A GLOBAL ANALYSIS OF THE SUSTAINABILITY OF MARINE AQUACULTURE

by

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Abstract

Following a review of the history and main characteristics of mariculture, a global assessment of its sustainability over the 10 year period from 1994 to 2003 was performed, which suggests that sustainability is low. The assessment is based on 13 indicators covering ecological, economic and social aspects of the industry and involving 60 countries and 86 species. The suite of indicators were based on a set of criteria meant to be independent of areas, species and time, so that they have wide application and will be applicable for years to come.

The indicators used in the analyses proved to be effective in differentiating levels of sustainability between countries and species and provided a benchmark on which to gauge progress within the industry in the coming decades. A single mariculture sustainability index (MSI), ranging between 1 and 10, was derived by combining the 13 indicators weighted by production to analyze differences between countries and species, and to compare the MSI with other indicators such as the environmental sustainability index (ESI) and the human development index (HDI).

The highest ranking countries for sustainable mariculture are Germany, the Netherlands, Spain, Japan and South Korea. In these countries, the common factor is farming (1) native species, (2) low trophic level species, (3) under non-intensive conditions, (4) for domestic consumption. The lowest ranking countries were Guatemala, Cambodia, Bangladesh, Honduras and Myanmar. The common factor in these countries is the culture of (1) non-native species, (2) higher trophic level species, (3) farmed intensively, and (4) destined for export, often to countries ranking high for mariculture sustainability.

The highest ranking species on the sustainability scale were mollusks, specifically bivalves, *i.e.*, blue mussels and cupped oysters. For finfish, the highest ranking taxa were Atlantic halibut, Spotted wolfish and European eel. The lowest ranking species belonged to the crustacean groups, specifically prawns and shrimp. Many of the most valuable groups such as shrimp and salmon were among the lowest scoring species in both developing and developed countries.

The global average MSI score was 5.1 based on 361 cases. Based on this analyses, it is suggested that the industry is at the cross-roads of sustainability. There are a number of options for the industry to ensure it is sustainable over the long-term, including the implementation of best management practices, economic incentives and consumer awareness, expressed as a willingness to pay higher prices for sustainability.

The results of this study provide the framework, indicators and baseline data on which to assess the sustainability of mariculture at global and regional levels, as well as across species. The MSI developed in this study can be used to generate globally, robust rankings of countries and taxa in terms of their sustainability.

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Glossary

Aquaculture: The farming of aquatic organisms

Brackishculture: The farming of aquatic organisms in water with a salinity between 0.05 - $3^{o}/_{oo}$ (the farmed species often can also tolerate fresh and sea water).

First class protein: Also called 'complete protein', first class protein originate from animal sources, *e.g.* meat, fish, dairy, eggs. They have a full complement of essential amino acids, in proportions similar to those in human tissues.

Mariculture: The farming of marine organisms in water of, salinity above $3^{o}/_{oo}$.

Net protein utilization (NPU): The term used to describe the percentage of protein which is actually available to be assimilated. Eggs and human breast milk have the highest NPU ratings of all foods and are therefore classified as complete protein.

Sea ranching: releasing eggs, larvae or juveniles on structured habitat into the natural environment to increase the recruitment of marine fish. Sea ranching goes back to the 17th century with activities such as transplanting fish and construction of 'fish reefs' in Japan (Honma, 1993).

Second class protein (also; **incomplete protein**): These are vegetable proteins, derived from grains, nuts, pulses and seeds. They are considered as incomplete because they are low in one or more of the essential amino acids. These amino acids are called limiting amino acids because they reduce the NPU of that protein. To obtain the essential amino acids from vegetable proteins in suitable ratios, they need to be combined. For example, grains contain allot of tryptophan but not much lysine, whereas pulses contain a lot of lysine but not much tryptophan so by combining grains and pulses a good balance is achieved. Traditional vegetarian cuisines (*e.g.* Indian) achieve such balance, which modern vegetarian diets do not.

Acknowledgements

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Chapter 1

1.1. Introduction

The world's population continues to increase and the demand for food is increasing accordingly, and so is the demand for fish. However, there is still considerable inequity between the rich and poor with respect to the distribution, supply and consumption of food, including seafood, throughout the world. In 2004, only 2.3% of the world's food production originated from capture fisheries and aquaculture (FAO 2006). Although this is a small percentage of the global total, fisheries have been a traditional source of protein and an income generator for many developing countries. However, this situation is changing due to current demands for seafood by the developed world and the growing middle class in developing countries.

In the developed world, the increased demand for fish products is partly being driven by the demand for high quality seafood, the lowered prices for many seafood products due to improved technologies, low production costs, increased awareness of the benefits of a seafood-rich diet, and more competitive marketing. However, capture fisheries alone can not meet this demand. Indeed, the recent FAO State of Aquaculture Report (FAO 2006) highlights the growing importance of aquaculture in meeting the demand for fish for direct human consumption.

Two major questions need to be addressed when discussing the potential of aquaculture to meet an increasing demand for seafood: (i) will it risk the food security of developing countries; and (ii) can it be done sustainably? In fact, in 2003, *The Economist* dedicated a large section of the magazine to the question of how the 'Blue Revolution' might be able to supply society with fish whilst limiting impacts on the environment. Since 2003, global marine fish landings have recorded no increases and the dismal state of capture fisheries has not improved (Worm *et al.* 2006). Clearly, if the future demand for fish products is to be met, aquaculture will have to play an increasingly important role. However, *The Economist*'s question remains – how can this be achieved without negatively impacting the environment, and, more importantly, how can the aquaculture industry be developed so that (i) it is profitable, and (ii) benefits are equitably distributed throughout society? If these questions can be addressed, then the likelihood of aquaculture achieving long-term sustainability is high. This then raises the subsidiary question: how will we know when aquaculture has reached its sustainability goal? This last question is of great importance to the mariculture sector (farming marine organisms), as expansion of land-based facilities is fraught with issues surrounding: (i) limited freshwater availability; and (ii) conflicts with other important land uses such as urban development and agriculture. However, development of mariculture is associated with a number of positive and negative environmental and socio-economic impacts. Some of the latter issues include habitat alterations, lack of waste management, use of antibiotics, displacement of coastal fishers, and the marginalization of coastal communities. However, mariculture also creates job opportunities for economically depressed coastal communities (Alder and Watson 2007).

