may be difficult

From our review we concluded that the Life Cycle Analysis (LCA) approach provides the strongest platform to conduct analysis over a range of different production systems, and at different scales of analysis. The approach is also readily amenable to updating or refining with new information.

LCA approaches are now in widespread use and are conducted at a variety of scales. There is an emerging body of LCAs that examines the environmental resources and emissions of aquaculture production systems (Pelletier and Tyedmers, 2007; Ayer and Tyedmers, 2009; Ellingsen et al., 2009). To date, however, the bulk of LCAs have been undertaken for single species and production systems (e.g., Mungkung et al., 2006; Pelletier et al., 2009) and comparability among studies remains a significant issue owing to the very wide range of choices available for describing LCA processes. There has been no effort to undertake a systematic global and regional level LCA comparison for aquaculture production of the type presented here.

LCA is a systematic four phase process comprising:

1. *Goal Definition and Scoping* — To a) define and describe the product, process or activity, b) establish the context in which the assessment is to be made and c) identify the boundaries and environmental effects to be reviewed for the assessment.

2. *Inventory Analysis* — To identify and quantify energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges).

3. *Impact Assessment* — To assess the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.

4. *Interpretation* — To evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results.

LCA practitioners make a distinction between screening studies that use readily available data and extensive studies that require a major investment of resources to gather new data. This study lies firmly at the screening end of this continuum and aims to provide a robust approach for answering the questions we pose. It also provides a foundation for further debate and refinement.

Our next requirement is to define the system boundaries for our analysis. In its full form LCA is a cradle-to-grave approach that begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. When complete, an LCA estimates the cumulative environmental impacts resulting from all stages in a product's life cycle. This often includes factors such as raw material extraction, material transportation, ultimate product disposal, that are often ignored by other methods.

In common with others studying aquaculture, however, we have adopted a more bounded approach (Figure 2.1) that excludes environmental costs associated with building infrastructure, seed production, packaging and processing of produce, transport of feed or produce, cooking the produce and disposing of the waste. Previous studies suggest that setting limits as shown in Figure 2.1 is defensible because the bulk of environmental resources and environmental emissions lies within these bounds (Pelletier and Tyedmers, 2007; Pelletier and Tyedmers, 2010). The biggest energy demands for aquaculture production systems occur on farm, for processing feed, for reduction of wild fish into fishmeal and fish oil and in the capture of wild fish to feed into the production process.

The main sources of eutrophying emissions (nitrogen and phosphorus) are those released from the farm (Pelletier and Tyedmers, 2007; Pelletier and Tyedmers, 2010).

The system shown in Figure 2.1 is generic and was used to analyze each of the 75 unique combinations of species group, country, production intensity, production systems, habitat and feed type. For some combinations particular processes become irrelevant or are reversed. With seaweed or bivalve culture, for example, nutrients are taken up from the environment rather than released. Similarly, with bivalves, since these extract food from the environment we set the feed production process to make no demands on energy, crop meal, fishmeal or fish oil.

Unit Processes

Data collection is the most time demanding task of LCAs. There are two types of LCA data required; foreground data and background data. Foreground data is the specific data required to model the systems (Goedkoop et al., 2008). This data refers to the biophysical resources required during aquaculture production, specifically, the amount of land, water, feed, fertilizers and energy required on farm. This data was collected from a variety of sources during a literature review.

Background data refers to predefined unit processes available in the standardized databases used by LCA practitioners and provided with several LCA software tools. Background data have been defined for a variety of agricultural production and energy production processes.

Figure 2.1 illustrates the system boundary of the model, distinguishing between the biosphere inputs (raw materials) and the technosphere inputs (any material transformed by human action) and indicating where emissions are released. The figure also distinguishes where foreground and background data has been used. By linking the foreground data to the background unit processes we capture upstream processes and their associated inputs from the biosphere and thetechnosphere (Goedkoop et al., 2008).

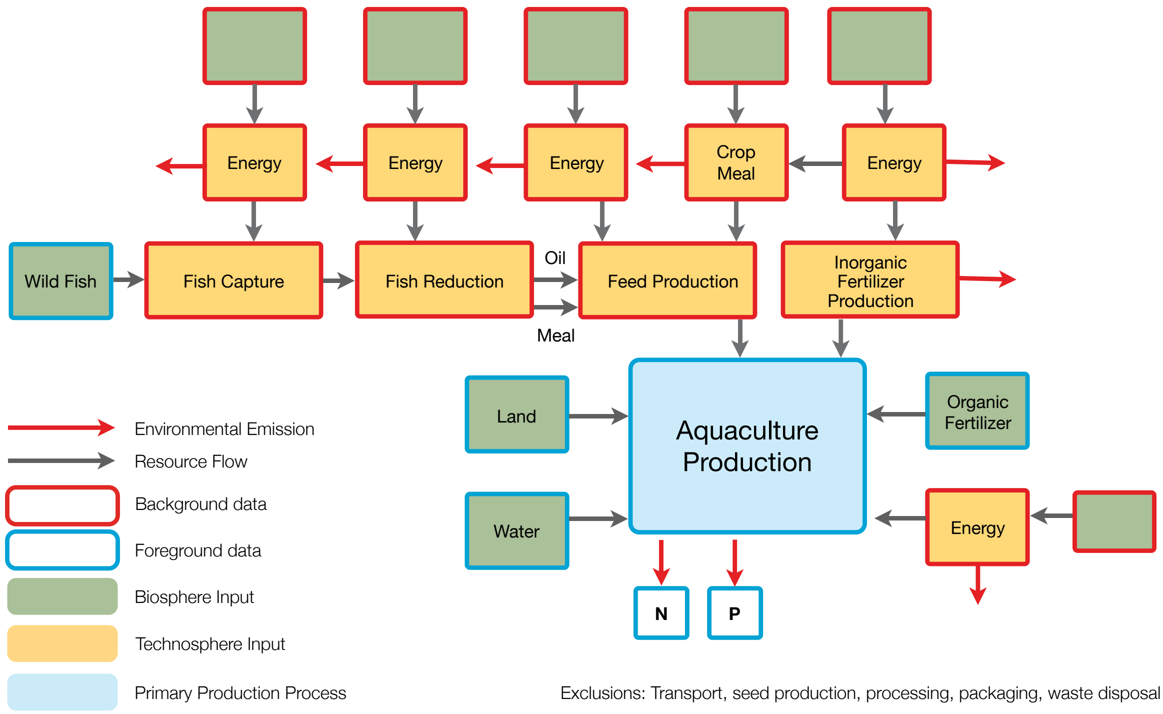


Figure 2.1: Graphical summary of the system boundaries and model structure for the Life Cycle Analyses undertaken in this study. Note: in the case of seaweeds, the flows to nitrogen (N) and phosphorus (P) would be negative (reversed).

In LCA parlance, the following demands on resources become our inventory categories:

1. The area of land required to grow fish.
2. The amount of wild fish used as fish feed.
3. The amount of organic and inorganic fertilizer required to grow fish.
4. The energy required for the various production processes involved (shown in Figure 2.1).
5. The amount of carbon dioxide the environment must assimilate from the production processes.
6. The amount of waste nitrogen and phosphorus the environment must assimilate from fish production.

As noted above, these six categories of demand were chosen because they are most likely to constrain the potential for sustainable aquaculture growth (Rockström et al., 2009; Duarte et al., 2009; Muir et al., 2009).

Process definition and model parameterization

Having identified the categories for inventory, we must now specify how inputs to the LCA are calculated. The following section describes the basis for this. Literature sources and the approach used to estimate model parameters are given in Table 2.5.

The foundation of our approach is to work back from aquaculture production P for each species group *i* within production system *j* in habitat *k* at intensity *l* with feed *m* for country *n*. (Note: These subscripts remain constant throughout this paper, unless otherwise stated). Using these data we first used the following equations to calculate the land or sea area required for production and the volume of freshwater required for inland systems:

$$Area_{i,j,k,l,m,n} = \frac{P_{i,j,k,l,m,n}}{\alpha_{i,j,k,l,m,n}}$$

$$Water_{i,j,k,l,m} = \frac{P_{i,j,k,l,m,n}}{\beta_{i,j,k,l,m,n}}$$

Where α is the production efficiency per unit production area, and β is the production efficiency per unit water volume. For production from coastal systems (marine and brackishwater) the freshwater requirement was set to zero.

To calculate total on farm energy use we modeled country specific energy mixes (IEA, 2010) to estimate the energy use efficiency γ such that:

$$FarmEnergy_{i,j,k,l,m,n} = P_{i,j,k,l,m,n} \cdot \gamma_{i,j,k,l,m,n}$$

Organic fertilizers are defined here as on farm wastes that enhance the natural productivity of the culture system. We distinguished four categories: cow, chicken and pig manure and plant compost and calculate organic fertilizer input as the sum of inputs into a given system from these sources i.e.:

$$OrgFertilizer_{i,j,k,l,m,n} = \sum_{p=1}^{4} \vartheta_{p,i,j,k,l,m} \cdot Area_{i,j,k,l,m,n}$$

Where $\vartheta_{p,\ldots}$ is the application rate of fertilizer *p* per unit aquaculture production area for a given production system.

Similarly, for inorganic fertilizer inputs we distinguished two sources, urea and Triple Super Phosphate (TSP), and calculate total application as the sum of these two inputs:

$$Urea_{i,j,k,l,m,n} = \mu_{1,i,j,k,l,m} \cdot Area_{i,j,k,l,m,n}$$

$$TSP_{i,j,k,l,m,n} = \mu_{2,i,j,k,l,m} \cdot Area_{i,j,k,l,m,n}$$

Where $\mu_{1,\ldots}$ and $\mu_{2,\ldots}$ are the application rates per unit area for urea and TSP, respectively for each production system.

Aquaculture feeds are a combination of fishmeal, fish oil, and crop meal. We estimated the total quantity of fish required to provide the necessary fishmeal and fish oil to meet observed fish production using the following equations:

$$FishMeal_{i,j,k,l,m} = \frac{P_{i,j,k,l,m,n} \cdot FCR_{i,j,k,l,m,n} \cdot \pi_{meal}}{\rho_{meal}}$$

$$FishOil_{i,j,k,l,m} = \frac{P_{i,j,k,l,m,n} \cdot FCR_{i,j,k,l,m,n} \cdot \pi_{oil}}{\rho_{oil}}$$

Where *FCR* is the Food Conversion Ratio, defined as the amount of processed feed required for every unit weight of fish produced, π is the proportion of fishmeal or oil in feeds and ρ is the yield of meal or oil per unit of wild fish from the fish reduction process. Because a given quantity of wild fish produces both meal and oil, we take the larger of the two values to represent total wild fish demand (Kaushik and Troell, 2010).

Energy requirements for the fish reduction process were copied from the unit process 'Fishmeal' from the DK data library supplied with SimaPro, the software used for our LCA analyses. This unit process states that reducing 1 kg of sandeel to fishmeal and fish oil requires 1332 kj of heat energy and 0.04 kwh of electricity. We assume here that the costs of reduction for sandeel apply to costs of reduction for other fish species. The energy needed for wild fish capture was based on estimates of the fuel oil required for fishing provided by Ellingsen and Aanondsen (2006). During fish reduction two products, fishmeal and fish oil, are produced. We allocated environmental burdens for each product based on the weight of each produced.

Total crop meal required was estimated from:

$$CropMeal_{i,j,k,l,m} = P_{i,j,k,l,m} \cdot FCR_{i,j,k,l,m} \cdot (1 - (\pi_{meal} + \pi_{oil}))$$

Once the main crop types were identified through literature review, unit processes were identified within the EcoInvent library that represented these crops. This was then used to estimate the energy needed to produce it. We defined main crop types as those that accounted for approximately 70% of all feed used in the grow-out of a unique species combination.

To calculate nitrogen and phosphorus emissions from aquaculture production we used a simple mass balance approach where the total weight of N or P from processed feed and fertilizer inputs was calculated and subtracted from the total N or P content of the fish produced. These quantities were calculated from the following equations:

$$Nfeed_{i,j,k,l,m,n} = P_{i,j,k,l,m,n} \cdot FCR_{i,j,k,l,m,n} \cdot \omega$$

Where ω is the percentage nitrogen by weight in feed.

$$NOrgFert_{i,j,k,l,m,n} = \sum^{4} \sigma_1 \cdot Area_{i,j,k,l,m,n} \cdot \vartheta_p$$

Where $\sigma_{1,1,...,4}$ is the percentage nitrogen by weight in cow, chicken and pig manure and plant compost, respectively.

$$NInorgFert_{i,j,k,l,m,n} = \tau_1 \cdot Area_{i,j,k,l,m,n} \cdot \mu_1$$

Where τ_1 is the percentage nitrogen by weight in urea.

$$NFish_{i,j,k,l,m,n} = P_{i,j,k,l,m,n} \cdot \varphi_1$$

Where φ_1 is the percentage nitrogen in fish tissue.

Phosphorus was calculated in the same way except that the percentage phosphorus in TSP replaced percentage nitrogen in urea to calculate the contribution from inorganic fertilizers. Although this approach is reasonable as a first approximation, we recognize that not all nutrients are lost. In some pond systems, for example, up to half of the nutrients may end up in sediments which can be re-used for agriculture (Islam, 2005).

Table 2.5: Parameter estimates and data sources for foreground data calculations. In cases where parameter estimates for a particular system could not be obtained directly from the literature, values for the system with the closest similarity or expert opinion was used. The proportion of records determined by expert opinion are shown in parentheses at the end of each list of data sources.

	Parameter	Description	Units	Data Sources
1	$\propto_{i,j,k,l,m,n}$	Production per unit area.	$t.ha^{-1}$	Atmomarsono and Nikijulluw, 2004; Barman and Karim, 2007; Biao and Kaijin, 2007; Brown, 2000; Cao et al., 2007; Chen, 2003; CIFA, accessed in 2010; Cruz, 1997; El-Sayed, 2007; Gupta and Acosta, 2004; Losinger et al., 2000; Nakada, 2002; Nur, 2007; Phan et al, 2009; Phuong, 2010; Rosenberry, 1999; Sturrock et al., 2008; Sumagaysay-Chavoso, 2007; Unknown, accessed in 2010; Weimin and Mengqing, 2007. (9%)
2	$\beta_{i,j,k,l,m,n}$	Production per unit water volume.	$t.m^3$	Dugan et al., 2007; Muir et al., 2009 (18%)
3	$\gamma_{i,j,k,l,m,n}$	On farm energy use efficiency per unit fish production.	$Mj.t^{-1}$	ADB, 2005; Bosma et al., 2009; Bunting and Pretty, 2007; Henriksson, 2009; Olah and Sinha, 1986; Pelletier and Tyedmers, 2010; Tlusty and Langueux, 2009; Troell et al., 2004. (25%)
4	$\vartheta_{1....4.i.j.k.l.m}$	Application rate of cow, chicken and pig manure and plant compost for each production system	$kg.ha^{-1}$	Barman and Karim, 2007; Cruz, 1997; Cruz-Lacierda et al., 2008; de Silva and Hasan, 2007; El-Sayed, 2006; El-Sayed, 2007; FAO, accessed in 2010; Flores-Nava, 2007; Hung and Huy, 2007; Weimin and Mengqing, 2007. (73%)
5	$\mu_{1,...,2,i,j,k,l,m}$	Application rate per unit area of urea and TSP, respectively for each production system.	$kg.ha^{-1}$	Atmomarsono and Nikijulluw, 2004; Barman and Karim, 2007; Cruz, 1997; Cruz-Lacierda et al., 2008; El-Sayed, 2006; El-Sayed, 2007; Flores-Nava, 2007; Hung and Huy, 2007; Pelletier et al., 2009. (70%)
6	$FCR_{i,j,k,l,m,n}$	Food conversion ratio. (Food required: Fish produced, by wet weight)	-	Tacon and Metian, 2008; FAO, 2004. (10%)
7	π_{meal} π_{oil}	The proportion by weight of fishmeal and oil in pellet feeds.	-	Barman and Karim, 2007; Tacon and Metian, 2008. (10%)

	Parameter	Description	Units	Data Sources
8	ρ_{meal} ρ_{oil}	The yield of fishmeal or oil per unit wet weight of fish.	-	Péron et al., 2010.
9	$\omega_{1,...,2}$	The proportion by weight of nitrogen and phosphorus, in fish feed.	-	Craig and Helfrich, 2009.
10	$\sigma_{1,,2,1,...,4}$	The proportion by weight of nitrogen and phosphorus (i = 1,..,2, respectively) in cow, chicken and pig manure and plant compost (j = 1,..,4, respectively).	-	Barman and Karim, 2007.
11	$\tau_{1,...,2}$	The proportion by weight of nitrogen and phosphorus in urea and TSP, respectively.	-	Graslund and Bengtsson, 2001.
12	$\varphi_{1,...,2}$	The proportion by weight of nitrogen and phosphorus, in fish tissues.	-	Ramseyer, 2002; Tanner et al., 2000.

Note: In all cases subscripts denote: species group *i* within production system *j* in habitat *k* at intensity *l* with feed *m* for country *n*.

From Inventory to Impact Categories

From the estimates derived using the methodology described above we ran an LCA analysis for each of the 75 unique combinations. All analyses were conducted using SimaPro V 7.0 (Goedkoop et al., 2008). In common with other LCAs impacts were assessed using a mid-point approach, which takes the inventory results and translates them into impact measures that fall somewhere short of the ultimate impacts (end points) of interest. With acidification, for example, one might choose an impact end point as area of forest lost through acid rain. This will be difficult to estimate, however, so researchers usually use the inventory data to estimate the aggregate acidification burden on forests as a mid-point measure. For this study, the following six impact categories were used:

Eutrophication: includes all impacts due to excessive levels of macronutrients in the environment caused by emissions of nutrients to air, water and soil. Expressed as t PO_4 equivalents[3].

Acidification: acidifying substances impact on the functioning of ecosystems and human well-being. Acidification potentials are expressed in t SO_2 equivalents.

Climate Change: reflects the characterization model developed by the Intergovernmental Panel on Climate Change (IPCC). Results are expressed as climate change potential in t CO_2 equivalents.

Cumulative Energy Demand (CED): represents the direct and indirect use of industrial energy, expressed in Gj, required throughout the production process.

Land Occupation: calculated as the sum of direct and indirect land occupation, using equivalence factors adjusted for each type of land (e.g., arable, pasture, sea) for relative levels of bioproductivity. The higher the bioproductivity of the land, the higher the equivalent factor becomes (Wackernagel et al., 2005)[4]. Land occupation is expressed in ha equivalents.

Biotic Depletion (Fish): the amount (t) of wild fish required to support observed aquaculture production. There was no differentiation of the type of fish used during the production process, but we assume that all the fish used for feed are small pelagic fish species.

[3]Although nitrogen is often the limiting nutrient in marine systems, it is convenient to express eutrophication potential in terms of PO4 throughout and does not affect the conclusions.

[4]All species within ‘coastal’ habitats were classified as occupying sea (equivalence factor 0.36). Species cultivated in ‘inland’ habitats were assumed to occupy arable land (equivalence factor 2.19). Thus, if cultivation of a species group required 1 hectare of sea area it was characterized as requiring 0.36 hectares. In contrast, species requiring 1 hectare of arable land (e.g., carp, tilapia) was characterized as requiring 2.19 hectares of land.

The definition and approach used for estimating eutrophication, acidification and climate change was the 'CML Baseline 2001' impact assessment methodology of The Institute of Environmental Sciences of Leiden University (CML) (Guinée et al., 2002). The standard method to calculate Cumulative Energy Demand (CED) was based on the method published by EcoInvent version 1.05 and expanded by PRé Consultants for energy resources available in the SimaPro database (VDI, 1997).

Results

Table 2.6a summarizes the overall impact of the 82% of 2008 production that was modeled in this study along with a projection of the impacts for the total production that year. Putting such figures in context is, of course, challenging, but one indication of the relative significance of these values can be obtained if one compares estimates for CO_2 emissions with those available for other sectors (Table 2.6b). This table suggests that aquaculture contributes about 0.96% to total CO_2 emissions and between 6.3 and 7.5% of agriculture emissions. This is based on IPCC estimates of total agricultural emissions ranging between 5120 $MtCO_2$-eq/yr (Denman et al. 2007) and 6116 $MtCO_2$-eq/yr (US-EPA, 2006) in 2005. If one were to offset the CO_2 contribution from all aquaculture production it would cost about US$ 52.5 billion at the current market price for CO_2 in offset markets of around US$ 15 per tonne (World Bank, 2010).

Table 2.6: (a) Total estimated impacts from the 75 production systems modeled in this study and an estimate of the complete global impact assuming that, as with total aquaculture production, each calculated estimate represents 88% of the total. (b) Sectoral comparison of CO_2 emissions. (Note: not all categories are mutually exclusive so figures do not add up to the total estimate). Source: UNSTATS Environmental Indicators, accessed December, 2010.

a)	Eutrophication (Mt PO_4 eq)	Acidification (Mt SO_2 eq)	Climate Change (Mt CO_2 eq)	Land Occupation (Mha)	Energy Demand (Tj eq)	Biotic Depletion (Mt)
Modeled	3.33	2.60	298.26	55.77	3,431,361	15.11
Total	3.92	3.06	350.89	65.61	4,036,895	17.78

b) Sectoral Source	Total Emission (M tonnes CO_2 eq)
Energy	22,952
Transport	4,815
Industrial Processes	2,105
Agriculture	4,650
Waste	1,057
Aquaculture (this study)	385
Total	**30,824**

Relationships with aquaculture production

As expected, for the most part, data for all impact categories show a positive relationship between overall production levels and impact (Figure 2.2). The only exceptions to this are for the subset of the data representing species that extract food from the natural environment. With the exception of a relatively minor contribution (on a global scale) to eutrophication through pseudo-feces deposits to bottom sediments by mollusks, these make no contribution to eutrophication or biotic (fish) depletion. This is apparent from the horizontal line of data points at the bottom of these panels in Figure 2.2. Despite these linear relationships, however, there is clearly considerable variance in impact for a given level of production. This is especially true for acidification, climate change, cumulative energy demand and land occupation.

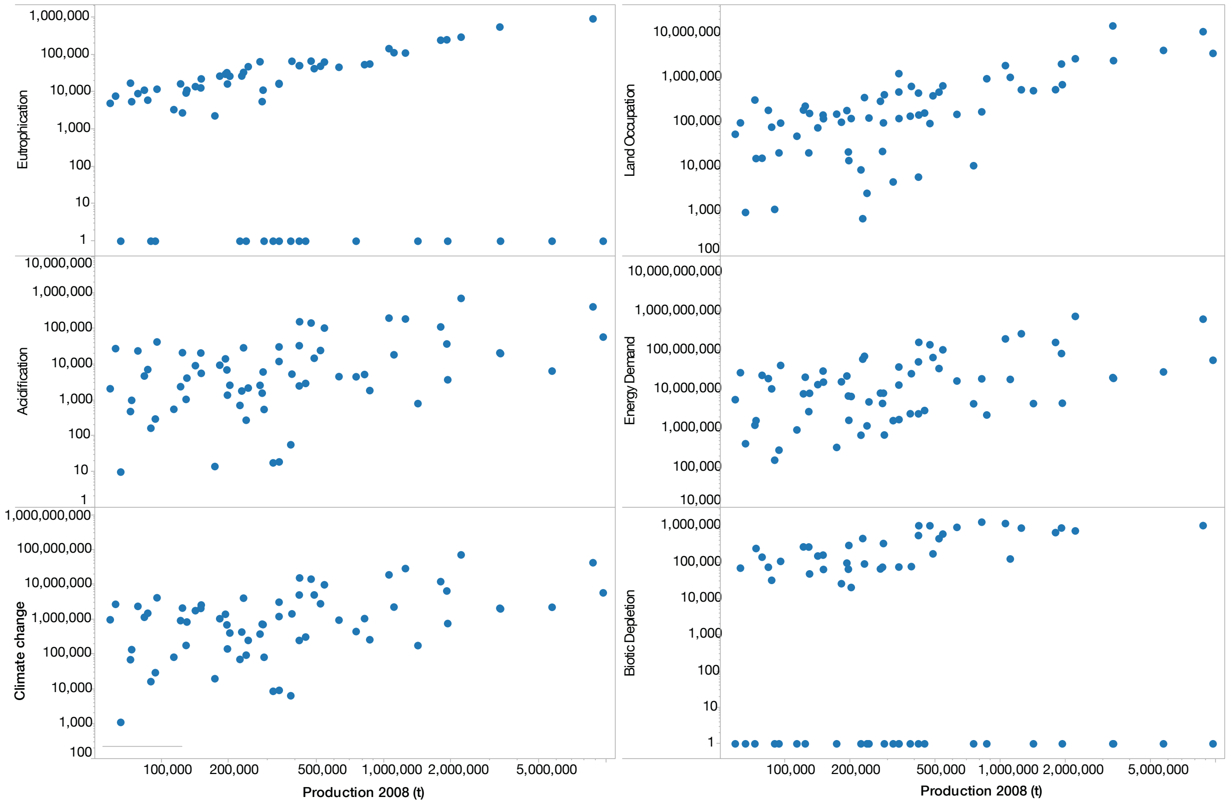


Figure 2.2: The relationship between overall production levels for each of the 75 unique production combinations and level of impact: Eutrophication (t PO_4 eq); Acidification (t SO_2 eq); Climate Change (t CO_2 eq); Land Occupation (ha eq); Cumulative Energy Demand (Gj); Biotic Depletion(t).

Impacts by habitat and production system

Given the positive relationship between production and absolute levels of impact described above it is unsurprising that, with its dominance as a production system, inland pond culture contributes the greatest impact overall for all impact categories (Figure 2.3, upper panel). Nevertheless, despite this overall dominance, demand for wild fish (biotic depletion) is also notable for marine cage and pen production. Negative values for eutrophication in bottom and off-bottom culture reflect bivalve farming where nutrients are taken up from the environment. However, although we can rightly view this as a regional removal, we must recognize that at a more local scale impact through the deposition of pseudo-feces will occur.

When one considers efficiency of production, and compares levels of impact for a given unit of product, impacts from pond and cage and pen production dominate in both freshwater and marine systems (Figure 2.3, lower panel). With the exception of land occupation, however, cage and pen culture has consistently greater impact. Overall, however, cage and pen production in inland waters appears to cause the greatest impact. One must also bear in mind that deposits into freshwater pond sediments are also often used for agriculture.

Figure 2.3: Upper panel: The absolute environmental impact of 2008 aquaculture production categorized by production system and habitat: Eutrophication (t PO_4 eq); Acidification (t SO_2 eq); Climate Change (t CO_2 eq); Land Occupation (ha eq); Cumulative Energy Demand (Gj); Biotic Depletion (t). Lower panel: The relative environmental impact, per tonne of product categorized by production system and habitat: Eutrophication (kg PO_4 eq); Acidification (kg SO_2 eq); Climate Change (kg CO_2 eq); Land Occupation (ha eq); Cumulative Energy Demand (Mj); Biotic Depletion (kg).

Impacts by species group

In absolute terms, we see that carps dominate overall impact (Figure 2.4, upper panel), reflecting the fact that carp production is greater than that of other species groups. Production in the “Other finfish” category is also notable, however, particularly for acidification, climate change and energy demand, three measures that are correlated with one another. A recent review of environmental impacts of marine finfish culture provides further perspectives on this production category (Volpe et al., 2010). For the biotic depletion category, total demand for fish to produce shrimps and prawns and salmonids almost reaches that for carps.

In relative terms, eel production stands out as being especially environmentally demanding (Figure 2.4, lower panel), reflecting the highly intensive and energy demanding nature of eel production systems. No other species group dominates impact categories to the same extent, although shrimps and prawns tend to be among those causing the most impact, while salmonids are notable for their demand for fish. Figure 2.5 further summarizes the relative efficiency of production for species groups categorized by habitat and production system.

Land occupation impacts vary with species group and system, but largest impacts are not surprisingly associated with pond farming, particularly in Asia and South America. One should recognize, however, that LCA does not fully capture biodiversity and other values associated with land use for aquaculture. More local analysis will be is required to determine such impacts. Impacts of concern may relate to loss of biodiversity associated with replacement of habitat by ponds, or loss of ecosystem functions such as those associated with carbon sequestration or provision of nursery areas for wild fish populations.

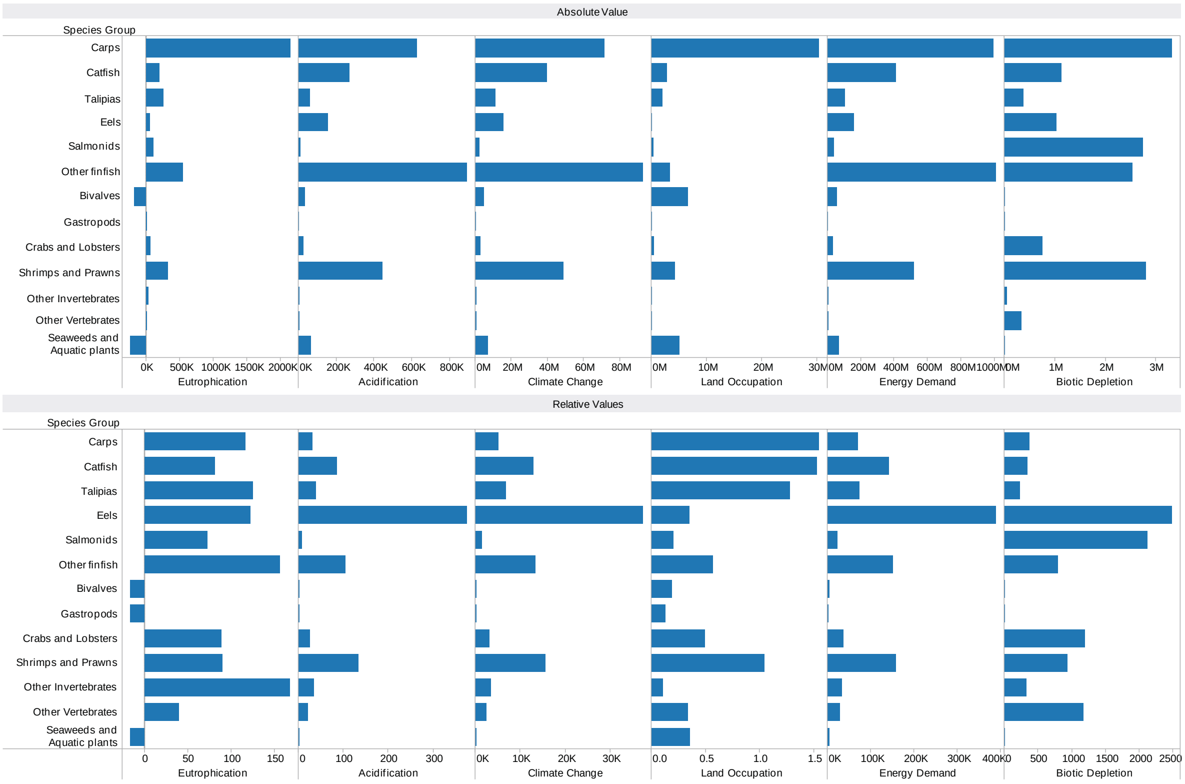


Figure 2.4: Upper panel: The absolute environmental impact of 2008 aquaculture production categorized by species group; units as for Figure 2.3 (upper panel). Lower panel: The relative environmental impact per tonne of product categorized by species; units as for Figure 2.3 (lower panel).

Figure 2.5: The relative environmental impact of 2008 aquaculture production categorized by habitat, production system and species group; units as for Figure 2.3 (lower panel).

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Impacts by country

Figures 2.6 and 2.7 summarize the absolute and relative impacts of aquaculture production for the 18 countries in our analysis[5]. Figure 2.6 gives a clear sense of the overall dominance of China, but also illustrates how absolute demand for fish is somewhat more evenly distributed, reflecting the mix of species that are produced in different regions. The demands of salmonids and shrimps and prawns, for example, explain the bulk of the fish demand for Europe and the Americas.

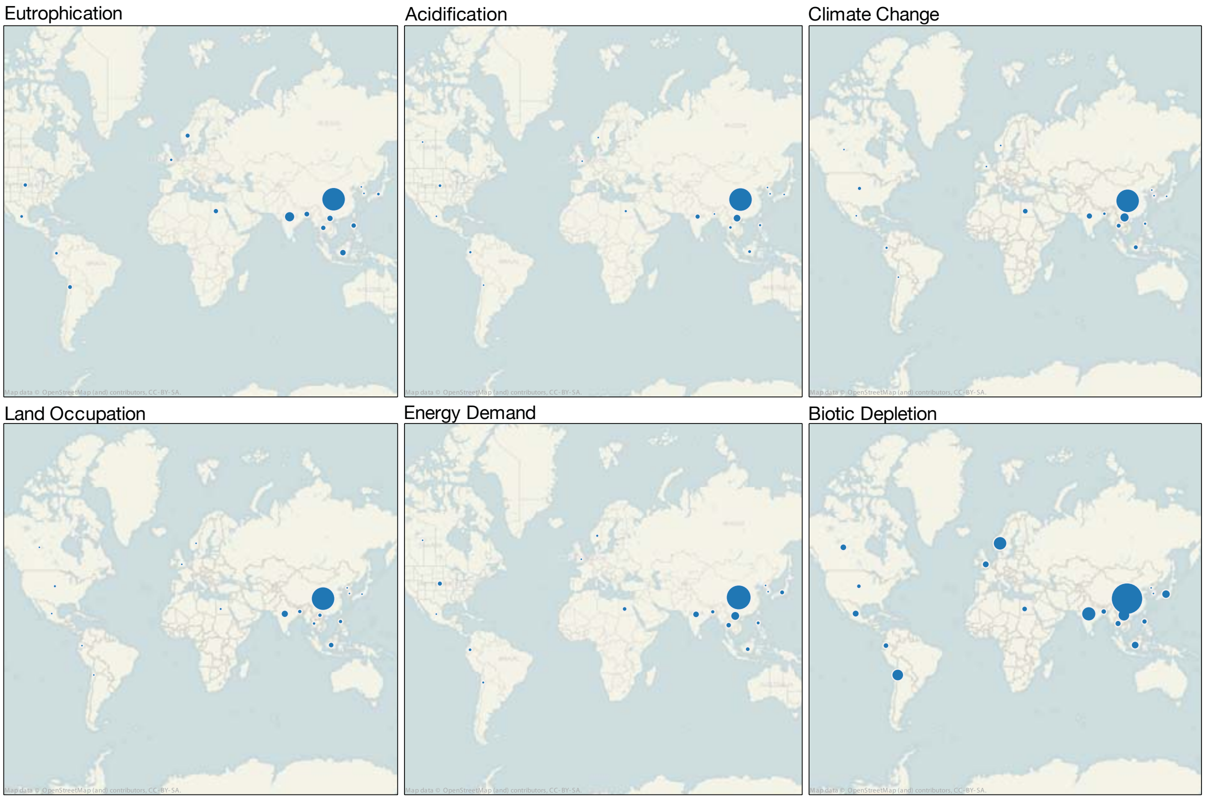


Figure 2.6: Maps showing the absolute size of total environmental impacts of 2008 production for each of the 18 countries analyzed in this study. Scales have been omitted from these figures for clarity.

In terms of efficiency of production with respect to environmental impacts, the picture is rather more variable (Figure 2.7). For eutrophication, for example, results are broadly comparable across all countries, whereas for four of the remaining impact categories, aquaculture production is markedly more "efficient" in the salmon producing nations of north Europe, Canada and Chile, and for Japan. Not surprisingly, however, this picture reverses for efficiency in production with respect to wild fish consumption (biotic depletion) where the salmon producing countries, are joined by those where shrimps and prawns dominate the production mix.

[5] Scales have been omitted from these figures for clarity.

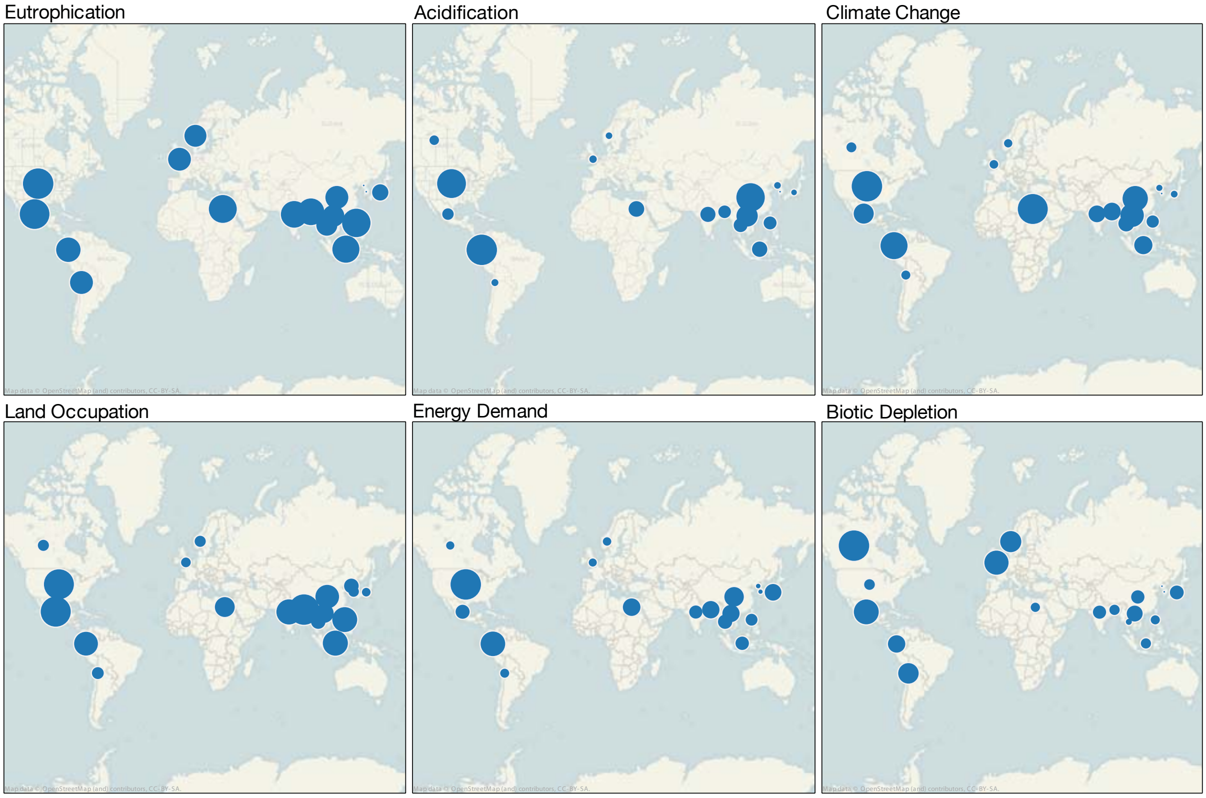


Figure 2.7: Maps showing the relative size of environmental efficiencies (indicated by the average environmental impacts per tonne of production) for each of the 18 countries analyzed in this study.

Further insight into how these values are derived can be obtained by looking in more detail at how environmental efficiencies differ across countries that culture the same species groups (Figure 2.8). Taking shrimp and prawn culture in coastal systems we can see, for example, that China is much less efficient, in relative terms, than other producers with respect to acidification, climate change potential and energy demand (Figure 2.8 upper panel). By contrast, the eutrophication burden through production of other finfish is markedly greater in Indonesia and the Philippines than it is for other producers. For salmonid production, environmental performance is broadly similar across countries, but Canada appears to have greater relative demands for fish-based feeds (Figure 2.8 upper panel). For inland carps and tilapia production, no single country stands out across all impact categories, but for catfish the United States and Vietnam are among the least efficient in most cases.

Of particular interest in Figure 2.8 is the variation between countries for a given species. In 22 of the 36 comparisons shown, the best performers had impacts per tonne produced that were more than 50% lower than the worst performers. This variation indicates that large efficiency gaps in environmental performance exist between countries, indicating great potential for improvement (see discussion).

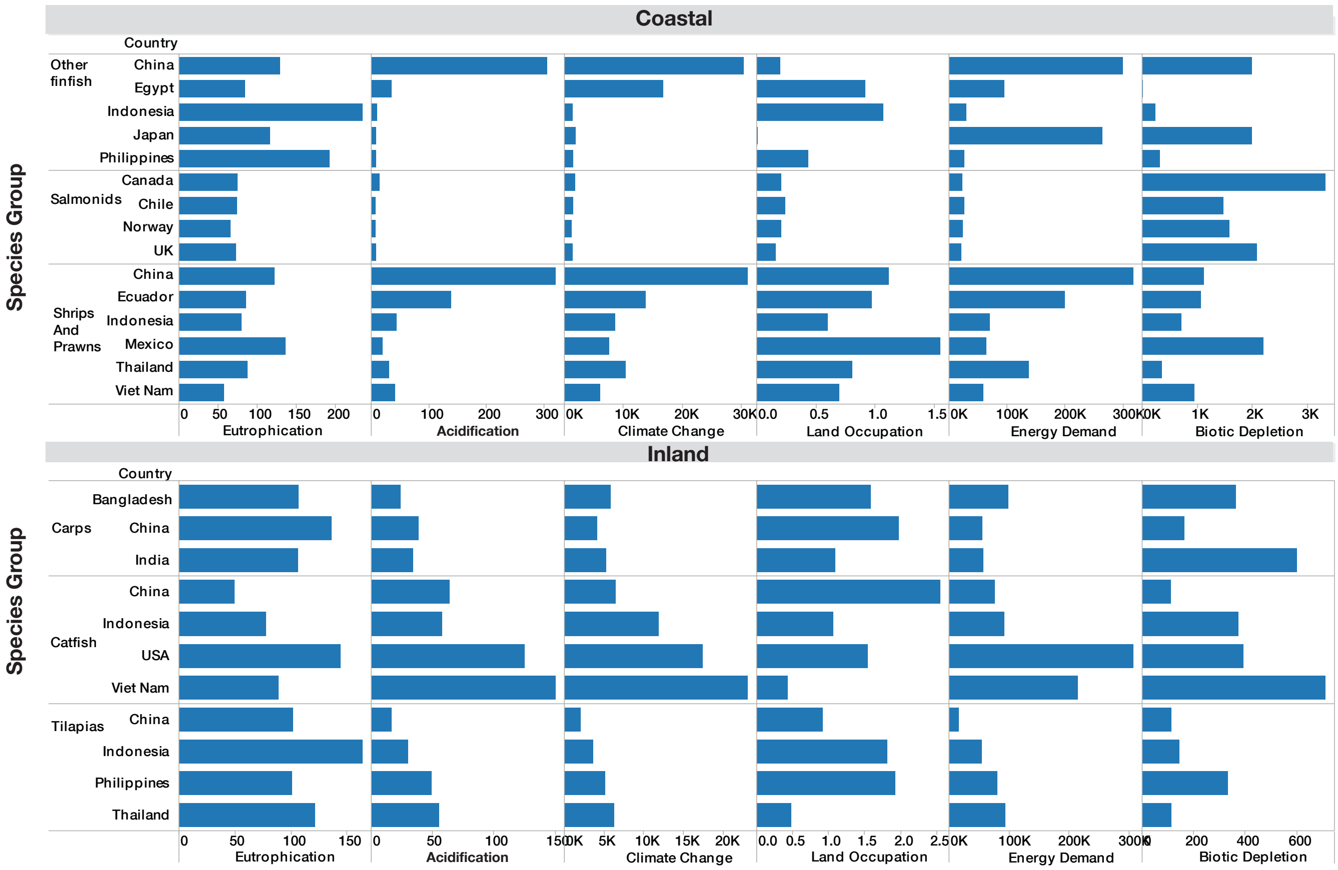


Figure 2.8: A comparison of environmental efficiencies across countries growing the same species group.