In the 1970s, aquaculture development was chiefly promoted as a means to address food security in the developing world. In response, various initiatives were implemented to develop the industry in Asia, Africa and Latin America. Over the last three decades, aquaculture has expanded significantly in Asia and in Latin America, but not in Africa. Much of this expansion has been in the development of high value and export-oriented species within the mariculture sector, which has not had the anticipated impact on food security, or improvement in the livelihoods of coastal communities. Indeed, many would argue that poor coastal communities in Asia and Africa have at best not gained from these developments, and at worst suffered from a reduction in food security and the loss of livelihoods.

A number of options exist to address the sustainability issues surrounding aquaculture, with some of them focused on mariculture. Examples include the FAO Code of Conduct for Responsible Fishing (FAO 1995), best management practices, technological advances (e.g. recirculation systems) and economic incentives (e.g., certification). Currently, there are a number of codes of conduct and protocols for improving the sustainability of aquaculture. Implementation of some of these options is underway in a number of countries, with differing levels of commitment, especially, in the developed world, e.g., in Europe and Australia. However, no certification schemes exist that allows one to determine whether the industry, especially, the mariculture sector, operates in a sustainable manner.

1.2. Research question and objectives

The central research questions of this thesis: are current mariculture practices sustainable at the global scale; and can countries and species be ranked according to their sustainability? In order to answer this, four subsidiary questions must first be addressed:

1. How is ecological, economic and social sustainability of the mariculture sector measured?
2. What are the best indicators to measure the impact the mariculture industry has on ecosystems and coastal communities?
3. Are data available to assess sustainability of the mariculture industry using the indicators identified in 2?
4. How reliable are these indicators in assessing the sustainability of mariculture at the global level?

1.3. Sustainable development and mariculture

In 1987, the Brundtland Report (WCED 1987) clearly put the notion of sustainable development on the world agenda. It also challenged government, industry and society to address issues related to declining environmental quality and natural resource capital to ensure that the opportunities of future generations would not be compromised. The report further notes that the pursuit of sustainable development requires:

- A political system that secures effective citizen participation in decision making;
- An economic system that is able to generate surpluses and technical knowledge on a self-reliant and sustained basis;
- A social system that provides solutions for tensions arising from disharmonious development;
- A production system that preserves the ecological basis for development;
- A technological system that can search continuously for new solutions;
- An international system that fosters sustainable patterns of trade and finance; and
- An administrative system that is flexible and has the capacity for self-correction.

The report generated a flurry of activities within governments, and amongst international agencies, to define and implement programs that would ensure sustainable development.

In 1988, FAO adopted and defined sustainable development, (i.e., by extension - sustainability) as:

> *"the management and conservation of the natural resource base, and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development must conserve land, water, plant and animal genetic resources, is environmentally non-degrading, technically appropriate, economically viable and socially acceptable"* (FAO 1988).

Since 1988, FAO has implemented a number of initiatives, including the FAO Code of Conduct for Responsible Fishing (FAO 1995), to address sustainability issues. However, few if any, initiatives included a systematic assessment of sustainability within the fisheries and aquaculture sector, or for a particular resource.

The activities and issues associated with the expansion of mariculture stand in mark contrast to the requirements for sustainable development. Many conservationists argue that mariculture does not conserve the natural resource base, since many farmed species are fed fish, habitats altered and coastal waters polluted (Naylor *et al.* 2000). While many investors in mariculture have succeeded economically, the coastal communities, which often depend on fish resources as their prime source of protein (Pauly and Alder 2005), especially in developing countries, have paid a steep price for this development. In some areas, their fisheries have been disrupted or they have been displaced. As a consequence, fishers and non-fishers often have not benefited economically from mariculture through increased direct employment opportunities such as post-harvest processing or other indirect opportunities such as shipping. These and other issues also raise the question of whether the industry will be able to satisfy the needs of future generations.

The rapid development of the mariculture sector and the expectation that help meet future increases in seafood consumption, implies a strong need to develop a conceptual framework on which to develop a set of indicators to monitor and evaluate the sustainability of the industry can be based.

1.4. Measuring sustainability

Existing sustainability indices include the Environmental Sustainability Index (Esty 2002), Index of Sustainable Economic Welfare (ISEW) and the Gini Index or HDI Human Development Index (UNDP 2006). These are based on a suite of indicators that measure and integrate a number of ecological, social and economic parameters. Despite a need to measure the overall sustainability of the aquaculture industry, no such index exists.

Ideally, a mariculture sustainability index (MSI) needs to incorporate indicators that have been chosen in consultation, preferably through a consensus building process, with stakeholders. Industry, government, conservation groups and civil society are key actors in defining and implementing these indicators. The process should be iterative, allowing all stakeholders to contribute to the development of the MSI and have a sense of ownership and commitment to using them. In such circumstances, the probability of the indicators being used for policy making, thus raising awareness of the need for better management and sustainable growth in the industry, is high. Undertaking such a process, was beyond the financial resources and outside of the time frame of this study. Hence, existing literature was used to guide the construction of a conceptual framework and a suite of indicators for measuring sustainability in the mariculture sector.

1.5. Thesis structure

Chapter 2 is a literature review that (i) outlines the evolution and history of aquaculture; (ii) places aquaculture in a global context and mariculture within this context; (iii) reviews the current range of marine culture systems and technologies; and (iv) highlights the challenges surrounding sustainable mariculture. The conceptual framework for developing a Mariculture Sustainability Index forms much of Chapter 3, which also identifies appropriate indicators that would constitute such an index, as well as data sources and methods to evaluate indicators themselves. Chapter 4 is an assessment of the sustainability of 361 mariculture cases spanning 60 countries and 86 species or species groups. The thesis concludes in Chapter 5, with a discussion of this assessment and the potential benefits of having industry and governments apply the indicators developed in Chapter 3. Finally, discuss areas for further research.

Chapter 2

2.1 History of aquaculture

According to FAO's definition of sustainability, the development of a set of indicators to assess whether or not aquaculture is sustainable requires an understanding of its development, current production status, and practices (Costa-Pierce 2002). Moreover, if indicators are to be relevant and practical the various culturing technologies, existing systems in place, trends in species cultured, the industry's potential environmental and socio-economic impacts, and the challenges associated with evolving into a sustainable sector must all be understood. This chapter reviews the development of the aquaculture sector from its earliest beginnings, thereby providing insights into the drivers of current aquaculture practices and technologies. The latter are also reviewed here. This chapter then presents the status and trend of global, major taxa and species production providing context for aquaculture within the broader realm of fisheries. The potential impacts of current practices, technologies and production levels are then discussed along with their implications and challenges with respect to sustainability in general and poverty and food security in particular.