Drivers of impact

An important tool in understanding our results is contribution analysis. This shows which processes are playing a significant role in the impact results. Often, even in an LCA containing hundreds of different processes more than 95% of the results are determined by just ten or fewer. Figure 2.9 summarizes the contributions to impact of the five main processes in our models for each of the species groups[6].

This shows clearly that it is the fish production process itself which contributes most to eutrophication, whereas, for most groups, acidification and climate change impacts are contributed primarily by the national energy production process. This indicates that much of the variation in acidification and climate change impacts across countries for a given production system will be driven by the energy mix that supplies that country. Production in a country such as China that is dominated by coal production, therefore, will be greater than in a country with a large proportion of energy coming from nuclear or hydro power.

As we would expect biotic (fish) depletion is driven primarily by the feed production process. Fertilizer production processes for urea and TSP, generally contribute little to the total impact.

An interesting feature of this analysis is the exceptions to the general pattern. It is notable, for example, how the feed production process dominates most impact categories for salmon aquaculture and, to a lesser extent, for tilapia and carps.

[6] One feature of this analysis that it is important to bear in mind is that a given process may occur in several places in the model; energy production, for example, will contribute to both feed and fertilizer production processes. Figure 2.9 shows the sum of all these contributions from a given process.

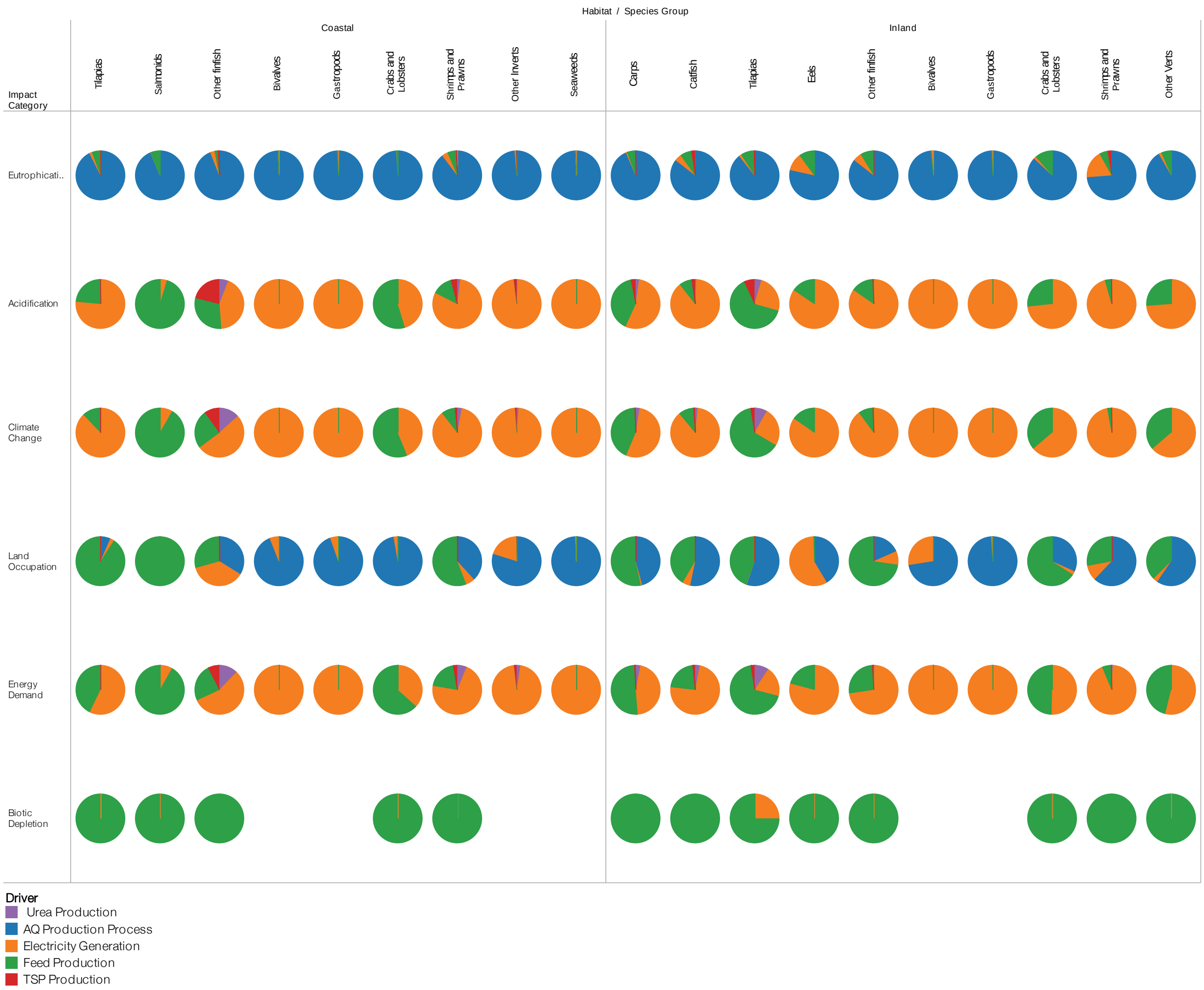


Figure 2.9: The total proportional contribution to impact of the five main processes for each species group.

Sensitivity analysis

With 75 separate LCAs a complete analysis of both within and between model sensitivities would be an enormous and impractical undertaking. In view of this, we focused on those models where we felt the greatest uncertainties existed. The results of our analysis can be sensitive to both the functional form (structure) of our model and its parameterization. Assumptions made during the goal setting and scoping phases affect model structure and the quality of available data determines the uncertainty in input parameters. Our primary uncertainties concerning both model structure and parameterization are with feed and fertilizers.

For feed, we used 5 categories and assigned each of our 75 production systems to one of these. Natural feeds provided by the inherent productivity of the system were not considered as having any negative environmental effect and were not, therefore, included in the inventory stage of the LCA. Mash feeds are farm-made and require little processing. Where the databases provided with Simapro allowed, we chose crops ‘at farm’ to represent the lesser degree of processing of mash compared to pellet feeds. Pellet feeds were treated as industrial feed, meaning that processes were chosen from the database to better represent the higher degree of processing needed for this feed type.

For fertilizers we assumed that organic fertilizers are only used in extensive and semi-intensive systems, inorganic fertilizers only in semi-intensive systems and none of them in intensive systems (unless otherwise stated). As noted earlier, we encountered some difficulties in finding data on fertilizer use and had to appeal to expert opinion to fill in the gaps, especially for China.

For some systems where data were poor, we also examined sensitivity to the food conversion efficiency and assumptions about on-farm energy use.

To explore the sensitivity of impact results to these issues we examined models for 3 species groups (carps, shrimps and prawns, tilapias) and for each species group we compared the results for 2 countries (China + 1). We changed the assumptions on feed, by either modifying the feed source, by assuming that there is only one crop in the diet (the one having the biggest share in the feed composition) or by substituting one crop by another when it couldn't be found in the EcoInvent database (e.g., coconut (=husked nut) for groundnut). We only changed one parameter at a time unless otherwise stated. Table 2.7 summarizes the set of contrasts we examined. In essence, these can be considered plausible, but less likely options compared to our baseline choices.

Table 2.7: Summary of the models used to examine sensitivity relative to baseline results.

Country	Intensity	Uncertainty	Variation from Baseline
			Carps
India	semi-intensive	Feed source	Replaced husked nuts PH by rapeseed extensive at farm CH
		Feed source	Rice only (main crop)
		Food conversion	FCR 2 instead of 1.5 (i.e. same as for intensive)
India	intensive	Feed source	Replaced husked nuts PH by rapeseed extensive at farm CH
		Feed source	Replaced husked nuts by rapeseed conventional FR
		Feed source	Rice only (main crop)
		On-farm energy	Changed on farm energy (=20,000 instead of 65,000)
		On-farm energy	Changed on farm energy + rapeseed extensive
China	semi-intensive	Feed source	Rapeseed only (main crop)
		Food conversion	FCR 2 instead of 1.5 (i.e. same as for intensive)
		Fertilizer	Added inorganic fertilizers (150/150)
		Fertilizer	Removed organic fertilizers
China	intensive	Feed source	Rapeseed only (main crop)
China	extensive	Fertilizer	Added inorganic fertilizers (50/50)
			Tilapia
Thailand	semi-intensive	Feed source	Cassava only (main feed)
		Food conversion	FCR 1.7
Thailand	intensive	Feed source	Cassava only (main feed)
		Food conversion	FCR 1.3
China	intensive	Feed source	Wheat grains extensive at farm/CH cf livestock feed wheat
		Feed source	Livestock feed soy instead of soybeans at farm US
		Feed source	Soybeans at farm US only (main feed)
			Shrimps and Prawns
China	extensive inland	Fertilizer	Removed urea and TSP
	semi-intensive inland	Feed source	Wheat only (main crop)
		Feed source	Replaced wheat grain organic CH by livestock feed wheat
		Fertilizer	Added urea and TSP (50-50)
	intensive inland	Feed source	Replaced wheat grain organic CH by livestock feed wheat
		Feed source	Wheat only (main crop)
	semi-intensive coastal	Feed source	Wheat only (main crop)
	intensive coastal	Feed source	Wheat only (main crop)
		Feed source	Soy meal instead of husked nuts
		On-farm energy	Change on farm energy to be same as Thailand
Thailand	intensive coastal	Feed source	Replace soybean meal Brazil at farm by soy meal

CH = Switzerland; FR = France; PH = Philippines; US = United States.

Results

Most of the results for our alternative models differed relatively little from their baseline counterparts (Figure 2.10). Of the 180 comparisons that were made, 113 (63%) were within ± 10% of their baseline value. Given that these comparisons were chosen as those most likely to be sensitive to our assumptions, this is encouraging.

There were, however, some notable deviations. The most striking of these concern assumptions about on-farm energy use in China for shrimp and prawn farming. Using energy-use values equivalent to those used for Thailand reduced impacts on acidification, climate change, land impact and energy demand by between 50 and 60% over baseline estimates. Other comparisons for shrimp and prawn farmed were very similar to one another.

For tilapias, the only major deviations occurred with respect to estimates of land occupancy for intensive farming in China, which increased from between 110 and 140% with altered assumptions about feeds. For carps, changed assumptions concerning on-farm energy use in India reduced estimates of acidification and climate change by between 50 and 60%. A large (50%) increase in estimates of land occupation also occurred when feed supply assumptions were altered for intensive carp production in China.

Overall, we conclude that our baseline models are generally robust and are not overly sensitive to model assumptions. In common with the findings of others, however, significant sensitivities do exist and can markedly affect results. This helps point towards those areas for greatest immediate attention. Improving estimates of on-farm energy use in emerging economies, developing new process descriptions for crop production in developing countries and improving data on the exact feed sources used for aquaculture are particularly important.

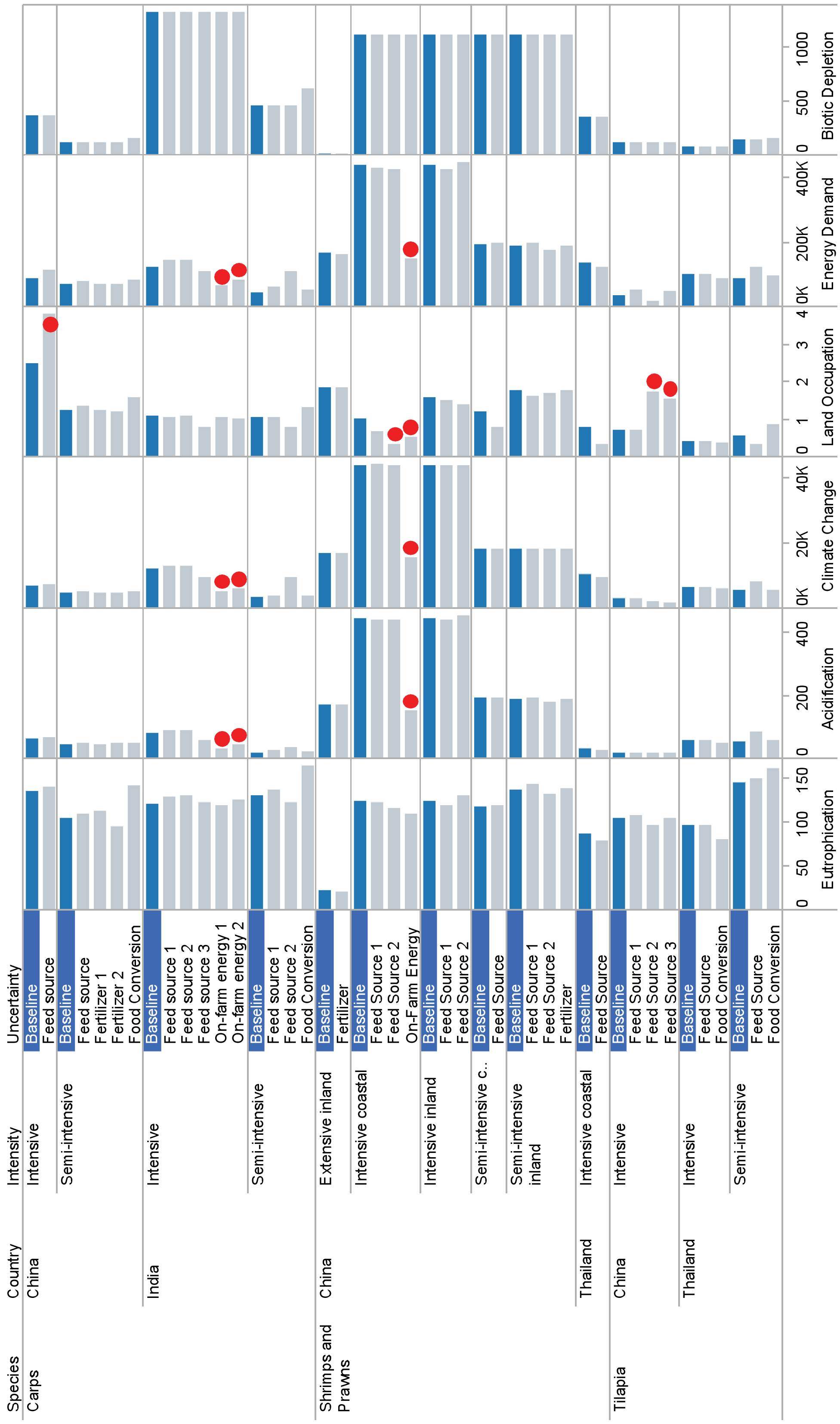


Figure 2.10: Summary of sensitivity analysis results. Details of comparison are given in Table 2.7 Red dots denote large deviations from baseline estimates.

Comparisons with other LCA studies

As well as exploring the sensitivity of our results to model assumptions and parameter estimates, we can also ask how our results compare with those from other studies. We can get some insight into this question by comparing them with those of the more detailed LCA studies that have been undertaken for selected systems. Table 2.8 summarizes comparable findings for studies on salmon, tilapia and catfish.

In drawing these comparisons, we stress that our system boundaries exclude medicine, seed and fingerling production, and construction and other processes. In contrast, the data we are comparing them with come from cradle-to-farm-gate LCAs, which include some or all of these processes. These considerations, combined with the high degree of complexity and choice available when constructing LCAs, render 'like with like', or benchmark comparisons with other studies impossible. The value of our study is in the comparative analysis across systems globally, using a consistent, albeit coarse approach. The comparisons below are offered, therefore, to stimulate debate, rather than validate estimates.

Comparing data from these studies with our own findings (in parentheses in Table 2.8) we find considerable variation in the level of agreement across impact categories and systems. While broadly comparable, estimates from our four salmon studies for energy use, climate change and acidification are consistently lower than those published by Pelletier and co-workers. In contrast, our estimates for eutrophication are consistently higher. Examination of the inventory data for these studies show that our input values for feed, on-farm energy use, and nitrogen and phosphorus emissions are very similar to these earlier studies. This suggests, therefore, that the discrepancy is largely due to the less comprehensive treatment of feed formulation in our study.

Table 2.8: Comparison of results from other published studies. All values are per tonne live weight of product. Data in parentheses are from the current study. Literature sources: 1. Pelletier et al., 2009; 2. Pelletier and Tyedmers, 2010; 3. Bosma et al., 2009.

Study	**Source**	**Energy Demand (MJ-eq)**	**Climate Change (kg CO_2-eq)**	**Eutrophication (kg PO_4-eq)**	**Acidification (kg SO_2-eq)**
Salmon Norway	1	26,200 (23,300)	1,793 (1,290)	41.0 (66.1)	17.1 (6.38)
Salmon Chile	1	33,200 (26,700)	2,300 (1,520)	51.3 (73.5)	20.4 (7.26)
Salmon Canada	1	31,200 (22,300)	2,370 (1,850)	74.9 (75.0)	28.4 (13.5)
Salmon UK	1	47,900 (21,500)	3,270 (1,390)	62.4 (73.0)	29.7 (8.17)
Tilapia Indonesia	2	26,500 (33,300)	2,100 (2,010)	45.7 (131.0)	23.8 (70.4)
Catfish Vietnam	3	13,200 (215,000)	8,930 (23,100)	40.0 (89.0)	459.0 (150.0)

On a comparative basis the more detailed LCAs of Pelletier and colleagues rank the UK as being the least efficient across all categories. In contrast, our own analysis is much more variable. Again this may reflect the way feed issues have been treated in the various studies, but it may also be a function of how nitrogen and phosphorus emissions are treated.

For tilapia in semi-intensive systems in Indonesia, our estimates for eutrophication and acidification are consistently and considerably higher than those of Pelletier and Tyedmers (2010), but the largest single difference is between the estimates of energy demand for catfish in Vietnam.

Discussion

Life Cycle Analysis in aquaculture is in its early stages and, of the few case studies available, most focus on salmon. This is, perhaps, unsurprising given the relatively dispersed and small, to medium, scale nature of much of the industry and the fact that so much of aquaculture production occurs in developing countries.

The objective of the analysis described in this section was to compare and contrast the global and regional demands of aquaculture for a range of biophysical resources across the suite of major species and production systems in use today. This complements the more detailed studies for production of particular species. By undertaking a broader scale scoping comparison we are able to identify more clearly, and on a standard methodological foundation:

1. How environmental impact compares across systems and geographies.
2. Which species groups or production systems are especially demanding on biophysical resources.
3. How environmental performance differs among countries for similar systems.

The distribution of absolute impact values shows where greatest attention should be paid for achieving environmental performance improvements.

In many respects, our results are broadly consistent with expectations. First, with explainable departures, such as for bivalve and seaweed culture, absolute impact levels correlate with overall levels of production. As a consequence, when one looks at the global picture in absolute terms, the impact of Chinese aquaculture, and carp culture in particular, stands out.

In contrast, relative efficiencies in production by species, system or country provide an indication of the potential for performance improvement. Of particular significance in this regard are the comparisons between species cultured in the same system in different countries. Here we find considerable variance reflecting a combination of differences, both in production practices where farm level choices and management may exert significant influence on ecological impacts, and in systemic country specific conditions over which fish farmers may have little control. One factor that farmers cannot control, for example, is the mix of energy sources used by a country to generate electricity, which has impacts on climate change and acidification estimates.

To the extent that observed variances reflect differences in species and system choices and management practices, we have an indication of the potential for large improvements in efficiency. Shared learning of best practice across the industry should provide significant opportunities to close efficiency (productivity) gaps. It is perhaps unsurprising that the salmon industry shows least variation across both countries and impact categories (see Figure 2.8). The explanation for this almost certainly lies in the greater investments in salmon farming research, the global nature and competitiveness of the industry and the fact that the sector is dominated by a few large companies. This suggests that similar research investments, combined with the right institutional, policy and market drivers, could lead to dramatic performance improvement in many other aquaculture sub-sectors.

We return to these issues when we consider the policy implications of this study. Before doing so, however, we explore how production in the aquaculture sector compares with that for other animal food sources.

Photo by Francis Murray
CHINA

3. COMPARISON

PHOTO CREDIT: The WorldFish Center

3. The environmental efficiencies of animal production systems: How does aquaculture compare?

"there isn't any more land. We are exploiting the available production factors to a great extent. The environment is becoming more polluted. Increased production has to come from high-yielding farming." (Jacques Diouf, 2006 in *Flachowsky, 2007)*

The growing demand to consume animal products continues to rise. This is particularly true of the developing world where, between 1980 and 2005, the consumption of terrestrial animal meat increased from 14.1 to 30.9 kg/capita; it is predicted to increase further to 36.7 kg/capita by 2030 (FAO, 2009a, WHO, 2010). This growing demand for animal products risks increasing undesirable impacts on the environment.

Livestock meat production can be grouped into two categories: ruminant species (such as cattle, sheep and goats) and monogastric species (such as pigs and poultry). Generally speaking, ruminant species are either produced intensively or in extensive grazing systems, while monogastrics are produced in traditional or industrial systems (FAO, 2009a). Four production systems, however, dominate the sector: grazing, rain fed mixed (defined as a combination of rain-fed crop and livestock farming), irrigated mixed, and landless/industrial systems (Steinfeld et al., 2006).

These species categories and production systems place different demands on ecological goods and services. For example, the traditional monogastric production systems for chickens and pigs are considered overall to have negligible environmental impact due to their extensive nature, limited manufactured feed demand and their dominant position in small-scale household oriented production systems. Intensive systems for pigs and poultry, however, lead to greater impacts, although they are less damaging than beef production (see below). As detailed in Table 2.2, aquaculture production systems also fall into several categories: extensive, semi-intensive and intensive. As with livestock these systems differ in the environmental impacts they impose.

Because livestock farming is more established as a major food production sector its impact on the environment has received more attention than aquaculture. In recent years, for example, a large number of studies on the environmental impact of livestock have been produced (FAO, 2009a). In 2006, however, an early effort to compare the environmental costs of aquaculture with those of livestock was undertaken by the FAO (Bartley et al., 2007). Such comparisons are important to help ensure that the animal food production sector develops in ways that use available resources wisely. As the authors of the FAO report point out, there is thus "a need to present a balanced picture of the environmental costs of all food-producing sectors and to formulate environmental policies that deal with the impacts of all sectors... So long as this balanced picture of environmental costs is absent, policy does not reflect farming realities, the prices of food products cannot reflect the real costs of their production, especially for ecosystems and communities, and both the public and government receive very mixed messages [regarding policy options]". (ibid., p.5).

Although largely focused on methodological issues, the FAO study provides some initial comparative understanding. Here we briefly summarize the findings from the FAO study along with other available literature. We stress, however, that the methodological foundations for such comparisons remain under-developed and appropriate data are sorely lacking.

Comparative analysis of impacts

Conversion Efficiencies

An important (and perhaps the clearest) perspective on relative impacts of animal-source food production can be obtained by considering feed conversion ratios. From this perspective fish come out well because, in general, they convert more of the food they eat into body mass than livestock. Poultry for example, convert about 18% of their food and pigs about 13%; in contrast, fish convert about 30% (Hasan and Halwart, 2009). Much of this difference reflects the fact that fish are poikilotherms (cold blooded) and do not expend energy maintaining a constant body temperature. Moreover, because aquatic animals, especially finfish, are physically supported by the aquatic medium few resources are expended on bony skeletal tissues. As a result the usable portions of finfish are high compared to those of terrestrial animals, especially cattle (Moffitt, 2006). From such principles, therefore, it would appear that the environmental demands of finfish production will be lower. This certainly appears to be the case when comparing finfish with beef or pork. Looked at in another way, the production of 1 kg beef protein requires 61.1 kg of grain while 1 kg pork protein requires 38 kg and 1 kg fish protein requires less than 13.5 kg (calculated from White, 2000).

Of course, for species such as mussels and oysters that grow on the natural productivity of the ecosystem, the question of food conversion efficiency becomes moot. Although unlikely to be a mainstream food commodity, in many respects, these animal food sources are among the most desirable from an ecological sustainability perspective.

A complementary perspective on the question of efficiency is provided by Smil (2001) who compared feed and protein conversion efficiencies for several animal based foods (Table 3.1). As with other analyses, finfish come out favorably compared with pork and beef, and are broadly comparable with poultry and dairy products. With these superior conversion ratios aquaculture may become a significant competitor to monogastric species in regions such as South East Asia and sub-Saharan Africa (Bartley et al., 2007).

Table 3.1: Protein content of major animal foods and feed conversion efficiencies for their production. (Based on Figure 5 of Smil, 2001). Calculations of feed conversion efficiencies based on average US feed requirements in 1999.

Commodity	Milk	Carp	Eggs	Chicken	Pork	Beef
Feed Conversion (kg of feed/kg live weight)	0.7	1.5	3.8	2.3	5.9	12.7
Feed Conversion (kg of feed/kg edible weight)	0.7	2.3	4.2	4.2	10.7	31.7
Protein Content (% of edible weight)	3.5	18	13	20	14	15
Protein Conversion Efficiency (%)	40	30	30	25	13	5

A key concern with the intensification of both the fish and the livestock sectors is demand for fishmeal and fish oil in feed formulations (see Section 4). Although farmed fish convert feeds more efficiently than livestock (Moffitt, 2006; Brummett, 2007; FAO, 2009a), aquaculture is presently more dependent on fishmeal and fish oil than other animal production sectors (Table 3.2). The share of fishmeal used by aquaculture grew from 8% in 1988 to about 35% in 2000 (Delgado et al., 2003) to 45% in 2005 (World Bank, 2006) and estimated to be 56% in 2010.

Species such as salmon are particularly dependent, because the main source for several essential fatty acids is oily fish. Indeed, it is this dependency by aquaculture and the growth of the aquaculture sector that is believed to have forced the livestock sector to search for other protein substitutes in livestock feed (Bartley et al., 2007). Prohibiting the use of animal offal in livestock feed to reduce the risk of mad-cow disease, has also increased pressure to produce vegetable protein for animal feed. Recent estimates by the Fishmeal Information Network indicate that 56% of world fishmeal production is now consumed by fish with 20% for pigs and 12% for poultry (Table 3.2).

Although fishmeal use is controversial in some quarters, one must also recognize that substitution with suitable land-based crops brings with it demands on land and water use and perhaps the production of a nutritionally inferior product to its wild counterpart (Karapanagiotidis et al., 2006, 2010). As production methods intensify, and the animal derives more of its nutritional requirements from crop-based feedstuffs, total lipid levels tend to rise and lipid profiles shift to become dominated by less desirable omega-6 fatty acids.

Despite such concerns, however, the high cost and limits to supply of fishmeal and fish oil are likely to drive the current trend of increased use of crop substitutes in animal-source food production. Soybean meal use rose from around 20 million tonnes in the 1970s to over 120 million tonnes in the early 2000s (Bartley et al., 2007) and further increases in its use seem assured.

Table 3.2: Percentage of world fishmeal market use by sector. (Source: Fishmeal Information Network (FIN, accessed in 2010)).

	2002	2007	2008	2010
Ruminants	1	-	-	<1
Pigs	24	24	31	20
Poultry	22	7	9	12
Fish	46	65	59	56
Others	7	4	1	12

Environmental Emissions

With respect to environmental emissions, the livestock sector is often characterized as having a “severe impact on air, water and soil quality because of its emissions” (de Vries and de Boer, 2010). It has also received considerable attention as a contributor of greenhouse gases (Steinfeld et al., 2006). Extensive livestock systems contribute indirectly through land degradation and deforestation, while in intensive systems, the application of manure that emits methane and enteric fermentation directly contributes to climate change. All this said there is considerable variation among meat production systems and comparisons are fraught with difficulty. With the exception of poultry, however, it seems likely that aquatic animal products have rather less impact than other animal production systems from an environmental emissions perspective. This conclusion is further supported by the data on nitrogen emissions shown in Table 3.3, which show that, while emissions of waste nitrogen and phosphorus vary considerably, aquaculture systems generally perform well compared to beef and pork.

Table 3.3: Summary of data on nitrogen and phosphorus emissions for animal production systems. Data for beef, pork and chicken are derived from Flachowsky (2002) in Postrk, 2003. Data for fish are derived from this study.

Commodity	Nitrogen emissions (kg/tonne protein produced)	Phosphorus emissions (kg/tonne protein produced)
Beef	1200	180
Pork	800	120
Chicken	300	40
Fish (average)	360	102
Bivalves	-27	-29
Carps	471	148
Catfish	415	122
Other finfish	474	153
Salmonids	284	71
Shrimps and prawns	309	78
Tilapia	593	172

Land Use

To compare land use we took our data on the land required to produce 1 tonne of edible fish product and compared this with data provided by de Vries and de Boer (2010) who summarized the land required to produce 1 tonne of edible beef, pork and chicken (Table 3.4). These data suggest that land use demands are broadly comparable.

Table 3.4: Estimates of land demand (direct and indirect) for animal-source food production.

Commodity	Yield tonne/ha (edible product)
Livestock	
Beef	0.24 – 0.37
Chicken	1.0 – 1.20
Pork	0.83 – 1.10
Aquaculture	
Bivalves	0.28 – **20**
Carps	0.16 – 0.90
Catfish	0.20 – 1.23
Other finfish	0.38 – 3.70
Shrimps and prawns	0.34 – 1.56
Tilapia	0.15 – 3.30

Alternative approaches to calculating land use, however, come up with markedly different conclusions. Based on an analysis for British Columbia summarized in Box 3.1, for example, Brooks (2007) concluded that "the landscape directly affected for cattle production is several hundred times greater than it is for production of the same amount of food in salmon aquaculture". Such contrasting conclusions serve to illustrate the complications of comparative analysis and point towards the importance of adopting a standardized methodology that is explicit about the basis for calculation.

Environmental impacts associated with land use will also vary with the ecological values of land used, for example grasslands, wetlands, mangroves and seagrass beds all providing different ecological services. More detailed analysis is required to account for these differences.

Water Use

Livestock production is a significant user of freshwater resources, with an estimated 8% of global human water use devoted to the sector. While around 2% is consumed through direct consumption the majority (more than 98%) is primarily associated with the production of feed crops (Verdegem et al., 2006). In intensive systems where livestock are concentrated in feedlots, water use is particularly high because of the high demand for concentrated feed and additives that require an increased production of raw materials such as cereals and oil crops (Steinfeld et al., 2006). Current published estimates suggest that producing 1 kg of edible beef requires 15,500 l of water compared to 3,900 l for 1 kg of edible chicken (World Bank, 2010[7]) and varies between 11,500 and 45,000 l for 1 kg of fish.

There are, however, a number of issues concerning calculations of water consumption in food production that make evaluation and comparisons difficult. For example, much of the water used to produce crops is 'green' rather than 'blue' water; i.e. infiltration and not surface water from lakes or rivers is used (see Molden et al., 2003; Verdegem and Bosma, 2009). The exception is, of course, irrigated crop production.

Another complication arises because the bulk of global aquaculture production is from semi-intensively managed ponds. The majority of these ponds tend to be filled and drained once per year with water added periodically to counterbalance water lost through seepage and evaporation. While one might consider this water use, because it is needed for physical support, to supply dissolved oxygen and for dispersal and assimilation of wastes, one could also argue it to be a form of water storage and that seepage losses from ponds represent an ecosystem service, serving to recharge groundwater reserves. The latter argument only holds, however, if seepage is uncontaminated by nitrogen and phosphorus wastes and preliminary experiments suggest that nutrient uptake by sediments is enhanced as seepage water moves through the pond bottom interface (Verdegem et al., 2006). Of course, coastal aquaculture has a further major advantage in this respect in that it makes use of seawater.

Feed associated water use in aquaculture comes mainly from the production of feed crops and grains.

Box 3.1

Brooks (2007) compared land use by salmon farming and cattle rearing in the following way:

- The edible meat yield from an Angus steer is 42% of live weight
- The yield of salmon filets is approximately 50% of the live weight
- A salmon farm producing 2500 tonnes of live salmon would supply 1250 tonnes of edible filets which is equivalent to 5411 steers weighing 550 kg each.
- In the Pacific Northwest, one acre of actively managed pasture supports one cow for 7.5 months (7.5 animal month units or AMUs) and it takes approximately 30 months to produce a marketable steer.
- 5411 steers require 162338 AMUs or 8658 acres (3504 hectares) for 2.5 years.
- The substrate under well sited salmon farms chemically remediates in six months to a year and biologically remediates in another year showing a full return of the normal benthic community.
- In contrast, in the Pacific Northwest, it will take hundreds or a thousand years for the pastures to return to the original old growth forest.

	Edible Portion (kg)	Yield	Footprint (ha)	Remediation Time (y)
Salmon	1,250,000	0.5	1.6	2
Angus Beef Cattle	1,250,000	0.42	6,982	200+

Use associated with fishmeal and fish oil and with other feed sources (e.g. meat and bone meal) are negligible (Verdegem and Bosma, 2009).

Conclusion

Because vegetarianism is unlikely to ever be a voluntary choice for the overwhelming majority of people, as global demand for food rises, finding ways to be more ecologically efficient consumers of animal food will become increasingly important. Indeed, many would

[7] Data in the literature usually refer to Pimentel et al. (2004) who assumes that the production of 1 kg of beef requires 100,000 l of water. These figures seem a little bit outdated. The World Development Report provides more recent figures taken from www.waterfootprint.org (incl. direct and indirect water consumption).

argue that it is essential if the ecological demands of our food production systems are to remain within acceptable bounds (e.g., Rockström et al., 2010). Comparisons indicate that dairy foods can be produced most efficiently in terms of 'feed protein to food-protein conversion efficiency', but that herbivorous fish from aquaculture, eggs, and chicken come close. In contrast, pork production converts feed protein to meat only about half as efficiently.

Examining these issues from a nitrogen budget perspective Smil (2001) concludes that American beef cattle herds require at least five to six times the feed energy per unit of lean meat compared to the country's broiler population. As a consequence its production also requires 5 to 6 times as much nitrogen fertilizer to produce the requisite feed. Smil estimates that the United States would have to use less than half its concentrate feed, and hence less than half of the N-fertilizer used to grow it, if its protein-rich diet were composed of equal shares of dairy products, eggs, chicken, pork and farmed fish.

Beyond the clear issues concerning beef production, however, analyses indicate that there is no simple answer to the question of which animal production system has least environmental impact. Each system makes different demands on environmental services and the appropriate trade-offs between them relative to the benefits of providing a particular form of animal source food will be context specific. Clearly, aquatic products have some advantages, not least the efficiency gains possible from farming a cold blooded animal, but much depends on the species, systems and management practices.

Available analyses also rarely make reference to the variability that is found in the efficiencies associated with the various intensities and methods of production used for the various animal products. This is clearly an important consideration that bears further examination, particularly because, with the high demand put on resources, there is a trend in intensifying animal farming rather than extensifying it (Gerber et al., 2007). There are clearly trade-offs between alternative approaches. Extensive systems require more land and are more dependent on ecosystem services for their productivity (freshwater, fuel, food, water purification, nutrient cycling, etc.), while intensification means more inputs and effluents and also more (fossil fuel) energy (Prein, 2007). We need to better understand and quantify these trade-offs in order to better manage and mitigate environmental impacts. Pathways for future development of these sectors will clearly have a significant influence on future impacts, and targets for management interventions.

In this context it is important to appreciate that, in contrast to livestock, from a biophysical perspective there remains considerable scope for aquaculture expansion. Limits to land availability mean that livestock production will only intensify, while aquaculture will both intensify within the existing area under production and grow into new areas.

Another issue one must consider is the potential for integrated agriculture-aquaculture systems (e.g., poultry and carp) which, although not examined using life cycle approaches, have been considered more ecologically efficient than monoculture systems (Prein, 2007; Gabriel et al., 2007). There has been a trend away from such systems in China, the traditional home of integrated farming, due largely to economic drivers, and the inability to recover value from the ecosystem services they provide. A new look at such systems using LCA tools is warranted, but above a threshold size such systems may become inefficient and difficult to manage. This may limit the growth potential of these integrated systems.

Finally, while not a focus for this study, and not really amenable to analysis using an LCA framework, it is also important to recognize concerns over biodiversity loss. The loss of biodiversity is a significant concern with livestock, with major issues of overgrazing leading to erosion, desertification and tropical deforestation for conversion to pasture (Brown, 2000). But, while the scale of habitat loss in the livestock sector, with massive conversion of habitat to extensive grazing, far outweighs that of the aquaculture sector, aquaculture development can still threaten biodiversity. These threats include habitat loss in fish and shrimp nursery areas (e.g., Primavera, 2006), use of inland wetlands for conversion to ponds, as seen in India and Bangladesh and risk of genetic pollution from escape of farmed fish (see also Section 4). Conversion to ponds in wetland areas such as mangroves in particular can lead to loss of ecosystem services, including loss of carbon sequestration properties. For the most part, managing these threats will require local studies coupled with sound planning processes.

4. LOOKING FORWARD

PHOTO CREDIT: Randall Brummett

4. Looking Forward

With the stagnation or, optimistically, only limited growth in wild catches any increase in demand for fish can only be met by aquaculture (Delgado et al., 2003; Bostock et al., 2010). But how big is the aquaculture sector likely to become and what are the environmental implications? In this section we explore this question by first examining the drivers of increased demand for aquaculture products and how are these likely to evolve in the coming years. We then go on to briefly review the sector's efforts to overcome some of the environmental constraints to meeting this demand. Finally, we examine published projections for how production by the sector may evolve and examine the implications of such growth for biophysical resource demands.

Demand drivers

Growth in population, wealth and urbanization

At first sight, one would imagine that population growth would be a major driver of increased fish production. At present, however, world population growth averages 1.17% per annum according to The World Bank. This represents less than one fifth of the current rate of increase in global farmed fish production. As a result, increased demand resulting from population growth is currently a relatively minor driver of fish production, at least in global terms. A more important determinant of demand for fish and other animal source foods is wealth (Speedy, 2003)[8].

Increases in per capita consumption of animal source foods are fastest where food consumption levels are low, wealth and urbanization is increasing rapidly, and domestic supply is also increasing (Delgado et al., 1997). It is these factors that explain the explosion of demand for meat, milk and fish in the emerging economies of Asia. In China, for example, the annual rate of population growth is currently around 0.51%, adding an estimated 6.6 million people to its population each year. And, although the growth of Chinese aquaculture production is many times this rate, Speedy (2003) estimates that, as a result of increased personal wealth, demand is likely to increase from 25 kg per person per year in 2005 to 35 kg per person per year by 2020. And it may not just be wealth. Although increased wealth is closely associated with increased urbanization, urbanization per se may also contribute to increases in animal source food consumption. Delgado et al. (1997), for example, suggests that changes in food preference driven by urbanization alone has in the past accounted for an extra 5.7–9.3 kg per capita consumption of meat and fish per annum. Similarly, Betru and Kawashima (2009) present data from Ethiopia indicating urbanization affects animal food consumption rates independently of income. In contrast, however, Stage et al. (2010) present data from India and China and cite studies from Vietnam and Tanzania indicating that families with equivalent incomes in rural and urban settings do not differ in their consumption of animal source foods.

With growing wealth and urbanization as key drivers of change in fish demand we can expect the largest growing market over at least the next decade to come from emerging economies. More generally, global trends in urbanization, which generally correlates with increased wealth, suggest that developing country demands for fish will increasingly dominate. By 2025, almost six out of ten people on earth are likely to live in urban centers, and over half of these will live in the cities of developing countries. In 2009 there were 2.5 billion urban dwellers in the developing world, compared to 0.92 billion in the developed. By 2025 those figures are expected to rise to 3.52 and 1 billion respectively. This represents a shift in numerical dominance from 72% of the world's urban dwellers

[8] In economics parlance the demand for many animal source food products is 'income elastic', meaning that income growth increases demand. Indeed, some animal source foods can even be considered luxury goods, meaning that a 1 % increase in income will lead to an increase in demand of more than 1 %.