Aquaculture as a source of food production for humans developed primarily in two geographic areas: Europe and the Mediterranean; and later in Asia, particularly China. Archaeological records have revealed that fish and shellfish have been important sources of food supplies. Early humans, *i.e.*, Cro-Magnon (25-10,000 BP) are known to have used fish hooks and nets. Some sites even suggest that they may have constructed primitive ponds that held fish, though it is unlikely that any direct care was provided. Nonetheless, this impoundment symbolizes the first stage of aquatic farming (McLean 2003). This "proto-aquaculture", that is, the precursor to aquaculture as we know it, was further developed by the Egyptians of dynastic times, circa 4000 BP (Fig 2.1). The importance of fish culture and the development of apparently drainable ponds, along with ornamental fish ponds, have been documented in illustrations from the tombs of pharaohs. Aktihep's burial place for example appears to show men removing tilapia from a fish pond (Basurco and Lovatelli 2004).

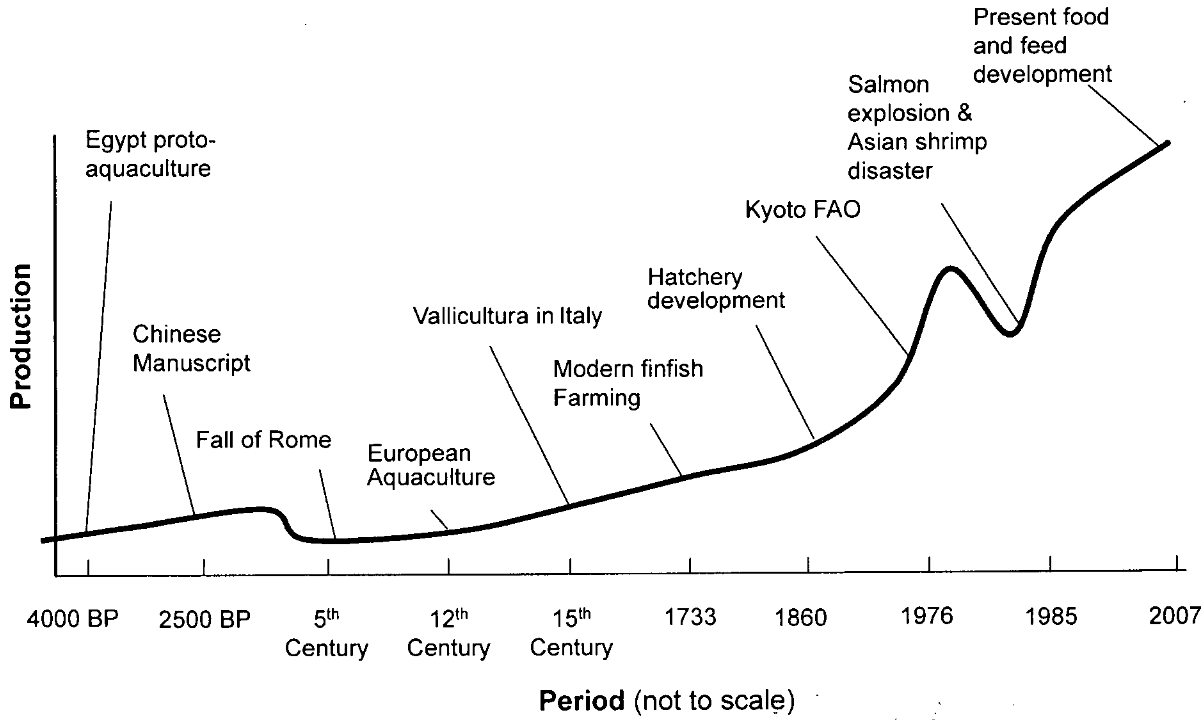

Figure 2.1 Conceptual overview of the historical growth of aquaculture from its earliest records to current and projected future growth.

2.1.1 Aquaculture in Asia (4000 BP to 2500 BP)

It is in Asia, especially in China around 4000 BP (Li and Mathias 1994), that we can best trace the origins of aquaculture. In the warm southern provinces, freshwater ponds were stocked with different species of carp, in conjunction with grazing livestock so that the ponds would be fertilized. This ancient practice, which creates a micro-ecosystem linking water, fish, and livestock through products and crops, is still in existence today, and is better known as 'integrated fish farming' (Lin 1991; Li and Mathias 1994). Fan-Li wrote the first extensive treatise on fish culture approximately 2500 BP (Li and Mathias 1994) . His text outlined the design and layout of fishponds, the breeding of fish and the rearing of fry, thus providing clear evidence of the technological development required to separate proto-aquaculture from aquaculture. Much of the information from the treatise is still used in Asia today.

2.1.2 Aquaculture in Asia in the 20th Century

Coastal countries such as Japan developed large-scale aquaculture to supply its population with fish and shellfish centuries ago. At the end of the 18th Century, Japan developed cage culturing to farm yellowtail (*Seriola quinqueradiata)* while trapping sardines and anchovies as bait in the same cages (Takashima and Arimoto 2000). More recently, Japan expanded marine finfish aquaculture to enhance some of its commercial fish stocks. It has become one of the main producers of farmed marine finfish in the world, with Yellowtail, Red sea bream, Coho salmon, Horse mackerel, Stripped jack, flatfish and pufferfish representing the main cultured species. Total production of farmed fish reached 250 000 tonnes worth 2.4 billion USD in 1997 (Takashima and Arimoto 2000). Other Asian nations invested primarily in crustacean species, in particular highly valued shrimps and prawns. In the 1990s, small but unique markets, such as the live reef food fish trade (LRFFT) developed in much of Southeast Asia and the Indo-Pacific region in countries such as Indonesia, Malaysia, Philippines, Thailand, Papua New Guinea and Australia. Targeted species mainly comprise groupers (Serranidae). Although sourced primarily from capture fisheries, mariculture is playing an increasing role in the production of these highly valuable fish (Sadovy and Cornish 2000).

2.1.3 Aquaculture in Europe, the Mediterranean & the Americas (2800 BP - World War II)

By 2800 BP, the Etruscans (in what is now Tuscany and surrounding areas of Italy) operated some of the earliest extensive marine farms in the Mediterranean (Kirk 1987). Molluskan (shellfish) culture was practiced in Ancient Greece *circa* 2500 BP. Around 2200 BP, at Baia, near Naples, Italy, the Romans were active in the culture of Seabass, Seabream, mullets and shellfish such as oysters (Kirk 1987). This is generally considered to be the first true sea ranching activity in Europe, and possibly worldwide; although recently uncovered records seem to indicate that clam terraces were used by native communities of the Northwest Pacific as early as at least 4000 years BP (Harper *et al.* 2002).