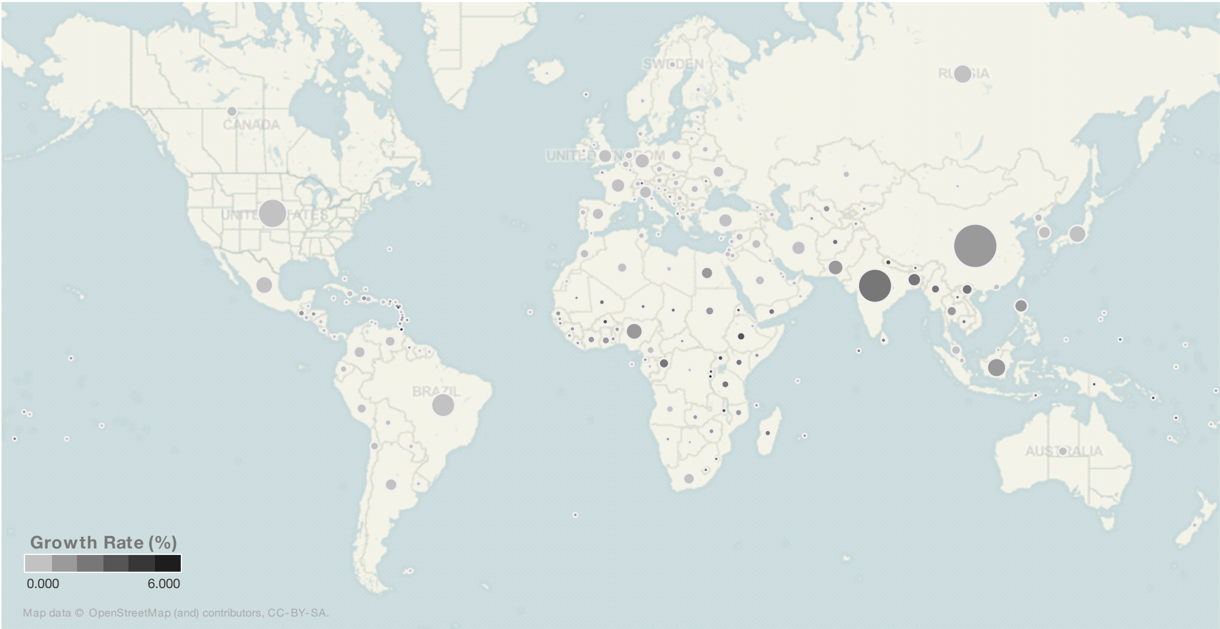


Figure 4.1: The relative size of urban populations of countries in 2009 (indicated by circle size) and the projected annual average rate of growth in urbanization to 2050 (indicated by shading). Data extracted from UN World Urbanization Prospects 2009 Revision (UN, 2010).

living in the developing world today to 80% in 2030. By 2050 the projections are for 5.19 billion in the less developed regions and about 1.1 billion in the developed world. Figure 4.1 summarizes the current levels of urbanization and the projected annual average growth rate to 2050.

Cultural factors and product attributes

Fish product attributes must also be considered in the context of other foods. Growing recognition of the health benefits of fish consumption, for example, can alter patterns of demand relative to meat products for some consumers, although the overall importance of health information may be relatively limited (Shroeter and Foster, 2004). Conversely, concerns about mercury levels in carnivorous fish such as salmon and tuna, have depressed demand in some markets (Oken et al., 2003).

Product issues for other foods, also affect demand. For example, Egypt has experienced a substitution effect, in part a result of what happened to the poultry sector. Poultry lost significant market share after 2006 because of fears of avian flu, which caused some 30 deaths in the country (WHO, 2010). Similarly, in Nigeria the avian flu outbreak led to a shift in consumer preference away from poultry towards beef, pork and fish (Obayelu, 2007). Future zoonotic or other animal health issues, widely anticipated by experts due to increasing intensification of production methods and trade liberalization, may have dramatic effects on markets for animal derived foods. Depending on where disease strikes this may either stimulate or reduce demand for fish.

In the coming years we can expect demand side processes such as seafood awareness, food safety, quality convenience, sustainability and ethics to become even more important. Trends will be driven not only by developed country consumers, but also by the growing middle class in the developing world. While the significance of such issues took decades to appear among developed world consumers it seems likely that the attitudes of wealthier consumers in the developing world will evolve much faster. Consumer trends in major Asian markets, particularly China and Southeast Asia, are currently poorly understood, but will have a major influence on aquaculture production trends.

For developed countries, while overall demand seems unlikely to change markedly, the value of purchases is expected to rise through value addition (Cressey, 2009) and aquaculture products will continue to substitute for both expensive and cheap wild fish products (see for example Beveridge et al., 2010). The rise of supermarket chains in Asia, and elsewhere in the developing world, will also have major implications for the many small producers currently engaged in aquaculture production (Reardon et al., 2010).

OECD countries represent a relatively small but nonetheless important sector of the global market for aquatic foods in view of their purchasing power and demand. Increasingly, they not only consume their own farmed aquatic foods but also those of many developing countries (OECD, 2008, 2010). Much of the production of farmed Vietnamese striped catfish, for example, is targeted at EU member states where it has gained rapid market penetration as a cheap substitute for the increasingly expensive marine white fish traditionally supplied from domestic fisheries. Striped catfish is often promoted by supermarkets and sold as highly profitable convenience products such as seafood pies or ready-to-cook breaded filets. We can also expect other inexpensive farmed species such as tilapia to penetrate wealthy western markets provided the following conditions are met:

- Fish continues to be considered as a healthy option to other animal food sources
- Trade policies that affect farmed fish continue to be liberalized
- Developing country aquaculture producers can continue to meet wealthy country food safety standards
- Supermarkets continue to capture significant economic benefit from the value chains and thus continue to develop and market value-added convenience products
- Farmed aquatic foods can be produced and brought to markets in environmentally sound ways
- Pricing continues to make aquaculture a competitive animal source food.

Price

Demand for fish depends on the price of the product. Most often fish products are what the economists term own-price elastic, meaning that when the price falls, people buy more. However, it is not only changes in the price of fish that matter, but also the changes in the prices of competing (substitute) food products. The trend in prices over the past 15-20 years has been for food fish prices to rise, although not for several aquaculture products, such as salmon. In contrast, red meat prices have fallen by approximately 50% over the same period. Although data are scant, it would appear that the prices for capture fisheries products have increased, but those of aquaculture products have decreased. Salmon and shrimp for example, previously considered high value products, are now significantly lower in price, and have broadened their consumer base tremendously.

Although predicting how absolute and relative prices of meat, fish and milk will evolve and affect consumer choice is difficult, some quantitative projections have been attempted. The Fish to 2020 analysis by Delgado et al. (2003) provides perhaps the most comprehensive recent attempt. This analysis concluded, as one would expect given urbanization and economic growth trends, that China and India will lead the global growth in per capita consumption, with 1.3 and 0.9% per year, respectively. Other developing countries of Southeast Asia and Latin America are in the middle rank with 0.4 and 0.5% growth respectively. The rest of the world is likely to see static or declining per capita consumption. Supported by the World Bank, efforts are now underway by to update these projections and forecast trends out to 2030.

Environmental constraints to sector growth

The last decade has seen a dominant narrative arguing that aquaculture growth will be constrained by local environmental factors and the carrying capacity of the environments where production occurs (Hempel, 1993; WRI, 1998). This view has been re-enforced by evidence from several intensive production sectors. We have seen major disease outbreaks in the prawn and salmon industries (Flegel, 1997; Wiwchar, 2005; Kautsky et al., 2000), evidence of genetic pollution and transmission of parasites and disease to wild salmon stocks (Pearson and Black, 2001), and habitat destruction, eutrophication and antibiotic pollution in many systems (Emerson, 1999).

However, while these concerns are undoubtedly legitimate, there are signs that such problems are commonly confined to the early stages of intensification and can be overcome as the sector matures (Asche, 2008). Reduction in pollution with organic wastes (per tonne of fish produced) in the Norwegian salmon industry, for example, appears to be related to industry growth (Tveterås, 2002). With the development of new vaccines, the absolute volume of antibiotics used in Norwegian salmon production also declined markedly despite continuing production increases (Figure 4.2). i

In most cases there are two drivers that stimulate an aquaculture sector to address environmental constraints (Asche, 2008). The first is the reduction in productivity and hence profit that results from the negative feedbacks from the effects of a deteriorating production environment on fish health and increased risk of disease outbreaks.

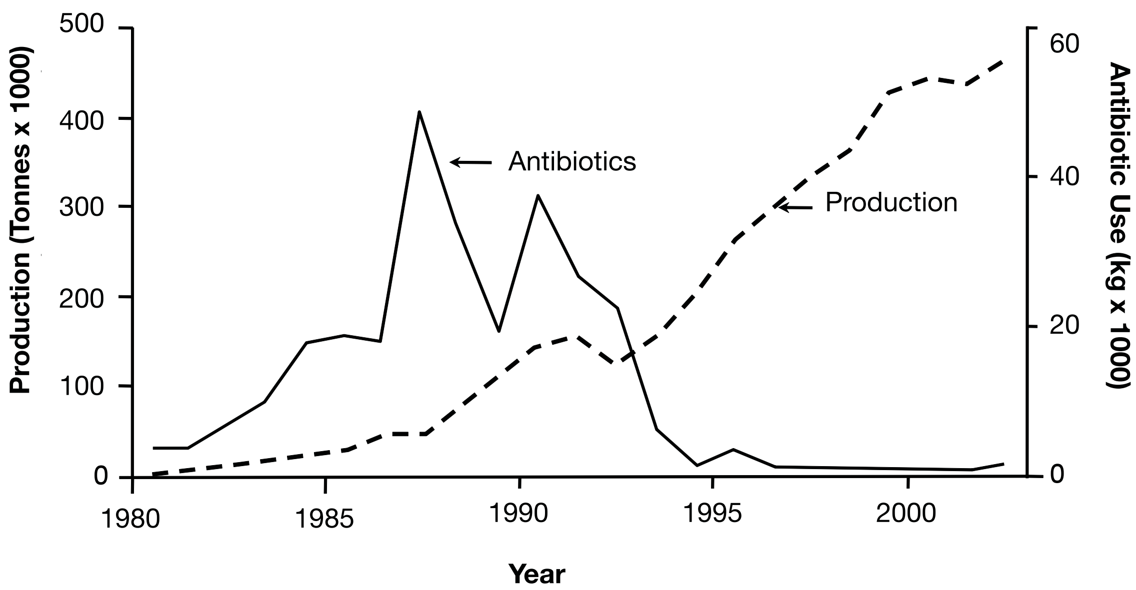


Figure 4.2: The rise and decline of antibiotic use in the Norwegian salmon industry compared to the trend of rising production (adapted from Asche, 2008).

The second is government regulation, which is essential for limiting the impact of those effects that do not affect the productivity of the industry itself (e.g., limits to pollutants in effluents). A third driver, currently favored by NGOs such as WWF in western markets, is to move the sector towards environmental improvements by raising retailer and consumer awareness of environmental impacts.

Driven by profit, intensification has only been possible because prevailing economics have allowed increased reliance on nutritionally complete feeds and energy-intensive technologies, such as aeration and oxygen injection. These production innovations have depended largely on private sector investment. This trend is likely to continue. For many parts of the industry, we are likely to see considerable increases in intensification in the coming decades and new approaches for handling environmental concerns.

One innovation that is, at first glance particularly attractive from an environmental standpoint, is the development of Recirculation Aquaculture Systems (RAS). Such systems offer a high degree of control over environmental variables, and high levels of biosecurity and waste treatment. They are of particular interest for locations close to consumer markets. However, while the virtues of urban RAS have been promoted for some time (Costa Pierce et al., 2005) they have yet to fulfill their potential. RAS are highly complex with high capital and operational expenditure and have not always operated reliably or profitably. They also have high energy demands and carbon footprints although these could be reduced by use of non fossil fuel energy sources (wind energy, solar, etc). With little take-up of the technology, there is minimal incentive or revenue stream for suppliers to invest in the necessary development and manufacturing capacity for standard mass-produced low-cost systems.

While intensification of the currently dominant systems will undoubtedly continue, there is also interest in using the abundant areas off-shore to reduce environmental pressure. Cage (synonymous with 'pen') systems dominate the production of high value marine fish species, especially in Europe, North and South America. As a result of climate change, and competition for near-shore coastal areas (with accompanying concerns about their local environmental impact in some parts of the world), some investment has been made in the design of offshore cage systems able to withstand the extreme wave and wind climates associated with more exposed environments. Such systems rely on stronger materials, more robust designs and integrated cage and mooring systems that allow cages to be submerged below the water surface to avoid hostile weather conditions (Beveridge, 2004; Grøttum and Beveridge, 2007) . Although these technologies will continue to be developed they are unlikely to result in any significant expansion of production in view of the high capital and operating costs and the limited market for the high value farmed fish that can be produced in such systems.

Feeds

Despite the trend in intensification of production methods the majority of aquaculture production is still derived from extensive and semi-intensive aquaculture of omnivores and herbivores. There are powerful economic incentives to intensify production, however, and we can expect to see increasing dependence on feeds. This brings with it concerns about the resultant demands on biophysical resources and impacts on food security.

The bulk of aquaculture feedstuffs are of crop origin—maize, soya, wheat—and crop production makes substantial demands on ecosystem services (Tilman et al., 2002). Using such materials to feed fish and shrimp may lead to competition for use of the same materials for human food or bio-fuels, with consequent implications for prices and affordability. It may also lead to changes in crop production (e.g., change in land use from growing human food staples to production of aquaculture feedstuffs). Demand on ecosystem services may be further exacerbated by the global trade in the feeds and feedstuffs that sustain aquaculture production. For example, the Egyptian aquaculture industry uses an estimated 1 million tonnes of aquaculture feed per annum. All feedstuff ingredients are imported, primarily from North America, which may add to the overall environmental cost of production.

Other important aquaculture feedstuffs include 'trash' fish, fishmeal and fish oil, derived from industrial and artisanal fisheries, and widely used to sustain shrimp and carnivorous fish production (Tilman et al., 2002). Fishmeal and oil are particularly important for these species groups because they require long-chain fatty acids that are only found in high amounts in these feed sources. There are concerns that these 'feedfish fisheries' aggravate food security in parts of the world by diverting fish from direct human consumption to aquaculture. It appears, however, that, while there is considerable scope to increase the proportion of feedfish for human consumption in Latin America, the situation is more ambiguous in Asia where use of such feedstuffs in small-scale aquaculture disadvantages some but has considerable livelihood benefits for others (Huntington and Hasan, 2010).

Notwithstanding these concerns the track record of innovation to deal with these resource constraints is impressive in those parts of the aquaculture sector where industry competition has driven efficiency increases. This is most evident in the salmon industry where production costs have declined dramatically. In Norway, for example, production costs have decreased by 60% in the last 20 years. Although reductions in labor demand account for a substantial proportion of this, technical innovation to improve, for example, feeding efficiencies is also significant (Subasinghe et al., 2003). Decreasing dietary fishmeal and fish oil inclusion in aquaculture feeds and limiting their use to starter, broodstock and 'finisher' feeds are among the most immediately implementable strategies for further efficiency improvements (Tacon and Metian, 2008). This may in time be complemented by selective breeding. Fish have the ability—albeit limited—to de-saturate and elongate lipids, which varies not only among species but also families. Identifying the genes that control this and determining the heritability of the trait may facilitate selective breeding of strains with reduced dependence on fish oils (Aquaculture News, 2009).

Last, long promised microalgal based technologies capable of producing commercial quantities of affordable material that can substitute for fishmeal and fish oils in aquaculture feedstuffs may be beginning to become commercially viable (Durham, 2010).

Aquaculture will increasingly have to compete with other animal production sectors for use of feedstuff crops and agricultural by-products. The sector will be able to continue to secure access only if it can afford to pay the going rate and if the roles of aquaculture in food security and economic development are sufficiently recognized to have resulted in an enabling policy environment.

Genetics, selective breeding and Genetically Modified Organisms

Aquaculture production is almost entirely comprised of plants and animals derived from broodstock that have been in captivity for only a few generations. As a result, growth of farmed aquatic organisms is similar to, or because of poor management of captive breeding systems, worse than that of their wild counterparts (Brummett et al., 2004). Domestication, in which life history traits are altered through selective breeding to meet human needs, affords the possibility to develop more productive (i.e., fast growing, disease resistant, high flesh yield) strains. The development of faster growing strains reduces demands on some ecosystem services, such as land and water. However, although yet to be thoroughly studied it is probable that the development of faster growing strains, as being pursued at present, will have only little effect on the demand for feed. In essence current breeding programs primarily select for fish that eat more, not explicitly for fish that convert food more efficiently into flesh. It may, however, be possible to widen breeding objectives to select for both faster growth and better feed utilization.

Farming provides the opportunity to influence every aspect of the life cycle of an animal, including many of the attributes that might appeal to consumers: color, size, shape, nutritional composition. The relative importance of genes in determining many of these attributes, however, is as yet unknown as is our understanding of the genes involved or the heritability of these traits. Powerful new tools, such as genetic markers, are expected to increasingly assist us in identifying these genes and gene complexes.

At present, genetic improvement programs are underway for a dozen or so widely farmed species, including both marine shrimps and freshwater prawns, common and Indian major carps, tilapias, African and channel catfish, rainbow trout and Atlantic salmon. Results from such selective breeding programs can be impressive: the selectively bred Jayanti strain of Labeo rohita (‘rohu’), for example, widely used by Indian farmers, grew up to 17% faster per generation over five generations compared with local strains, across a range of production environments (Ponzoni et al., 2009).

The first genetically modified (GM) farmed fish is a strain of Atlantic salmon that grows twice as fast as other domesticated strains. Produced by AquaBounty Technologies, it is currently awaiting approval for commercial production by the U.S. Food and Drug Administration (USFDA). The animal has a single copy of a DNA sequence that includes code for a Chinook growth gene as well as regulatory sequences derived from Chinook salmon and ocean pout (Marris, 2010). Several other aquaculture species await permission for commercial use, including common carp in China (Aldhous, 2010). The permitting process has until recently taken many years, but in 2009 the USFDA announced that they intended to treat GM traits in farmed animals as veterinary drugs, potentially speeding up the licensing process. Nevertheless, strong public concern about the potential for adverse environmental effects should fish escape and breed with wild fish is likely to influence licensing arrangements. GM technology will only be adopted in aquaculture if it results in lower production costs, greater profits and expanded markets. Market size will, however, ultimately depend on the perceived safety of the product to consumers and, indeed, with the brand image of GM foods in general.

Another issue with respect to genetics concerns non-native species. A precautionary approach would, of course, severely restrict the use of alien species in aquaculture and rely instead on the development of native stocks. Currently, however, a considerable proportion of aquaculture production comes from non-natives (Figure 4.3). Even in China, where native carps dominate production, 12% of production comes from non-natives.

Recognizing that the current incentives for use of alien species in aquaculture remain high, particularly for developing countries, future efforts will need to be directed towards improving risk assessment and mitigation measures. Based on the FAO Code of Conduct for Responsible Fisheries (1995) and the ICES Code of Practice on the Introductions and Transfers of Marine Organisms (2005), IUCN provides a useful series of recommendations for national governments to implement responsible use of alien species in aquaculture (Hewitt et al., 2006). Tools for risk analysis associated with introductions of aquatic animals are also available (Kapuscinski, 2007; Arthur et al, 2009).

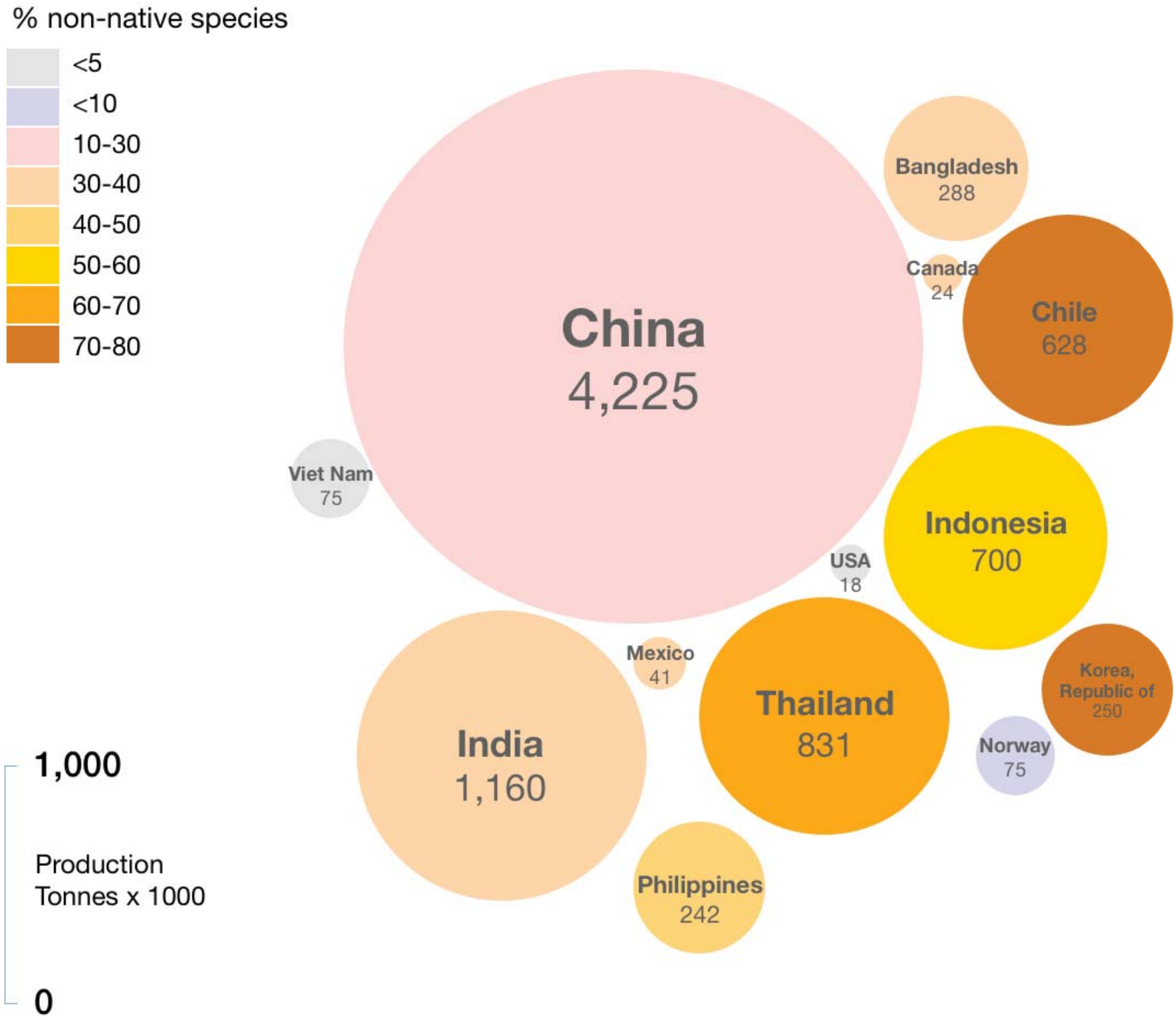


Figure 4.3: Summary of non-native species production for the systems modeled in this study. This calculation excludes seaweeds and accounts for 90% of global production in 2008. Values under each country are production (x 1000 t).

Fish Health

Aquaculture production methods are increasingly intensifying and farms are getting larger and more spatially concentrated. Because of this, there is a growing concern about increasing risks from the spread of pathogens and infectious aquatic animal diseases and the increased movement of aquatic animals. Inter-regional trade and the introduction of new species and strains to meet economic and market demands both pose significant risks. The use of trash fish is also a risk factor in the transfer of pathogens. Current estimates suggest that between one third to a half of fish and shrimps put into cages or ponds are lost to poor health management before they reach marketable size (Tan et al., 2006).

Although technologies and measures for aquatic animal disease prevention, control and treatment have improved significantly in recent years, abuse of antimicrobials and other veterinary drugs and associated environmental and human health risks remain a major concern. Antimicrobials and other medicines are of particular concern given their importance for human health. Uneaten feed provides a source of these contaminants to the environment, while ingested medicines are metabolized, excreted or voided in feces.

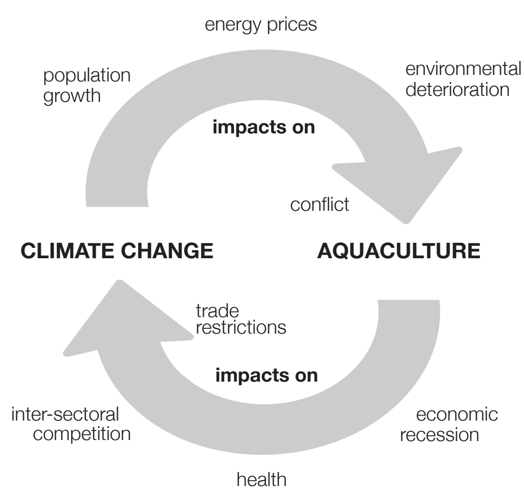
Accumulation of residues from these sources can increase antimicrobial resistance in farmed fish. Impaired decomposition of organic material in the environment because of declines in bacterial flora can also occur. Disease prevention often proves difficult and many farmers currently focus more on treatment than prevention, but increased use of antimicrobials as prophylactics and as growth promoters is possible in future. This will further increase the risks of developing new, drug-resistant strains of pathogens. Developing vaccines is one route to reducing use of veterinary drugs, but research in this area is currently restricted to relatively few species (e.g., salmon, trout, grouper) and vaccines are only effective against certain types of disease.

Environmental stressors, such as poor water quality, acting alone or in conjunction with other stressors such as over-crowding, poor handling or inadequate nutrition, compromise the immunity of farmed aquatic animals, increasing their susceptibility to attacks by pathogens present in the farmed environment. Increasingly, the aquaculture industry and others—national governments, the FAO, the OIE—recognize that effective biosecurity measures are needed to reduce the spread of pathogens. Adequate welfare standards are also required to minimize stress and reduce the incidence of disease and its consequent impacts on production and profits. Two other factors are also important. First, environmental standards have been developed for many of the compounds used as medicines by aquaculture, and have been widely disseminated, if perhaps less widely enforced. Second, food safety standards, designed to protect consumers from exposure to potentially harmful medicinal and other chemical residues, are driving more responsible use. Such standards are more widely used by developed countries, and for products from developing countries for export to them, but many developing countries will need to apply the same or similar regulations to protect their domestic consumers. Industry codes of practice may help, but legislation and its implementation, combined with capacity building, are also needed.

Climate change

Climate change – aquaculture interactions are two-way: climate change affects aquaculture, and aquaculture contributes to climate change (Figure 4.4). The figure below illustrates that the impact of climate change on the sector and those who depend on it and vice versa is moderated by a range of other external factors which may be occurring at the same time (Beveridge and Phillips, 2010).

Figure 4.4: The relationship between aquaculture and climate change. (From Beveridge and Phillips, 2010)



Climate change is likely to increase global seawater temperatures. Combined with sea level rises, changes can be expected in inshore salinities, currents and seawater mixing patterns, and in wind speeds and direction. The changes in the physico-chemical environment will impact on ecosystem structure and function—the distribution of species, aquatic productivity and the incidence of harmful algal blooms. Coastal areas and estuaries are likely to experience the greatest changes in biophysical conditions and ecology. Inland, changes in the levels and pattern of precipitation are likely to increase the incidence of flooding in some areas and drought in others and impact on groundwater and surface water reserves. Temperature rises will increase evaporative water losses, change stratification and mixing patterns of lakes, aquatic community composition and aquatic productivity (for reviews see Handisyde et al., 2006; Allison et al., 2009; Brierley and Kingsford, 2009; Cheung et al., 2009; Beveridge et al., 2010).

Temperature changes can be expected to impact not only on the aquatic environments that support aquaculture production but also on the farming operations themselves. Temperature increases will increase productivity especially in areas where anthropogenic nutrient inputs are increasing. The incidence of harmful algal blooms, however, is also likely to increase, limiting bivalve and other types of culture. Moreover, above some critical point elevated temperatures stress farmed aquatic animals sufficiently to markedly impact survival, reproduction, growth, production, and profits.

Climate change will thus directly affect aquaculture production through choice of species, location, technology and production costs. Development of heat tolerant strains is likely to be limited given the complex interactions between temperature and physiology. In short, adaptation strategies to climate change are likely to be limited. Instead, we can expect geographic winners and losers.

Aquaculture production will disappear from areas that become too hot, dry or stormy while areas presently considered as excessively cold may benefit, as is anticipated in coastal Norway.

With respect to the impact of aquaculture on climate change, perhaps the most specific effect concerns the use of wetlands and coastal mangroves . These habitats sequester high levels of carbon, and efforts are needed to ensure that any aquaculture should be sited in areas which such areas does not compromise such natural carbon sinks.

Production projections

“Aquaculture production has continually outstripped projections, and there is little reason to believe that it will not continue to do so.” (ARD, 2006)

The global picture

Notwithstanding our historic tendency to underestimate the rise of aquaculture, several projections of future production are available. We have drawn on these to examine likely future trends. Figure 4.5 shows actual aquaculture production up to 2008 (excluding seaweeds) against the values projected under various scenarios from published studies summarized in an analysis for the FAO (Brugère and Ridler, 2004). The various projections have been made under somewhat different assumptions and approaches. Two of the forecasts (Ye, 1999; Wijkström, 2003) assume constant fish prices and are based solely on demand driven by population growth and per capita consumption. In contrast, both supply and demand considerations and their effects on prices are included in the analysis by IFPRI (Delgado et al., 2003), which disaggregated food fish into high and low value categories on the basis of their markets and price elasticities.

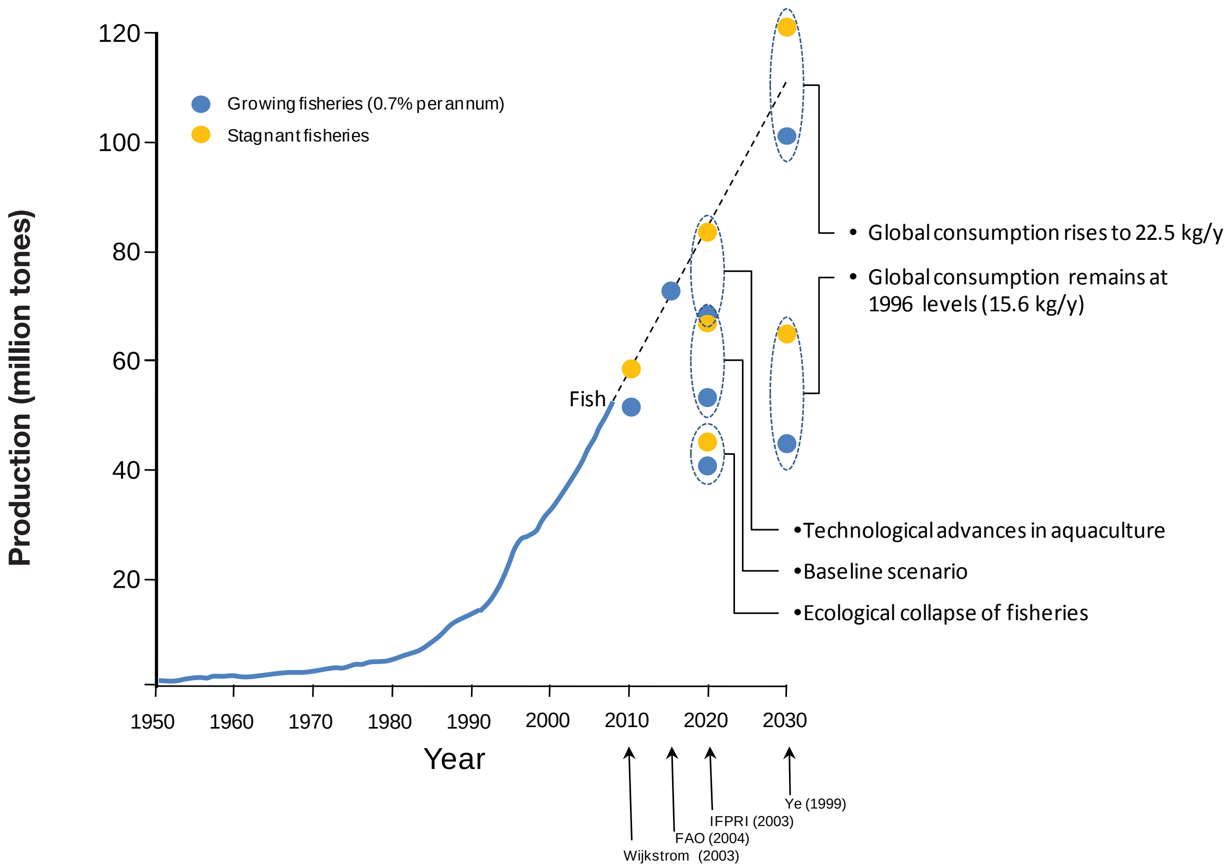


Figure 4.5: Comparison of historical trends in production of farmed fish with several projections of future aquaculture production. Circles denote projections based on supply and demand considerations under various assumptions, as summarized in Table 3 of Brugère and Ridler (2004). Historical production data are from FAOStat.

The studies by Delgado et al. (2003) and Ye (1999) consider alternative scenarios for the future. The IFPRI study explored six scenarios, three of which are considered here: a baseline scenario that embodied the authors “most plausible” set of assumptions, an extreme scenario where capture fisheries production, including fishmeal fisheries collapse with a minus 1% annual growth in production, and an aquaculture development scenario where technological progress increases production growth by 50% relative to the baseline scenario. Ye (1999) considered two scenarios: the first assumed per capita consumption would remain at 1996 levels, the second that it would rise to 22.5 kg/y, based on a combination of historical time trends and modeled relationships between GDP growth and consumption. Further richness to these predictions was added by Brugère and Ridler (2004) who considered how these projections might be affected by either no growth in wild capture fisheries or by a modest 0.7% growth.

Examining these various projections in relation to observed trends in production we derive an uncertainty envelope for total aquaculture production out to 2030 in the following way (Figure 4.6). Because the three projections up to 2015 fall broadly on the current growth trajectory for production, there is consensus among the studies that global production growth will continue along a similar trajectory to the recent past for the next five years or so.

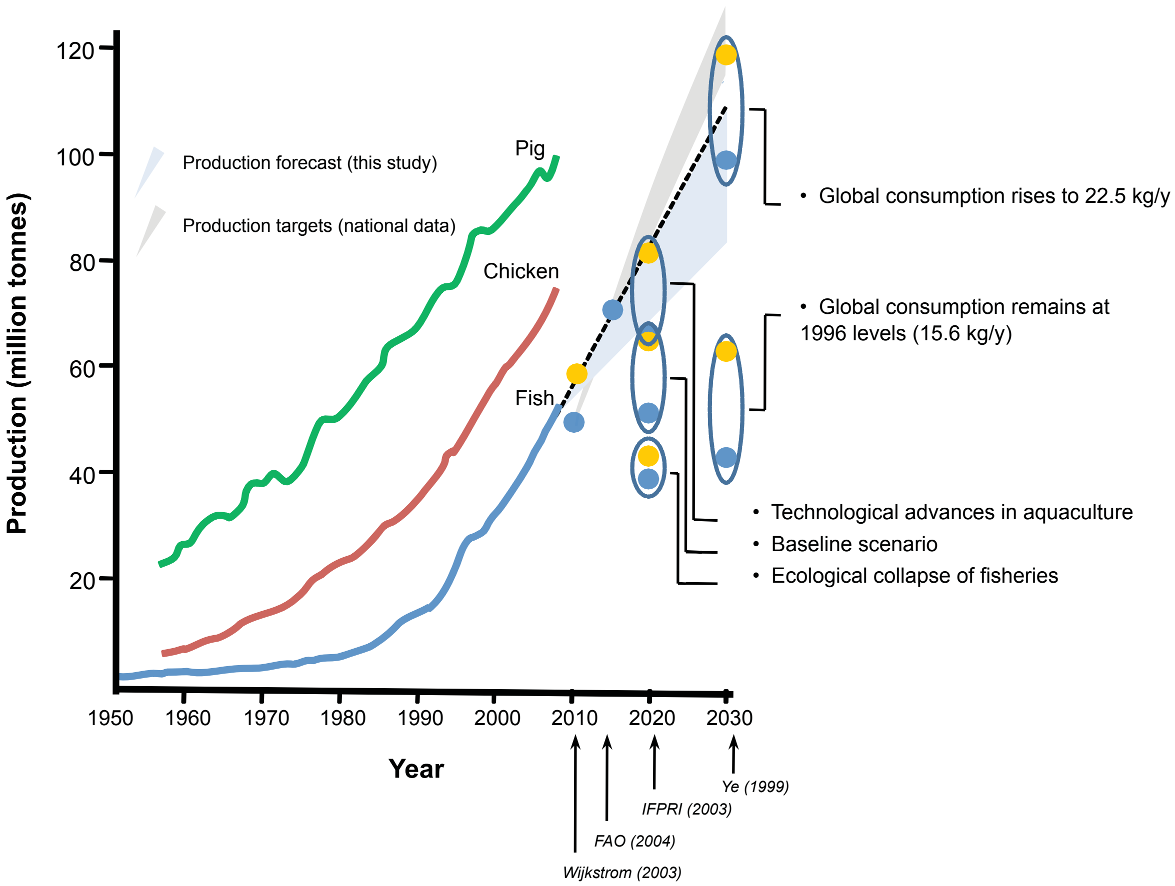


Figure 4.6: Comparison of historical trends in farmed fish, pig and chicken meat production, the likely production trajectory envelope and the combined aquaculture production targets envelope for nine countries (Bangladesh, India, China, Indonesia, Philippines, Thailand, Vietnam, Brazil, Chile, Canada, Egypt). Historical production data are from FAOStat, production target data are from Table 9 of Brugère and Ridler (2004). Aquaculture production predictions from Figure 4.5 are also shown.

Predictions for the latter half of the decade are variable, but if continued growth to 2015 holds we will have surpassed all but the most optimistic of the IFPRI scenarios to 2020. Thus, assuming that we do not see the catastrophic collapse of wild fisheries assumed by the most pessimistic scenario, but that we also see no growth in this sector[9] (Mills et al., 2010), the envelope for production by 2020 is between 65 and 85 million tonnes. The lower bound of this range corresponds to the IFPRI baseline scenario under a stagnant fisheries assumption and the upper bound reflects the continuation of the current production trend and the prediction for IFPRI technological innovation scenario under a stagnant fisheries assumption.

The bounds of uncertainty become even greater as we look out to 2030. For this time horizon, and in the absence of a new modeling effort, a conservative envelope is probably between 79 and 110 million tonnes. The lower bound represents a growth pattern that continues the trajectory for the IFPRI baseline scenario prediction for 2020. The upper bound represents the continuation of the current production trend and the IFPRI technological innovation scenario under a stagnant fisheries assumption. It also corresponds to the midpoint between the two projections by Ye for global consumption of 22.5kg.

One indication of the reasonableness of this likely envelope for the aquaculture production trajectory comes from a comparison with the targets for

[9] Although we assume no growth in the real supply of fish from the wild capture sector, we do envisage an increase in the supply reported in official statistics in coming years, in particular as better data on small-scale fisheries becomes available (Mills et al., 2010).

production that were identified in the national plans of nine countries (Brugère and Ridler, 2004, Table 9). Figure 4.6 compares the envelopes for these projections and shows that our estimated range falls below the collective ambitions of these nine countries. The envelope for production targets was created based on two scenarios—an annual growth rate for China of 3.5%, or a more modest rate of 2% (Brugère and Ridler, 2004). Although national targets are often over-optimistic there is little to indicate that the aquaculture sector as a whole will be unable to meet demand should it eventuate.

It is also interesting to examine how pig and chicken meat production has evolved and to observe the remarkably similar growth rates for production over the last decade (Figure 4.6). This suggests, perhaps, that all three sectors have been driven by similar demand drivers during this period and that all three production systems have been able to meet this demand.

Geographic distribution

The global distribution of production described here for 2008 is likely to still hold in 2010, moderated somewhat by some recent large changes (e.g., marked declines in Chile; marked increases in some sub-Saharan African states). For the next five years, therefore, we may further assume that the present global pattern of production will remain largely unchanged: i.e. that Asia will account for more than 90% of production, Europe for around 3–4% and South America, North America and Africa for 2% each, and Oceania for a fraction of a percentage point. Indeed, one can expect Asia to further consolidate its position by a few percentage points at the expense of the rest of the world.

The regional distribution of aquaculture production growth beyond the next five years is more difficult to predict. Three factors are particularly significant. First, the industry is now a major global provider of food which increasingly must compete for markets with other sources of animal-derived foods, all of which are changing too in response to market globalization. Second, like other food production sectors, aquaculture depends on a range of scarce or finite resources for which it must increasingly compete with others. Third, the sector is finally beginning to be taken seriously at policy level; governments are starting to develop and apply incentives and penalties to facilitate or regulate sectoral growth, the methods by which it is achieved, and trade. They are doing this to ensure that the sector makes appropriate contributions to social, economic and environmental objectives. Given these considerations and the complicated relations these factors will have with production costs and price to consumers one must be cautious with definitive statements about how the sector will evolve geographically.

There are, however, several conclusions that are probably robust. First, despite the investment, aquaculture production in Europe and North America has remained largely static over the past decade and is unlikely to grow substantially. This is primarily due to lack of available sites, competition from other producing countries and substitution of comparatively expensive, domestically produced fish such as cod by cheaper products from other parts of the world (striped catfish from Vietnam, tilapia from China). Marine production in the United States remains constrained by lack of an enabling legal framework, competition for coastal resources and competition from overseas producers (e.g., Latin America and Asia for shrimp). Similarly, freshwater production in the United States is limited by overseas producers able to produce identical (tilapias, carps) or substitute products (striped catfish) at highly competitive prices.

Second, production in Africa is very low but is growing fast in some countries, unconstrained by resources that are often underutilized. Despite the fact that fish is the most important source of animal protein per capita for many countries in this region and provides several essential vitamins and nutrients, fish consumption is the lowest in the world. Here it is projected that simply to keep pace with population growth a further 1.6 million tonnes—almost 10 times the current production levels—will be needed by 2016 (Beveridge et al., 2010). Growth in sub-Saharan Africa is increasingly being driven by investors in countries such as Uganda, Nigeria and Ghana, keen to develop enterprise type operations that target both domestic and regional markets (OECD, 2010). However, because of the very low production base and because of inefficient and poorly developed value chains, it is likely to take at least a decade before substantial increases in production in sub-Saharan Africa are realized. If this is correct, local aquaculture production will be unable to fill the gap between fish supply and demand that Africa faces over the next decade. Despite this overall picture, however, there will be large local increases in some countries and this will likely bring with it substantial resource demands.