The Romans spread mariculture throughout coastal Europe (Ravagnan 1975; Pellizzato 1978). However, with the fall of the Western Roman Empire by *circa* 476 AD, aquaculture and mariculture activities soon diminished and arguably disappeared from Europe altogether. It is not until the 12th century AD, that records indicate the re-emergence of freshwater aquaculture in central Europe. By the 15th century, large scale lagoon mariculture, referred to as 'vallicoltura', developed in the northern Adriatic (Ravagnan 1975). Growth of aquaculture and vallicoltura, such as that found in the Venice lagoon (Ghetti 1999), throughout the region might have been correlated with the role and influence of the Roman Catholic Church. Indeed, religious injunctions prohibiting the consumption of meat on Fridays led to increases in the demand for year-round fish supplies.

Centuries later, new foods (including fish) were introduced to the Americas by European colonists. Salmonid species were the most popular fish to be stocked where water conditions were suitable (Soto and Norambuena 2004). At the turn of the 20th century, advances in European aquaculture techniques and practices led to the development of what is know today as "modern" aquaculture. These practices were first developed for freshwater salmonid cultures in 18th century Denmark and Germany (H. Rosenthal, Institute of Marine Research, Kiel, 2004 pers. comm.). Soon thereafter these techniques spread throughout Western Europe, finding application also in the marine realm, through the culture of species such as modern Atlantic salmon and shellfish. The development of hatcheries and hatchery science allowed for the further evolution of salmonid and shellfish culturing and the associated growth in their production and value. Technological breakthroughs in the fields of breeding and larval culture, along with major progress in supplement feeding and feed manufacturing and engineering, further facilitated this evolution and expansion. Similar culturing techniques are now commonly used throughout a wide-ranging list of species such as shrimps and tilapia (Fitzsimmons 2000).

2.1.4 Globalization (Post World War II to present)

The technological developments in Europe outlined above quickly spread worldwide and were quickly implemented throughout Asia in countries such as the Philippines, Indonesia, Cambodia, Vietnam and more importantly China, where the bulk of contemporary production lies. Economic pressures from the World Bank and the UN among others (Kent 1995), may have in part been responsible for the rapid transition and expansion of aquaculture from traditional culturing systems to modern European based methods (Bardach 1997). This shift saw traditional low impact, low-yield, but historically sustainable production systems, being replaced by high-yield, intensive operations. The change of culture methods and the incorporating of western techniques shaped 1970s aquaculture baseline, marking a new development of intensive aquaculture, which has continued to the present. In the late 1970s, mariculture was also expanding in developed countries through a change from traditional extensive bivalve cultures to high-value species, specifically carnivorous finfish species (*e.g.* groupers) which were, and still are, caught as part of the capture fishery sector.

Flow-through and recirculation (re-circulating and recycling) culture systems, developed as a consequence of the expansion from extensive to intensive farming systems, based on the concepts developed in earlier stages of aquaculture production, as discussed above (Rosenthal 1985)

Advances in diet formulation and supplementation, such as improved industrial animal feed production systems (Tacon 1998) created the impetus for expanding the industry internationally. Expansion was targeted to the developing world, where labour is often cheaper, resources such as land and marine areas are more readily available, and in some countries, financial incentives for such developments provided (Alder and Watson 2007). Establishing modern aquaculture systems in developing countries, however, can be costly, concentrating wealth, as well as dramatically changing traditional methods of fish and shellfish culture (Pillay 2001; Goldburg and Naylor 2005)

The repercussions of these changes through all types of cultures and societies are still perplexing today. The benefits of transforming traditional aquaculture systems into modern intensive systems are still debated in terms of meeting the food security demands of an ever increasing local and global population (Tacon 1998: Kent 1995).

The 1976 Kyoto Technical Conference on Aquaculture was not only the first conference of its kind to be held, it also marked the beginning of a new era. Supported by the FAO and UNDP, the conference adopted the "Kyoto Declaration on Aquaculture", which identified the various forms of aquaculture production worldwide, and gave the catalyst to the potential for developing it into a major industry, providing the means of revitalizing rural life along with the possibility of supplying products of high nutritional value (Pillay 2001). The "Action Plan" agreed in conference is as follows:

- That aquaculture has made encouraging progress in the past decade, producing significant quantities of food, income and employment; that realistic estimates place future yields of food at twice the present level in ten years, and five times the present level in thirty years, if adequate support is provided;
- That aquaculture, imaginatively planned and intelligently applied, provides a means of revitalizing rural life and supplying products of high nutritional value, and that aquaculture, in its various forms, can be practiced in most countries, coastal and landlocked, developed and developing;
- That aquaculture has a unique potential contribution to make to the enhancement and maintenance of wild aquatic stocks and thereby to the improvement of capture fisheries, both commercial and recreational;
- That aquaculture forms an efficient means of recycling and upgrading low-grade food materials and waste products into high-grade protein-rich food;
- That aquaculture can, in many circumstances, be combined with agriculture and animal husbandry to the mutual advantage of both sectors, and contribute substantially to integrated rural development;
- That aquaculture provides intellectual challenge to skilled professionals of many disciplines, and a rewarding activity for farmers and other workers at many levels of skill and education;
- That aquaculture provides now, and will continue to provide, options for sound investment of money, materials, labour and skills;
- That aquaculture merits the fullest possible support and attention by national authorities for integration into comprehensive renewable resource, energy, and land and water use policies and programs, and for ensuring that the natural resources on which it is based are enhanced and not impaired;

- That aquaculture could benefit greatly from support and assistance from international agencies, which should include the transfer of technology, actively planned and executed, with research carried out in centres representative of the various regions concerned.

In response to the action plan presented in Kyoto in 1976, and with the help of FAO and UNDP, networks were created around the world, to coordinate and integrate the proposed ongoing multidisciplinary activities and research in developing regions. In Asia for instance, the Network of Aquaculture Centres in Asia-Pacific (NACA) was formed, with China, India, Thailand and the Philippines as major regional centres of research and specialization with regards to that region's particular requirements. Similar regional networks were established in, Africa and Latin America. The African lead centre was established in Nigeria and the Latin American lead centre in Brazil.

Twenty-five years later, the need for a similar conference was recognized, and the 2000 Conference on Aquaculture in the Third Millennium in Bangkok was held to review the progress made since the Kyoto conference and discuss the future of aquaculture (Silpachai 2001). The Bangkok Conference strengthened the 1976 Kyoto Declaration and further emphasized the role of aquaculture in alleviating rural poverty and improving livelihoods and food security, while maintaining the integrity of biological resources and the sustainability of the environment. Many countries adopted the Bangkok Declaration and Strategy on Aquaculture Development Beyond 2000 to guide policy makers and industry on the sustainable development of this industry.