Third, the current trends indicate that the majority of increases in global production to 2030 will come from South and Southeast Asia and China, with a continued drive by major producer countries such as China and Vietnam towards export to the strong European and North American markets. Increased import taxation, such as that currently being imposed by the United States against Vietnamese farmed striped catfish, can be expected to periodically moderate this trade (Worldfishing and Aquaculture, 2010), but the general trend is clear. The principal constraint to growth in production in the region, other than markets, is likely to be availability of resources (land, water) and environmental change.

Finally, of the countries in the Asian region, it is China where biophysical constraints seem most likely to slow the rate of production growth. While China is likely to further consolidate its position as the world's largest producer and consumer of farmed aquatic products, the resource base upon which this production depends will come under increasing pressure. As a consequence, it is difficult to imagine how current production growth rates can be maintained in the longer term. Balanced against this, however, will be considerable pressure to satisfy internal demand through domestic aquaculture production. While domestic production will meet some of this need, increasing imports can also be expected, some of which may be supplied by Chinese overseas aquaculture investments.

The implications of sector growth for biophysical resource demands

To explore and illustrate the consequences of current production practices for future biophysical demands of aquaculture might develop we have constructed a scenario in which production from our modeled systems (excluding seaweeds) will reach 100 million tons by 2030. We chose 100 million tonnes as a landmark figure and because it falls on approximately the upper quartile of our uncertainty envelope. Given the tendency of previous work to under-estimate aquaculture growth choosing a figure in the upper part of the range seems reasonable. We also made two other assumptions to avoid projecting forward trends that we believe are unlikely to persist and which have high leverage on the predicted environmental demands:

1. Production in China and striped catfish production in Vietnam will slow faster than in other countries owing to pressure on natural resources[10].
2. Whitefish production will grow relatively faster than other forms owing to increasing demand for this product category.

To estimate the distribution of global production, a scaled estimate of the recent (2003 – 2008) compound annual production growth rate was used to project forward production from the 2008 starting value for each production system. For all production systems the same scaling factor of approximately 0.42 was used for all years and systems. For China, we reduced production growth rates by a further 50% and for catfish in Vietnam by 90%. For all white fish products we increased growth rates by 20%.

Results

Figure 4.7 summarizes the change in geographic distribution of overall production between 2008 and 2030 under our growth scenario. The key feature of this result is the continued dominance by Asia, but the emergence of several other countries (India, Indonesia and Thailand) as key players. For Asia as a whole, this conclusion is almost certainly robust, although how production will be distributed across countries is far less certain given the dynamic nature of the sector. The spectacular rise to dominance in catfish production by Vietnam in recent years is a testament to how quickly things can change.

[10] Although catfish demand may well be met by producers in countries such as Myanmar, India and Bangladesh, we have not included this is our projections.

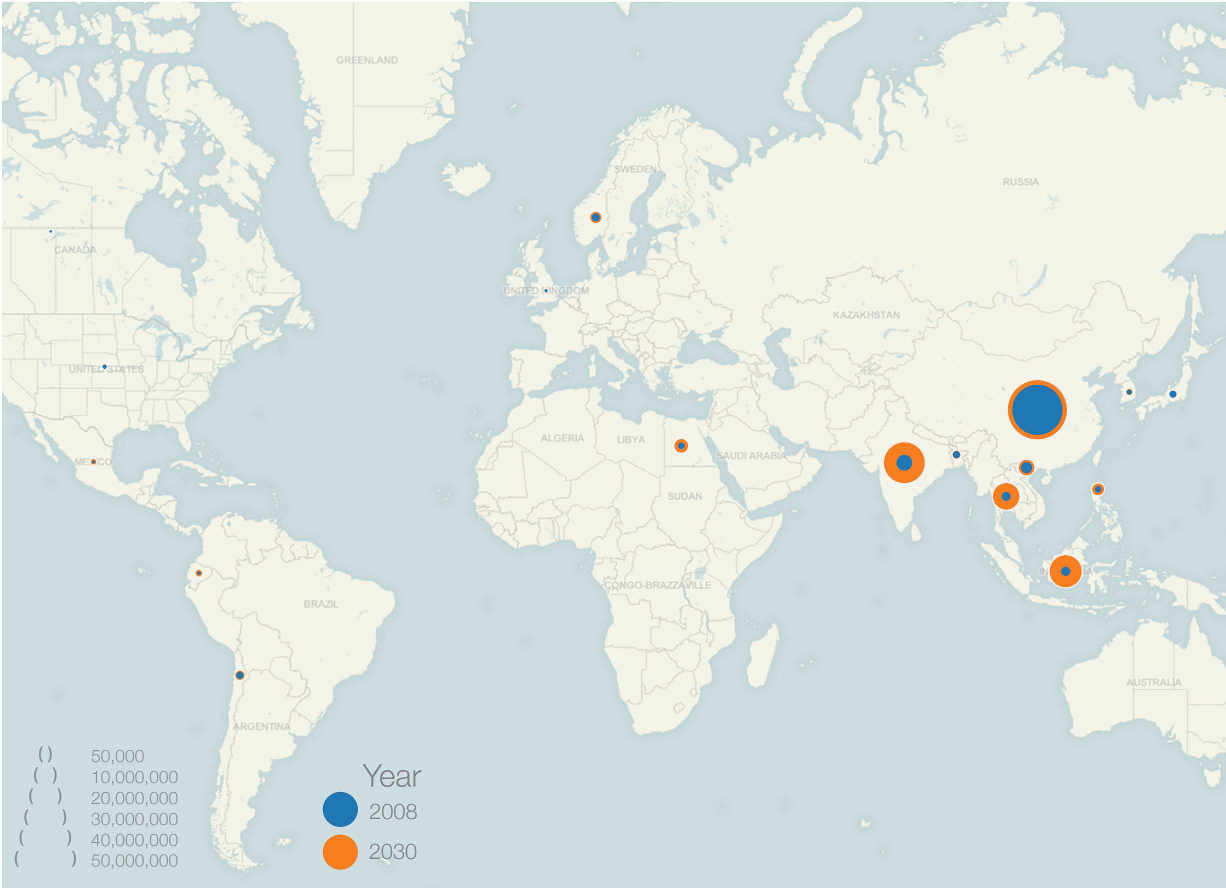


Figure 4.7: Projected change in production distribution between 2008 and 2030 for the systems modeled in this study, which produced 82% of world production in 2008 (data exclude seaweeds). Blue circles: 2008 production; orange circles: 2030 production.

Table 4.1 summarizes the change in overall environmental impact for each of our six categories. Increases in impact are between 99 and 168% over the 22 year period. Precisely what this will mean for countries and regions, is of course difficult to imagine but to put it in perspective, if the climate change contribution from aquaculture were offset at current market price of $15 per tonne of CO_2, the cost would rise from US$ 43.6 billion in 2008 to US$ 101.19 billion in 2030. The largest projected change is for eutrophication, which rose by 168%. This suggests that meeting demands for fish products into the future will require particular attention to issues of waste disposal. Of course, these projections assume current (2008) practices, whereas improved technologies, regulatory regimes and production practices should modify this trend; see earlier discussions on intensification.

Table 4.1: Projected change in total environmental impact between 2008 and 2030 for the systems modeled in this study, which produced 82% of world production in 2008 (data exclude seaweeds, and assumes current production practices).

Year	Eutrophication (Mt PO_4 eq)	Acidification (Mt SO_2 eq)	Climate Change (Mt CO_2 eq)	Land Occupation (Mha)	Energy Demand (Tj eq)	Biotic Depletion (Mt)
2008	3.57	2.54	291.2	50.61	3,358,468	15.11
2030	9.55	5.05	674. 6	113.63	7,622,647	37.88
% Change	168%	99%	132%	125%	127%	151%

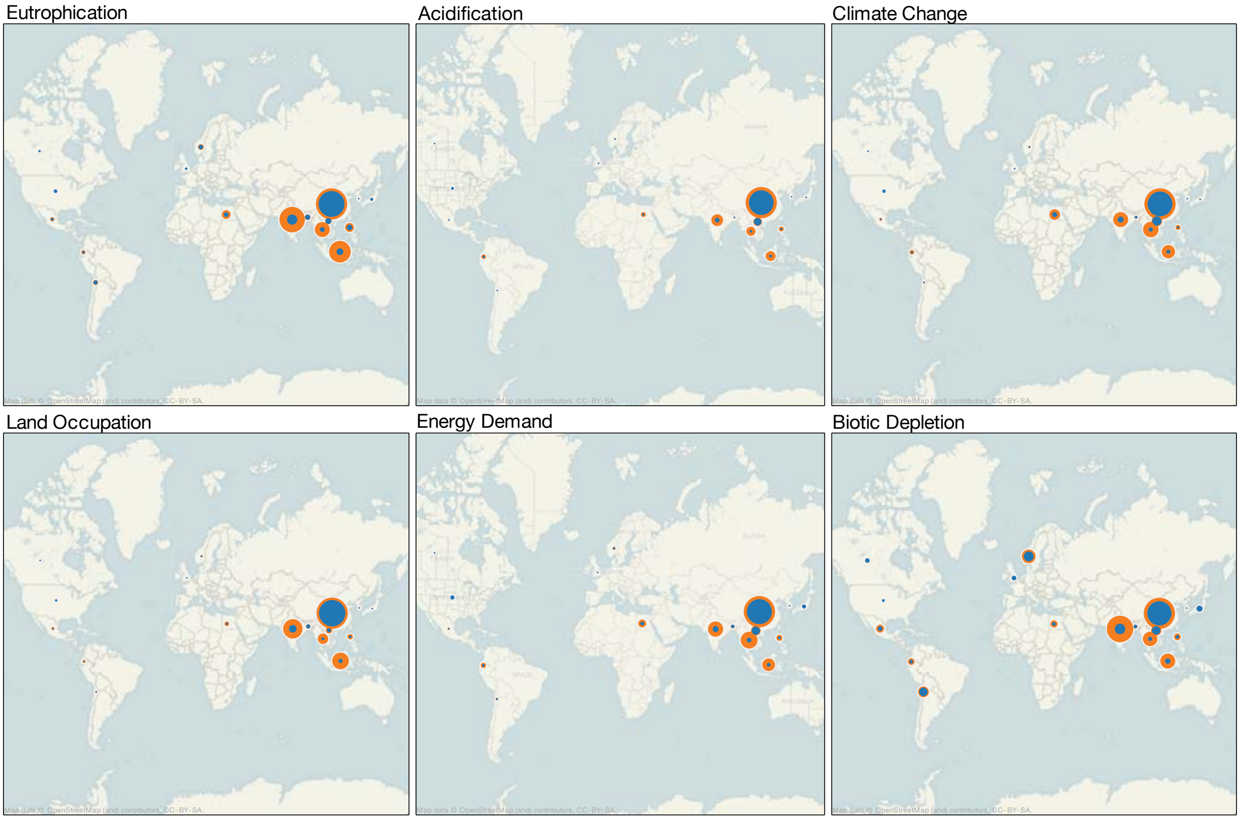


Figure 4.8: Projected change in distribution of environmental impact between 2008 and 2030 for the systems modeled in this study (data exclude seaweeds). Blue circles: 2008 production; orange circles: 2030 production.

Figure 4.8 shows the distribution of impact for each of our impact categories in 2008 and 2030. As we would expect these distributions map broadly to overall production levels, re-affirming the importance of focused support to Asian producers to mitigate the environmental impacts of aquaculture.

Conclusions

In this section we have explored the drivers of demand for aquaculture products and the environmental constraints to meeting this demand. We then examined published projections of future growth. These suggest that aquaculture production is likely to increase at a rapid pace. Finally, we explored the future environmental demands of aquaculture if it reached 100 million tonnes (excluding seaweeds) and in the absence of significant innovation and improvements in techniques and technology. Under this scenario we estimate that the environmental demands will be between 2 and 2.5 times greater than 2008 levels by 2030 for all the impact categories studied.

Photo by Stevie Mann
MALAWI

5. POLICY

PHOTO CREDIT: The WorldFish Center

5. Policy Implications and Recommendations

Understanding, quantifying and explaining the environmental impacts of aquaculture is essential for sound decision making. Policy-makers need this information to establish evidence based and fair environmental regulations. Fish farmers need it to implement better management practices and understand and comply with environmental regulations. And retailers and consumers need it to make informed choices and drive appropriate policy and farming practices.

In this section we distill the results of our LCA study into seven policy relevant findings. For each of these findings we then offer one or more specific recommendations for action. Following this we offer a more general conclusion and recommendations regarding the future of aquaculture. We then combine and further amplify our recommendations for key stakeholder groups (Table 5.1) before considering the future research investments that are needed to support sector development.

Study findings

Finding 1. Environmental impact is strongly correlated with overall production levels.

The absolute levels of environmental impact revealed by this study indicate those regions and production systems where efforts to regulate and reduce global environmental demands are best targeted. Based on these findings international agencies and institutions should:

- Develop approaches to encourage and support China and other Asian and Latin American countries to analyze impacts and better manage the sector towards improved environmental performance.
- Focus especially on improving production practices in inland pond, pen and cage aquaculture because these dominate global production.
- Focus especially on carps, shrimps and prawns as these are among the sectors which have the largest overall impacts in absolute terms.

The study also shows that the "other finfish" sector has high aggregate impact. Unfortunately this sector comprises many species, making a common approach difficult to develop. Recent comparative analyses of impacts in the marine finfish sector, however, have begun to tease this issue apart (Volpe et al., 2010).

Finding 2. Aquaculture systems vary markedly in their environmental performance, offering great potential for improvement.

The highly regulated nature of the salmon farming industry in some countries has led to considerable technical innovation that has both driven down costs and reduced environmental impact. This sector offers some lessons for the rest of the industry, as do many of the traditional systems of aquaculture in Asia with their low environmental impacts.

More generally, the potential benefits of leveraging cross-sector and cross-country learning deserves close attention as one of the most effective means for driving improvement. In view of this international agencies and regional bodies and government agencies should:

- Support or develop national and regional learning networks and innovation platforms for both policies and technologies that bring together government, the private sector, NGOs and research agencies to jointly identify and implement solutions that will overcome problems, establish and share best practices, and improve sector wide environmental performance.
- Support the research needed to define and develop practical measures for implementing the Ecosystem Approach to Aquaculture that has recently been developed by the FAO.

- Support emerging aquaculture sectors to understand cost drivers as a means to stimulate innovation and the uptake of more efficient production practices.

- Facilitate private sector investment in improving environmental performance.

Finding 3. Use of fishmeal and fish oils is widespread and reducing dependency on this resource requires a concerted focus on innovation in the feed sector.

Reducing the fishmeal and fish oil component in aquaculture feeds is a high priority for intensive and semi-intensive systems. This is true for traditional fishmeal and fish users such as salmon, but also for other emerging industries such as tilapia, catfish and shrimp. A range of largely complementary strategies based on the following principles and recommendations is needed to reduce feed constraints on sector development:

- Use locally sourced feedstuffs, including agricultural by-products (oil cakes, rice bran), and develop pre-treatment and processing methods to increase digestibility and nutrient availability and reduce anti-nutrients.

- Make better use of scarce and costly fishmeal and fish oil supplies by restricting their use to when it is a dietary essential or in finishing diets to improve the nutritional value of the product for consumers.

- Breed fish that have more limited demand for high quality marine lipids and protein.

- Develop systems of intensification for species such as carps and tilapia that will not rely on fishmeal and fish oils.

- Develop high quality protein and lipid sources from plants and microorganisms.

- Develop feeding technologies and management systems to optimize the conversion of feeds into aquatic animal biomass.

Finding 4. Reducing many impacts requires responses that are generic.

The above recommendations are specific to the aquaculture sector. There are, however, many steps that the sector can take that are more generic in nature. Our analysis shows, for example, that reducing the sector's impact on climate change and acidification is best served by adopting generic energy efficiency measures throughout the value chain. In view of this government agencies should:

- Facilitate energy and other resource use audits (e.g., water) across aquaculture value chains to help identify options for efficiency gains and cost savings.

- Where practicable, help make available to producers energy and other resource use data for their operations on a daily basis. This would help drive efficient practices, especially if combined with comparative data for other producers.

- Facilitate cross-sectoral dialogue on industry best practice in the food and agriculture sector.

Finding 5. Fish farming is an ecologically competitive option for producing animal source foods.

From an ecological efficiency and environmental impact perspective the benefits of fish farming relative to several other animal source foods are clear. For many regions, an increase in the production of fish, poultry and dairy products relative to meat is likely to make more efficient use of available resources. These products are especially suited to meeting the demand of growing urban populations (including the urban poor) through local peri-urban production.

In view of this national planning agencies should:

- Examine thoroughly the relative benefits of the various animal production sectors and consider policy drivers that can shift towards a more ecologically efficient production portfolio.

Recommending an aquaculture species choice based on our analysis is difficult because the picture that emerges is somewhat mixed. Eels are particularly demanding in relative terms, albeit with very low overall production, and shrimps and prawns and catfish generally have higher impact. Yet they all perform favorably in terms of resource demands compared to meat. Bivalve and mollusk farming is the least ecologically demanding of the animal source foods and provides an ecological service by removing nutrients. These groups are a particularly nutritious and environmentally sustainable option for consumers.

Finding 6. Aquaculture is likely to be an increasingly important contributor to food and nutrition security in developing countries where there is culture of fish consumption.

The contribution of fish to food and nutrition security will become increasingly important in the developing countries. This is particularly true for African and Asian countries where there is growing domestic and regional demand, especially from the growing urban populations, including the urban poor. In view of this, governments and industry in these countries will need to pay particular attention to:

- Stimulating the private sector to invest in commercial aquaculture where there is access to strong demand in domestic and regional markets.
- Evaluating research and policy development needs along the entire value chain from inputs to consumer markets.
- Supporting development of aquaculture production that will deliver sustained supplies at affordable prices for poor consumers.
- Supporting aquaculture both as a household livelihood and food and nutrition security support strategy in areas where production is feasible, but markets are weak.

Finding 7. Climate change cannot be ignored.

Without further and more wide ranging analysis it is difficult to anticipate the degree to which climate change will affect global aquaculture production. To more fully assess climate change impacts on the sector, a value chain approach must be adopted in which not only production but also essential upstream and downstream activities (e.g., seed and feed supply, transport and processing) are included. To make matters even more complex, climate change will interact with other factors such as population growth, changes in markets, trade barriers and energy prices to impact on aquaculture and aquaculture-related food security.

Aquaculture also affects climate change; although it is a relatively small contributor to greenhouse gas generation. To sustain present and future markets, especially in developed countries, the sector must minimize its potential for climate change impact. Certain key principles should be universally applied:

- Avoid use for aquaculture of sites high in sequestered carbon (mangroves, seagrass, forests).
- Organically enriched fish pond sediments, a potentially important source of methanogenesis, must be carefully dealt with, preferably for producing other foods.
- Energy consumption associated with pumping and post-harvest processing, transport and marketing must be minimized.

Tools such as Life Cycle Analysis (LCA) can help identify the most energy-consuming steps in value chains and evidence from other sectors suggests that often mitigation may not be that costly. But fiscal and economic incentives may be needed to encourage changes, and ultimately it may be consumers who, through exercising choice in what they eat, play the most important role in promoting mitigation.

General conclusion

The trends in many of the drivers of demand for aquaculture products suggest that the aquaculture sector will continue to grow to meet increasing demand for fish products. The environmental impacts of such growth can be managed through innovation, strengthened policy, capacity building and monitoring.

Increasing wealth and urbanization will result in rising demand for farmed fish in the coming decades. At a global scale, there is every indication that the aquaculture sector will be capable of meeting this demand. This will occur through both expansion of areas under cultivation and intensification of production. But to achieve these increases in ways that limit environmental impacts we offer four core recommendations to government and industry in all producer countries:

1. Continue to support innovation in the aquaculture sector, especially the development of productive technologies that make best use of land and water and feed resources and that minimize demands on environmental services.

2. Ensure that the regulatory environment keeps pace with sector development and support policy analysis and development that internalizes into aquaculture enterprises the costs of its environmental impacts.

3. Develop capacity in national agencies for supporting the development of sector regulation and for monitoring and compliance.

4. Monitor carefully how supply and demand for fish is evolving to ensure that support and investment is appropriate to the market opportunity.

These core recommendations apply globally, but there are regional differences in their relative importance for attention over the next three to five years. Based on the findings of this study, literature review and our own experience, Figure 5.1 summarizes our view of these differences.

Focus	Core Recommendation
1. Innovation	Continue to support innovation in the aquaculture sector, especially the development of productive technologies that make best use of land and water and feed resources and that minimize demands on environmental services.
2. Regulation	Ensure the regulatory environment keeps pace with sector development and support policy analysis and development that internalizes into aquaculture enterprises costs of environmental impacts.
3. Monitoring and compliance	Develop capacity in national agencies for supporting the development of sector regulation and for monitoring and compliance.
4. Supply and demand analysis	Monitor carefully how supply and demand for fish is evolving to ensure that support and investment is appropriate to the market opportunity.