2.2 Aquaculture status and trends

2.2.1 Global trends

Aquaculture has grown rather fast, with an average annual percent growth rate of 8 to 9% since the late 1980s (Tacon 1998, 2001; Pullin and Sumaila 2005; FAO 2004) (Table 2.1). There were few areas left in the world without some form of aquaculture, including mariculture (Figure 2.2).

Table 2.1. Aquaculture species groups in 2003, their respective percentage composition. Based on FAO 2004 statistics. (F: freshwater; B; brackish water; M: mariculture).

Group	Environment.	2000 (million t)	2003 (million t)	Annual growth rate %	Contribution (in %; 2003)
Finfish	F+B+M	22.7	27.1	5.8	49.3
	B+M	2.9	3.6	9.8	-
Mollusks	F+B+M	-	-	-	-
	B+M	10.7	12.3	4.9	22.5
Aquatic plants	F+B+M	-	-	-	-
	B+M	10.2	12.5	6.7	22.8
Crustaceans	F+B+M	1.8	2.8	16.7	5.1
	B+M	1.3	2.1	15.1	-
Other	F+B+M	0.14	0.17	7.1	0.3
	B+M	-	-	-14.0	-

The trend appears to continue in the 2000s; with total production surpassing 50 million tonnes (million t) for the first time in 2000 and by 2003, reaching approximately 55 million t valued at 67.3 thousand million USD (Figure 2.3).

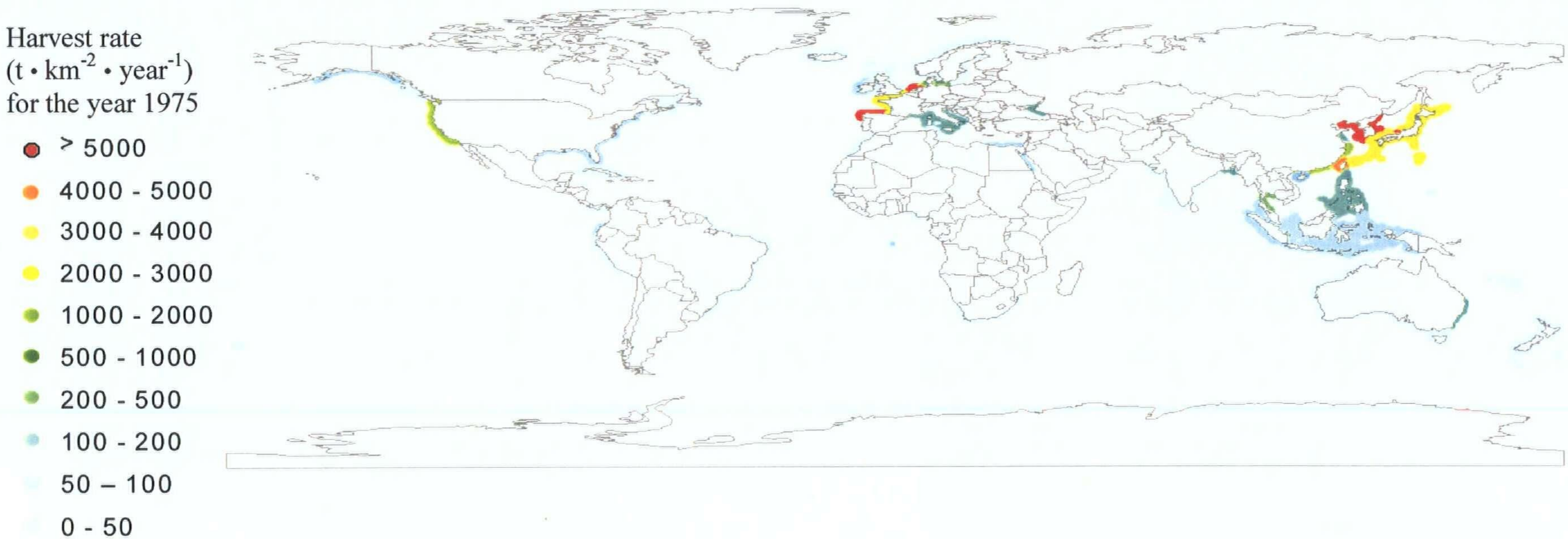

Fig 2.2a Global mariculture production in 1975. Map courtesy of Dr Reg Watson (Sea Around Us Project, Fisheries Centre, UBC, July 2007, pers. comm.).