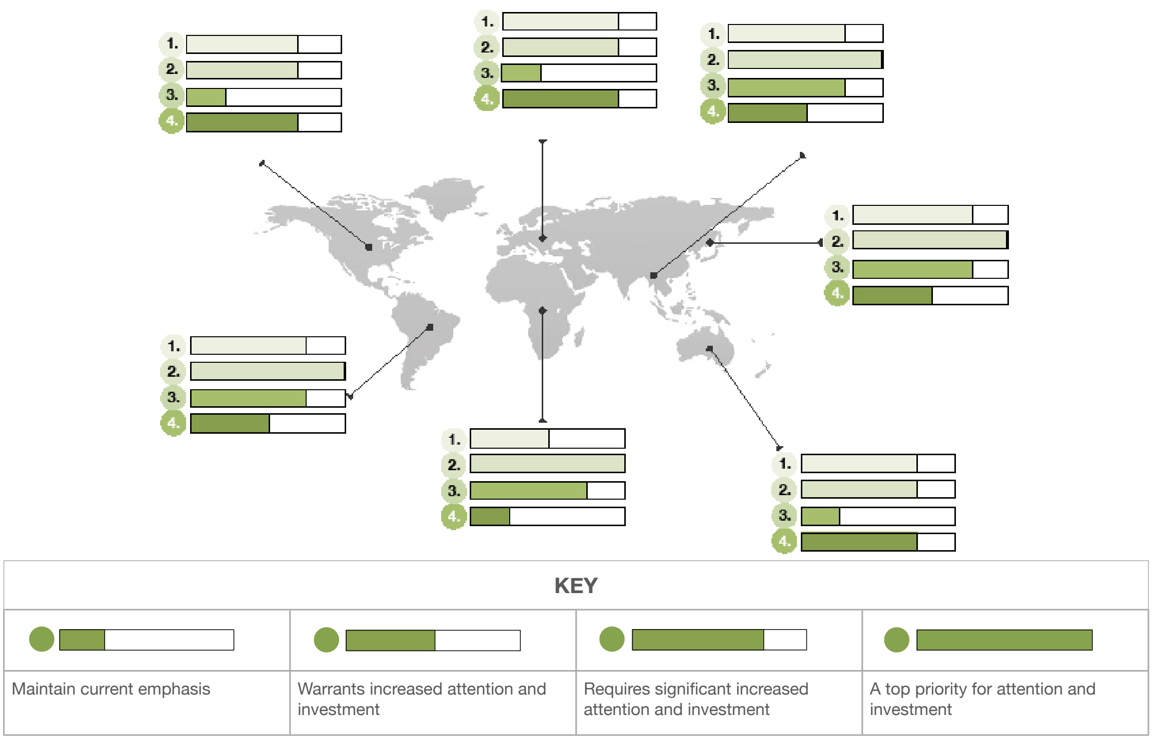


Figure 5.1: Core recommendations for government and industry in all producer countries and their relative importance for each region.

Table 5.1: Recommendations summarized for key stakeholder groups.

Stakeholder Group	Recommendations
Policy makers	• Use audits of energy and other ecological resources across aquaculture value chains as a guide for management decisions. • Make information on energy and other ecological resource impacts and efficiency measures accessible to producers. • Review and improve certification standards, Good Aquaculture Practice, Codes of Practices and other industry management codes and guidance documents to ensure they reflect ecologically efficient approaches to farm management and value chains. • Facilitate cross-sectoral comparisons and dialogue on best practices in food production within the livestock, fisheries and agriculture sectors. • Examine thoroughly the relative benefits of the various animal production sectors and consider policy drivers that can shift towards a more ecologically efficient production portfolio. • Avoid siting aquaculture farms in those wetland or coastal ecosystems with high values as sinks for sequestration of carbon, other greenhouse gases or nutrients.
Development and environmental organizations	• Encourage and support China and other Asian and Latin American countries to better manage the sector towards improved environmental performance. • Continue to encourage adoption in practice and policy of the Ecosystem Approach to Aquaculture. • Monitor performance of certification in the aquaculture sector, and seek ways to support and improve systems to deliver environmental improvements at scale. • Support development of regional knowledge sharing and learning networks for both policies and technologies. • Invest now in improvements in aquaculture technologies in Africa that will help set an ecologically sound foundation for future aquaculture growth. • Pay particular attention to carps, shrimps and prawns. • Pay particular attention to pond culture systems and to pen and cage systems in freshwater; focus on improving inland pond aquaculture. • Continue to engage and seek to partner with key retail chains to improve the ecological performance of the sector.
Private sector operators and investors	• Make better use of scarce and costly fishmeal and fish oil supplies. • Avoid using areas high in sequestered carbon for aquaculture. • Use locally sourced feedstuffs and develop pre-treatment and processing methods to increase digestibility and nutrient availability and reduce anti-nutrients. • Breed fish that have more limited demand for high quality marine lipids and protein. • Deal carefully with organically enriched fish pond sediments. • Minimize energy consumption on-farm and in the following value chain.

Photo by Mark Prein
BANGLADESH

Research needs

Acting on the above recommendations should be guided by sound science and implementing many will benefit considerably from further research. In this section we summarize the five research foci that we think are most important.

1. Support the adoption of inter- and intra-sectoral best practice in environmental performance by improving the knowledge base.

The analysis presented here indicates major differences in environmental resource demands within and between countries, species and farming systems. This indicates major opportunities for improving ecological performance. Research is needed to identify the better performers, combined with field verification, to align incentives and investments that will drive improvement.

Life Cycle Analyses, the methods of Volpe et al. (2010), certification standards and the Ecosystem Approach to Aquaculture are being used in various ways to measure performance and encourage improvement. Further work is needed, however, to improve the consistency and comparability of findings across the aquaculture sector and to provide practical guidance to farmers and regulators. The research needed includes:

- Developing a common and comprehensive analytical framework to facilitate comparisons of animal source food production systems that captures impacts on key planetary boundaries, such as the nitrogen cycle, biodiversity and climate change.
- Developing cost-effective LCA-based indicators for measuring ecological performance status and improvements that can be applied across scales, from farm to global levels.
- Developing LCA indicators for use with integrated farming systems and identifying incentives (e.g., economic, policy, markets) to improve the ecological performance of integrated aquaculture and agriculture at farm and landscape levels.
- Improving the LCA database on systems that are currently poorly covered by global datasets — focus first on major production systems in major producing countries (e.g., carps in China, Bangladesh; products for domestic markets).
- Determining the environmental benefits of certification using LCA tools, to identify improvements in certification standards.
- Determining how emerging supermarket chains in Asia and other entry points can be used to improve the environmental performance of aquaculture products for domestic or regional markets.
- Carrying out more in-depth LCA studies on trends in intensification, choice of farmed species, system design and management practices, to understand entry points for improvement and costs.
- Identifying the present frontiers of environmental performance and what can be done to support their adoption.
- Identifying which investment strategies, incentives and institutional arrangements best facilitate environmental improvement among small- and medium-sized enterprises.

2. Improve modeling and understanding of demand for farmed aquatic foods.

While there is strong evidence that the aquaculture sector will continue to grow to meet the anticipated increasing demand for farmed aquatic products, policy makers, producers and retailers need to better understand the drivers of fish consumption. This will require improved quantitative models of fish supply and demand. The Fish to 2030 initiative that is currently being supported by the World Bank, is particularly welcome in this regard. Research is also needed to ensure that policies designed to help meet demand for aquaculture produce are consistent with policy objectives for other sectors, such as environment, energy, food and nutritional security, and poverty and that policies are consistent at national and regional levels.

3. Provide guidance to help reduce environmental impact in high production domains.

Research is needed to help China and other Asian and Latin American countries better manage the aquaculture sector towards improved environmental performance. Because carp and shrimp and prawn aquaculture have among the largest overall impacts in absolute terms and pond and cage production systems dominate global aquaculture, efforts should focus on these commodities and systems. Attention should be paid to both technological and management interventions, and the incentives (e.g., policies, legislation, taxation, market) that produce the greatest environmental benefits.

Work in this area should also build on the recent efforts of Volpe et al. (2010) to further disaggregate the "other finfish" category, which has high aggregate impact, to help identify the species and systems to focus on.

4. Innovate in the feed sector to reduce dependency on fishmeal and fish oils.

Feed contributes a high proportion of the ecological footprint in many aquaculture systems, including impact on biodiversity. Further nutritional research is required to reduce dependency on wild fisheries as ingredients in aquaculture feeds. At the same time, replacement by other ingredients (e.g., internationally sourced plant ingredients) can lead to ecological resource demands that could offset any environmental improvements from fishmeal or oil replacement. Further research on aquaculture feeds using the LCA tool would be useful to identify feed and feed management strategies leading to genuine improved environmental performance.

5. Better integrate climate change considerations into the aquaculture sector.

The specter of climate change demands that we better understand how it will affect food security, at national, regional and global scales and whether this will affect demand and supply of aquaculture produce. Work is also needed to determine how the impacts of aquaculture on climate change can be mitigated and whether emerging funding mechanisms for climate change mitigation and adaptation can be used to support environmental improvements in developing country aquaculture.

The bottom line

Aquaculture is one of the most environmentally efficient ways to produce the animal source foods that a growing and urbanizing world population needs. It is one of the fastest growing food production sectors in the world and demand for aquaculture production will most likely continue to grow with rapid pace. But increasing production will have increasing environmental costs unless developed in a way that minimizes the demand on the environment.

This study is the first to provide a global picture of the demands fish farming makes on environmental resources using Life Cycle Analysis. It shows that there are huge opportunities for improvement in ecological performance across countries, regions and species groups. But we will only capture these opportunities if governments, businesses, non-government actors and researchers take steps together to improve production systems and techniques, invest in innovation, especially to reduce reliance on fish meal and oils, and strengthen regulation including improving monitoring and compliance.

If we do these three things we can make aquaculture a more sustainable endeavor that uses biophysical resources prudently so that it can play its role fully in meeting our future needs for fish.

Systems modelled in this study

Country	Habitat	Species Group	Production System	Intensity	Feed Regime	Production 2008
Bangladesh	Inland	Carps	Ponds	Extensive	Natural	173521
				Intensive	Pellet	83547
				Semi-Intensive	Mash	385602
Canada	Coastal	Salmonids	Cages & Pens	Intensive	Pellet	73260
Chile	Coastal	Salmonids	Cages & Pens	Intensive	Pellet	627878
China	Coastal	Bivalves	Bottom culture	Extensive	Extractor	3348250
			Off-Bottom Culture	Extensive	Extractor	5713407
			Ponds	Extensive	Extractor	750112
		Crabs and Lobsters	Cages & Pens	Extensive	Trash	197655
		Gastropods	Off-Bottom Culture	Extensive	Natural	224967
		Other finfish	Cages & Pens	Intensive	Trash	78141
				Semi-Intensive	Trash	470175
		Other Invertebrates	Ponds	Semi-Intensive	Mash	196575
		Aquatic Plants	Off-Bottom Culture	Extensive	Extractor	9703005
		Shrimps and Prawns	Ponds	Intensive	Pellet	95275
				Semi-Intensive	Pellet	539893
	Inland	Bivalves	Ponds	Extensive	Extractor	89392
		Carps	Ponds	Extensive	Natural	3325593
				Intensive	Pellet	1801363
				Semi-Intensive	Mash	8729682
		Catfish	Ponds	Extensive	Natural	337334
				Semi-Intensive	Mash	337334
		Crabs and Lobsters	Cages & Pens	Semi-Intensive	Pellet	518357
		Eels	Ponds	Intensive	Paste	417454
		Gastropods	Off-Bottom Culture	Extensive	Natural	93629
		Other finfish	Cages & Pens	Semi-Intensive	Mash	2225936
		Other Vertebrates	Ponds	Intensive	Pellet	286010
		Shrimps and Prawns	Ponds	Extensive	Natural	124004
				Intensive	Pellet	62002
				Semi-Intensive	Pellet	1054041
		Tilapias	Ponds	Intensive	Pellet	1110298
Ecuador	Coastal	Shrimps and Prawns	Ponds	Semi-Intensive	Pellet	150000
Egypt	Coastal	Other finfish	Ponds	Semi-Intensive	Pellet	58650
		Tilapias	Ponds	Intensive	Pellet	43575
				Semi-Intensive	Mash	283238
	Inland	Other finfish	Ponds	Semi-Intensive	Pellet	150663

Country	Habitat	Species Group	Production System	Intensity	Feed Regime	Production 2008
India	Inland	Carps	Ponds	Extensive	Natural	863927
				Intensive	Pellet	415965
				Semi-Intensive	Mash	1919839
Indonesia	Coastal	Other finfish	Ponds	Semi-Intensive	Pellet	277002
		Aquatic Plants	Off-Bottom Culture	Extensive	Extractor	1937591
		Shrimps and Prawns	Ponds	Extensive	Natural	113431
				Intensive	Pellet	141789
				Semi-Intensive	Pellet	28357
	Inland	Catfish	Ponds	Intensive	Pellet	86556
				Semi-Intensive	Mash	129835
		Tilapias	Ponds	Extensive	Natural	72358
				Intensive	Pellet	14471
				Semi-Intensive	Mash	202603
Japan	Coastal	Bivalves	Off-Bottom Culture	Extensive	Extractor	416000
		Other finfish	Cages & Pens	Intensive	Trash	229300
		Aquatic Plants	Off-Bottom Culture	Extensive	Extractor	337900
Korea, Dem. Rep.	Coastal	Aquatic Plants	Off-Bottom Culture	Extensive	Extractor	444300
Korea, Rep.	Coastal	Bivalves	Off-Bottom Culture	Extensive	Extractor	317418
		Aquatic Plants	Off-Bottom Culture	Extensive	Extractor	381076
Mexico	Coastal	Shrimps and Prawns	Ponds	Semi-Intensive	Pellet	121601
Norway	Coastal	Salmonids	Cages & Pens	Intensive	Pellet	818292
Philippines	Coastal	Other finfish	Ponds	Extensive	Natural	245117
				Intensive	Pellet	30639
				Semi-Intensive	Mash	30639
		Aquatic Plants	Off-Bottom Culture	Extensive	Extractor	1422691
	Inland	Tilapias	Ponds	Extensive	Natural	24193
				Intensive	Pellet	24193
				Semi-Intensive	Mash	193546
Thailand	Coastal	Bivalves	Bottom culture	Extensive	Extractor	65439
			Off-Bottom Culture	Extensive	Extractor	239946
		Shrimps and Prawns	Ponds	Intensive	Pellet	485800
	Inland	Tilapias	Ponds	Intensive	Pellet	27275
				Semi-Intensive	Mash	182536
UK	Coastal	Salmonids	Cages & Pens	Intensive	Pellet	128744
USA	Inland	Catfish	Ponds	Intensive	Pellet	233564
Viet Nam	Coastal	Shrimps and Prawns	Ponds	Extensive	Natural	288894
				Intensive	Pellet	9738
				Semi-Intensive	Pellet	22722
	Inland	Catfish	Ponds	Intensive	Pellet	1250000

Glossary

Acidification

A process that happens when compounds like ammonia, nitrogen oxides and sulphur dioxides are converted in a chemical reaction into acidic substances. The Acidification Potential (AP) is expressed relative to the acidifying effect of SO_2.

Algal bloom

A sudden and rapid increase in biomass of the plankton population. Seasonal blooms are essential for the aquatic system productivity. Sporadic plankton blooms can be toxic.

Alien species

A species occurring in an area to which it is not native.

Aquaculture

The farming of aquatic organisms in inland and coastal areas, involving intervention in the rearing process to enhance production and the individual or corporate ownership of the stock being cultivated.

Benthic

Of or relating to or happening on the bottom under a body of water.

Biodiversity

The variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part: this includes diversity within species, between species and of ecosystems.

Biophysical resources

Resources such as soil, nutrients, water, plants and animals.

Biotic depletion

The volume of wild fish required to support observed aquaculture production.

Bivalves

Common name for a class of aquatic mollusks characterized by two calcareous valves joined by a flexible ligament along a hinge line. This class includes various edible species, many of which are cultivated (e.g. mussels, oysters, scallops, clams).

Cage culture

Culture of stocks in cages. Cages are rearing facilities enclosed on the bottom as well as on the sides by wooden, mesh or net screens. They allows natural water exchange through the lateral sides and in most cases below the cage.

Coastal aquaculture

The cultivation of aquatic organisms where the end product is raised in brackish and marine waters; earlier stages of the life cycle of these species may be spent in fresh waters or marine waters.

Cumulative energy demand

It represents the direct and indirect use of industrial energy required throughout the production process.

Dissolved oxygen

The amount of oxygen (mg/l O2) in solution in the water under existing atmospheric pressure, temperature and salinity. Sometimes also expressed as parts per million (ppm) or as percent of saturation level.

Ecological services

Benefits arising from the ecological functions of healthy ecosystems. Examples of ecological goods include clean air, and abundant fresh water. Examples of ecological services include purification of air and water, maintenance of biodiversity, decomposition of wastes, soil and vegetation generation and renewal, pollination of crops and natural vegetation, groundwater recharge through wetlands, seed dispersal, greenhouse gas mitigation, and aesthetically pleasing landscapes.

Ecosystem

A natural entity (or a system) with distinct structures and relationships that liaise biotic communities (of plants and animals) to each other and to their abiotic environment. The study of an ecosystem provides a methodological basis for complex synthesis between organisms and their environment.

Ecosystem approach to aquaculture

An ecosystem approach to aquaculture (EAA) strives to balance diverse societal objectives, by taking account of the knowledge and uncertainties of biotic, abiotic and human components of ecosystems including their interactions, flows and processes and applying an integrated approach to the sector within ecologically and operationally meaningful boundaries.

Eutrophication

Natural or artificial nutrient enrichment in a body of water, associated with extensive plankton blooms and subsequent reduction of dissolved oxygen. The Nutriphication Potential (NP) is set at 1 for phosphate (PO_4). Other emissions also influence eutrophication, notably nitrogen oxides and ammonium.

Fatty acid

Organic acid composed of carbon, hydrogen and oxygen that combines with glycerol to form fats.

Feed conversion ratio (FCR)

Ratio between the dry weight of feed fed and the weight of yield gain. Measure of the efficiency of conversion of feed to fish (e.g. FCR = 2.8 means that 2.8 kg of feed is needed to produce one kilogram of fish live weight).

Feedlot

Type of animal feeding operation, primarily used to finish large number of cattle in pens prior to slaughter. Feedlots are associated with both the provision of high energy feedstuffs and the generation of considerable amounts of high moisture content wastes.

Feedstuff

Any substance suitable for animal feed.

Fish oil

Oil extracted from total fish body or from fish waste. Fish oils are used in the manufacture of fish feeds, edible fats and industrial products.

Fishmeal

Protein-rich meal derived from processing (boiling, pressing, drying, grinding) whole fish (usually small pelagic fish or bycatch) as well as residues and by-products from fish processing plants (fish offal). Used mainly as agriculture feeds for domestic livestock (poultry, pigs, cattle, etc.) and as aquaculture feeds for carnivorous aquatic species. It must contain not more than 10 percent moisture. If it contains more than 3 percent salt (NaCl), the amount of salt must constitute a part of the brand name, provided that in no case must the salt content of this product exceed 7 percent.

Gastropods

A member of the largest class of phylum Mollusca. Characteristics generally include: a foot upon which the rest of the body (called the "visceral mass") sits, a well-developed head, a protective one-piece shell, and body "torsion" - where most of the visceral mass is normally twisted anticlockwise 180 degrees so that the back end of the animal is positioned over its head. The class includes the snails, slugs, sea hares, sea slugs, limpets, conches and abalone.

Inland aquaculture

Aquaculture that takes place in freshwater.

Life cycle analysis

Life Cycle Assessment (LCA) is a method developed to evaluate the mass balance of inputs and outputs of systems and to organize and convert those inputs and outputs into environmental themes or categories relative to resource use, human health and ecological areas.

Mollusk

Invertebrate animal belonging to the phylum Mollusca with a soft unsegmented body and covered by a calcium carbonate shell, of 1 to 8 parts or sections. In some species the shell is lacking or reduced. The surface is coated with mucus and cilia. Major cultured mollusks are mussels, oysters, scallops, cockles, clams (bivalves) and abalone (gastropod).

Nitrogen

An odorless, gaseous element that makes up 78 percent of the earth's atmosphere, and is a constituent of all living tissue. It is almost inert in its gaseous form.

Pelagic

Relating to living or occurring in open water areas of lakes or oceans.

Pen culture

Culture of stocks in pens. Pen is a fenced, netted structure fixed to the bottom substrate and allowing free water exchange; in the intertidal zone, it may be solid-walled; the bottom of the structure, however, is always formed by the natural bottom of the water body where it is built; usually coastal e.g. in shallow lagoons, but also inland e.g. in lakes, reservoirs. A pen generally encloses a relatively large volume of water.

Poikilothermic

Having a body temperature, which fluctuates with that of the environment.

Recirculating system

A closed or partially closed system employed in aquaculture production where the effluent water from the system is treated to enable its reuse.

Trash fish

Small fish species, damaged catch and juvenile fish are sometimes referred to as 'trash fish' because of its low market value. Usually part of a (shrimp) trawler's bycatch. Often it is discarded at sea although an increasing proportion is used as human food or as feed in aquaculture and livestock feed.

Zoonotic

Pertaining to a zoonosis: a disease that can be transmitted from animals to people or, more specifically, a disease that normally exists in animals but that can infect humans.

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