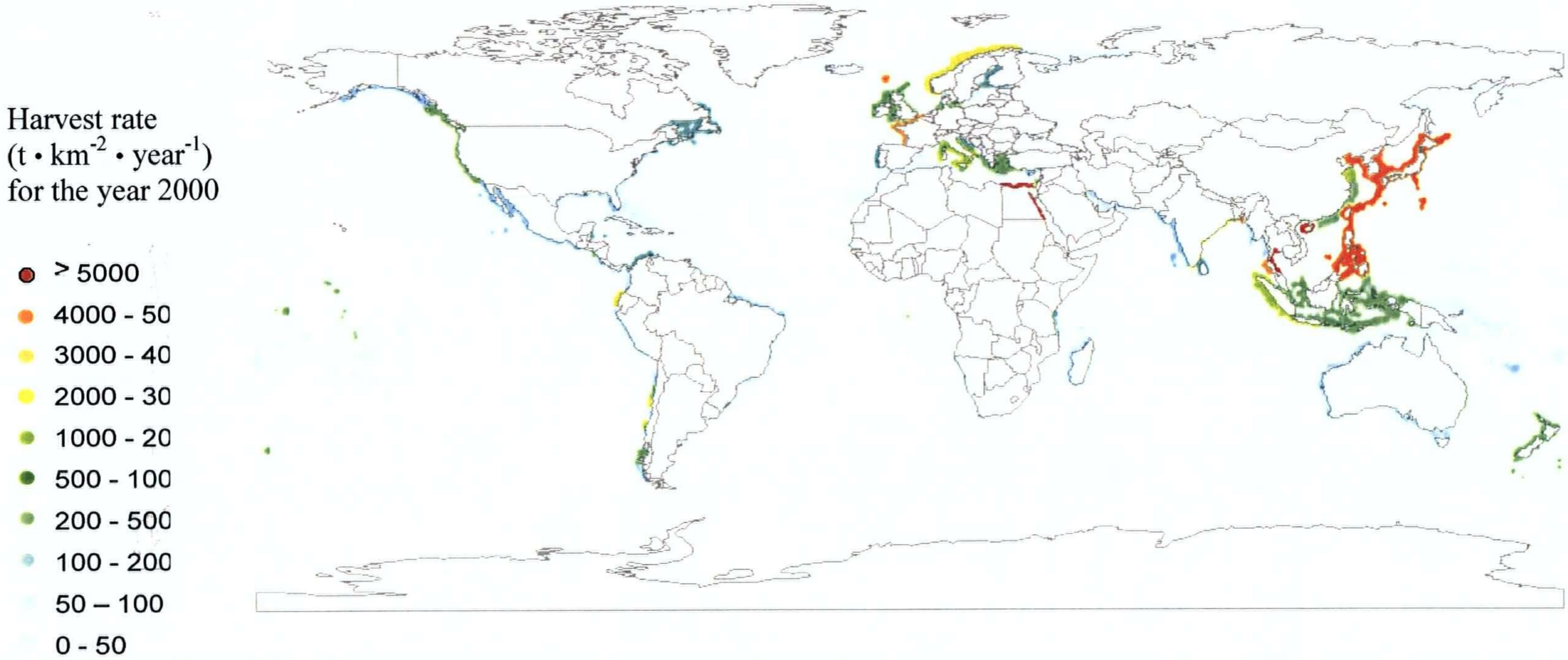

Fig 2.2b Global mariculture production in 2000. Map courtesy of Dr Reg Watson (Sea Around Us Project, Fisheries Centre, UBC, July 2007, pers. comm.).

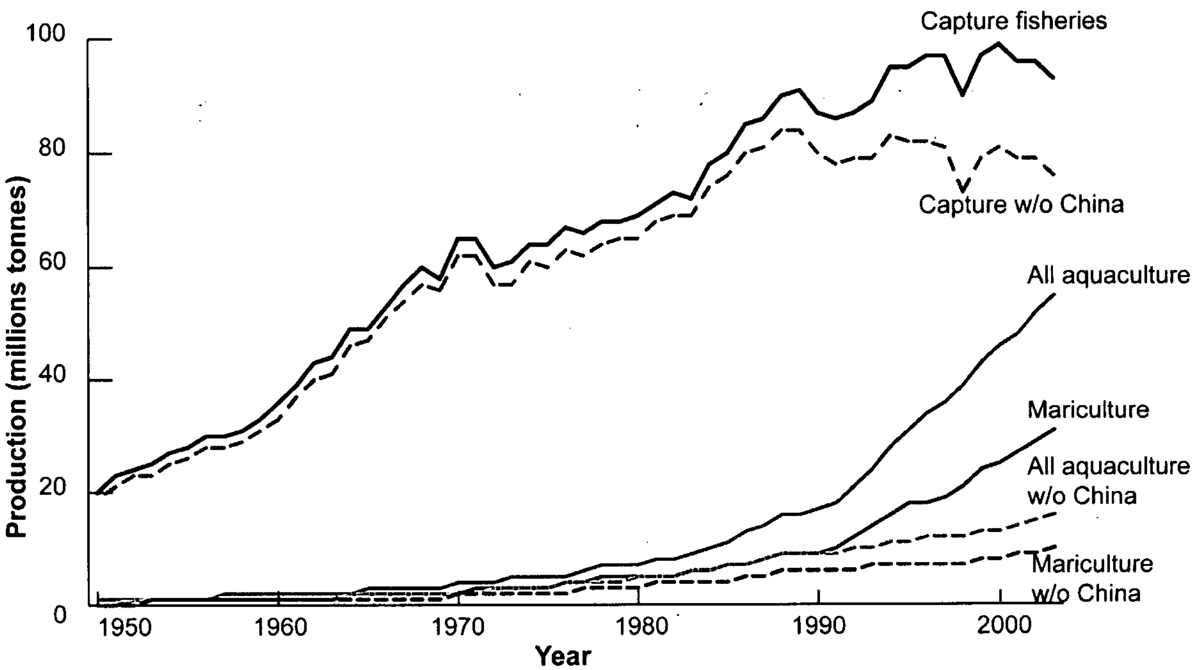

Figure 2.3. Trends in aquaculture production and marine fisheries landings (1950-2004) with and without Chinese data (FAO 2004)

Nevertheless, as for the period 2000-2003, the rate of growth has decreased slightly, to an average of 6.2% (FAO 2004). In comparison, livestock meat production has been growing at around 3% per year and the output from capture fisheries has reversed to -3% over the same period (FAO 2004). Mariculture and brackish water aquaculture (brackish culture) have shown similar trends (Table 2.2).

Table 2.2 Average annual growth rate percentage for the period 1950-2003 (F: freshwater; B; brackish water; M: mariculture).

Environmental Component	1950-59	1960-69	1970-79	1980-89	1990-99	2000-03
World Aquaculture	13.2	5.6	7.6	9.4	10.1	6.2
World Aquaculture minus China	7.2	6.4	8.2	7.7	3.9	5.7
M + B	11.5	7.9	8.5	7.3	9.9	6.7
M + B minus China	7.9	6.3	8.5	7.2	2.9	5.8
M + B minus algae	9.1	5.1	6.6	8.8	9.7	5.5
M + B minus (China + algae)	7.3	5.2	6.0	5.9	5.2	6.7
F minus (China + algae)	6.1	6.9	7.6	8.9	5.6	5.6
China F minus algae	30.3	0.5	4.2	17.9	13.2	5.7
China M + B minus algae	45.3	5.4	10.8	17.4	16.9	6.8

Global aquaculture production broken down by environmental components (with and without Chinese data) has fallen from an average annual growth rate of 10% to 7%. On the other hand, if we disregard the Chinese production and aquatic plant data, we find that by 2003, the mariculture sector (including brackish culture) has increased, from an average annual growth rate of approximately 5% to 7%. More so, the annual growth rate was above 11% from 2002 to 2003.

The major farmed taxonomic groups for 2003 and their respective mariculture components are finfish, which comprises nearly half of the total aquaculture production, with 27.1 million t (in marine, brackish and freshwater) or 49.3% of total production, followed by aquatic plants and mollusks (mostly marine and brackish water), with 12.5 (22.5%) and 12.3 million t (22.8%) respectively, which together account for 45% of total aquaculture production (Table 2.1). The remaining 5% consists of crustaceans, with 2.8 million t, but with the highest proportional growth among all sectors, i.e., an average annual growth rate 16.7 % (Table 2.1).

2.2.2 Production by major taxa

Prior to the rapid expansion of aquaculture in the 1970s, many taxa were farmed (around 100 species), but very few dominated the aquaculture sector - with the exception of carp and certain aquatic plants, which have a long history of culturing in Asia. Since 1970, there have been introductions of new fish and invertebrate species, which increased the number of cultured species to over 150 by the early 2000s. In 2004, almost 60 million t of aquaculture products worth over 70 billion USD were produced. Asia accounted for 92% of all production, and 80 % of its value. China alone accounted for 70% of the world's production, and 51% of its value. However, only 10 species (Table 2.3) now dominate the sector, and account for 75% of the total production and over half of total value (FAO 2004).

These 10 dominant species include eight of the traditional aquatic plants cultured in Asia. The remaining two species, Whiteleg shrimp (*Litopenaeus vannamei*) and Atlantic salmon (*Salmo salar*), are recent developments (since the 1980s). Whiteleg shrimp developed in tropical Asia as a substitute to *Penaeus* sp. and Blue shrimp species, which were disease affected in the 1980s and early 1990's (Pillay 2001). Salmon farming developed to meet the demand for high value fish in North America, Europe and Japan. Nine of these 10 species have recently gained in importance relative to other species, because of (1) a growing Asian population, (2) increasing incomes in Asia, and (3) the ease in which the new technologies and practices can be incorporated or totally replace traditional culture methods and species. In Asia, many of these species are now cultured for local and export markets, making the development of an industry for these farmed species financially profitable.

The recent development of shrimp aquaculture in Latin America has been possible due to the availability of investment capital from multi-national fish farming companies and the further development of efficient technologies and practices (McClennen 2004). Salmon has also gained in importance in response to the ever-growing demand for high-value and high-quality fish. The industry was able to capitalize on the long history of trout farming in Europe and North America to quickly develop the hatchery and rearing practices needed to provide consistent volume and high-quality products each year that can be sold at an affordable price to many consumers (Bardach 1997)

Table 2.3. Top 40 marine and brackish species and species groups produced (**Prod.** thousand tonnes) in the years 2000-2003 and their percentage make-up of global production (**M**: marine; **Br**: Brackish), (nei = not elsewhere included).

Rank	Species/sp. group	Species	M	Br	Prod.	% total
1	Aquatic plants nei	-	x	x	4900	17.25
2	Japanese kelp	*Undaria pinnatifida*	x		4600	16.17
3	Pacific cupped oyster	*Crassostrea gigas*	x		4400	15.33
4	Japanese carpet shell	*Ruditapes philippinarum*	x		2600	9.12
5	Laver (Nori)	*Porphyra* sp.	x		1300	4.41
6	Marine mollusks nei	-	x		1200	4.32
7	Yesso scallop	*Patinopecten yessoensis*	x		1200	4.05
8	Atlantic salmon	*Salmo salar*	x	x	1100	3.96
9	Zanzibar weed	*Eucheuma cottonii*	x	x	880	3.08
10	Whiteleg shrimp	*Litopenaeus vannamei*	x	x	720	2.54
11	Sea mussels nei	*Mytilus* sp.	x		680	2.39
12	Giant tiger prawn	*Penaeus monodon*	x	x	670	2.33
13	Milkfish	*Chanos chanos*	x	x	490	1.70
14	Blue mussel	*Mytilis edulis*	x		470	1.66
15	Blood cockle	*Anadara* sp.	x		430	1.51
16	Chinese river crab	*Eriocheir sinensis*		x	370	1.29
17	Wakame nei	*Undaria* sp.	x		260	0.90
18	Marine fishes nei	-	x	x	210	0.87
19	Rainbow trout	*Oncorhynchus mykiss*	x	x	210	0.74
20	Fleshy prawn	*Penaeus chinensis*	x		200	0.72
21	Marine crabs nei	-	x	x	170	0.68
22	Mediterranean mussel	*Mytilus galloprovincialis*	x		150	0.59
23	Flathead grey mullet	*Mugil cephalus*	x	x	140	0.52
24	Marine crustaceans nei	-	x	x	120	0.51
25	Green mussel	*Perna viridis*	x		110	0.41
26	Coho (=Silver) salmon	*Oncorhynchus kisutch*	x	x	110	0.40
27	Gracilaria seaweeds	*Gracilaria* sp.	x	x	100	0.37
28	Gilthead seabream	*Sparus auratus*	x		89	0.35
29	Banana prawn	*Penaeus merguiensis*	x	x	79	0.31
30	Percoids nei	Percoidea	x		78	0.28
31	Penaeus shrimps nei	*Penaeus* sp.	x	x	78	0.27
32	European seabass	*Dicentrarchus labrax*	x		50	0.27
33	Flatfishes nei	Peluronectiformes	x		42	0.18
34	Indian white prawn	*Fenneropenaeus indicus*	x	x	32	0.15
35	Chum (=Keta=Dog) salmon	*Oncorhynchus keta*	x		22	0.11
36	Cupped oysters nei	*Crassostrea gigas*	x		22	0.08
37	Tilapias nei	*Oreochromis* sp.		x	21	0.08
38	Kuruma prawn	*Penaeus japonicus*	x	x	2.4	0.07
39	Blue shrimp	*Penaeus stylirostris*	x	x	2.3	0.01
40	Whiteleg shrimp	*Litopenaeus vannamei*	x	x	1.1	0.01

The remaining 144 taxa are still important because their volumes are high (most are produced in excess of 100,000 tonnes) with many species traded globally for human consumption, pharmaceutical processing and other industrial uses. Taxa that are not traded globally are still important domestically, as they are a source of food and income generation for coastal communities. These 144 taxa also have the potential to gain in importance depending on industry investment, consumer preferences and environmental requirements.

The monetary value of mariculture species are headed by finfish valued at 240 billion dollars in 2000, which increased to a value of 260 billion by 2003, with the top groups consisting of salmonids, tilapias, jacks and mullets. Decapods (crayfish, prawns and shrimp) comprise 90% of the total farmed crustaceans' value of 37 billion USD in 2003, with leading species such as Whiteleg shrimp, Fleshy prawn, Giant tiger prawns, Banana prawn, Indian white prawn and Kuruma prawn.

Finfish recent and rapid expansion

Marine aquaculture of finfish has become more intensive over the last 15 years (Table 2.4), due mainly to the introduction of new technologies, the development of suitable sites, improvements in feed technology, an improved understanding of the biology of farmed species, the ability to increase water quality within farming systems and the increased demand for fish products (Divanach *et al.* 1996). It is now widely acknowledged that this intensive development of the finfish culture industry has been accompanied by an increase of its environmental impacts, such as disease transfer to wild fish, water quality and waste accumulation to name a few (Bardach 1997; Ervik *et al.* 1997). In the mid-nineties, in Germany, a threshold of 20 tonnes • year^{-1} was set for differentiating between major polluting aquaculture facilities, requiring a license for stock intensive productions, and less polluting facilities. In this context, the sustainability of intensive mariculture, including finfish aquaculture, has been questioned (Barg 1992; Suvapepun 1994; Naylor *et al.* 2000).

Table 2.4. Main finfish sub-groups and their annual growth rate (in %) based on production trends by decade. Based on FAO (2004) and Tacon (2001).

Taxa	1950-59	1960-69	1970-79	1980-89	1990-99	2000-03
Bass	-	-	247.9	43.4	42.9	9.1
Breams	30.4	0.6	6.8	14.6	12.8	4.4
Carp	18.6	1.8	5.5	14.1	11	3.7
Catfish	7.1	16.5	17.8	19.8	5.9	7.2
Flatfish	-	-	-	386.6	24.5	40.1
Jack/Mullet	3.5	31.7	16.9	0.9	1.9	12.1
Salmonids	12.4	13	7.8	13.3	11.2	7.3
Scombrids	-	-	-	46.4	234.6	16
Tilapia	13.7	3.7	15.5	13.4	12.3	10.9
Other fish	7.3	4.6	5.1	9	8.5	11.5
Total finfish	14.5	3	6.3	12.4	10.4	5.8

Fish, whether farmed or from capture fisheries, is an excellent source of high quality protein, which contains as much as 60% first class protein on a dry matter basis (Tacon 2001). It is also rich in vitamins, and contains variable quantities of fat, calcium, phosphorus and other nutrients important to human health and growth. Fish, in many ways, is even more nutritious than the meat from most warm-blooded animals. Nutrition experts have long agreed that fish with the addition of a variety of vegetable products, constitutes a completely balanced diet (Lossonczy *et al.* 1978). The improved understanding of the nutritional value of fish, in particular the Omega-3 fatty acids and their role in a healthy diet has increased the perceived value of fish in Europe and North American (industrialized) nations. This has led to a growing demand for fish (farmed and wild). The downside to eating fish is the risk caused by persistent organic pollutants (e.g. PCBs), heavy metals (e.g. mercury), present in both capture and farmed fish, residual antibiotics and synthetic carotenoids, the last two all too frequent in farmed fish.

The value of finfish (both ex-vessel and farm gate) is generally increasing, although at certain times, periods of over supply may cause prices to plummet. Aquaculture also has potential for increasing socio-economic benefits through developing farmed finfish initiatives, and generating employment opportunities in the harvest and postharvest sectors, as seen in the development of salmon farming. The key to socio-economic sustainability of the aquaculture sector is to ensure that benefits are distributed as widely and equitably as possible.

In some regions of the world and for a few species, large multi-national corporations, often subsidized by governments, dominate finfish aquaculture. An example of this is in the USA where catfish growers control the domestic market through their influence on US imports of potential competitors (Cherry 2006). In Chile, the government regulates fishing and environmental laws to benefit the salmon industry (Ibáñez and Pizarro 2002). When large multi-national corporations dominate the aquaculture sector, social issues emerge: the number of workers declines, employment concentrates in few areas, jobs become seasonal; there is no job security and wages are low, as is the case for salmon farming in Chile (Ibáñez and Pizarro 2002; Neira and Diaz 2005).

Crustaceans

Marine and brackish water decapods (shrimps and prawns) make up the major part of the world crustacean farming (Table 2.5), and Southeast Asia is the leading region. Overall, crustaceans now make close to one-fourth of the aquaculture crop in the world, and are mostly produced in the developing world, and in coastal areas. However, in many areas, this development occurred at great cost to coastal ecosystems and surrounding social communities, notably through habitat conversion and redistribution of wealth (Perez *et al.* 2000).

Table 2.5 Average growth rate (in %) in production of major crustacean sub-groups.

Taxa	1950-59	1960-69	1970-79	1980-89	1990-99	2000-03
Crab	7.9	-0.2	26.3	16.7	45.7	18.6
Shrimp	16.9	16.1	23.6	25.6	6.2	15.6
Other Crustaceans	-	21.2	34.5	26.0	26.5	43.7
Total Crustaceans	12.5	13.3	23.2	25.3	8.3	16.7

The annual percent growth rate of the shrimp farming sector has been significantly higher than other mariculture production sectors. In terms of growth, shrimp production had decreased to more modest levels during the 1990s (averaging 5%), relative to the double-digit growth rates observed during the 1970s (23%) and 1980s (25%). However, by 2000, the annual growth rate once again reached double digit form, averaging (17%) and is discussed below.

Since the 1980s, a great deal of attention has been paid to the emergence of high-value, export-oriented aquaculture crops in developing countries (Naylor *et al.* 2000; Tacon 2001). Modern shrimp culture is a classic example of such a crop. This sector, which relies on intensive, mono-culture stocking, mechanized water exchange, antibiotics and processed feeds, has become a major source of export earnings for a number of countries in Southeast Asia and Latin America (FAO 2004).

Shrimp farming has also emerged as a main source of employment and income for hundreds of thousands of people in Asia. Employment and income is generated in production, associated service and supply industries, such as feed mills, ice plants, drug and chemical suppliers, as well as in shrimp trading, processing and distribution, including retailing and exporting. In recent years, global prices for shrimp have been declining (FAO 2004), but returns from shrimp farming have until very recently continued to be considered high compared to other aquaculture and agricultural crop options.

The livelihoods of many small-scale farmers and communities in coastal Asia are still connected to the shrimp industry in various ways, e.g. supplying broodstock, catching larvae, etc. Most shrimp farming in Asia is still done by small-scale farmers owning less than 5 ha of land in rural coastal areas (Hall 2004). Therefore, it continues to play an important role in the economic well-being of coastal communities. However, with overproduction, dropping prices and issues of anti-dumping in major importing countries, its economic sustainability is questioned. Because earnings from the production, export and trade of shrimp products are so important, the expansion of shrimp farming continues in both Asia and Latin America. There is also an emerging interest in Africa, where there has been relatively limited shrimp farm development to date (Moehl and Machena 2000). The lessons learned in Southeast Asia and Latin-America should provide ample information to plan for a more sustainable sector in Africa.

Until recently most studies have either treated shrimp farming as a global activity, blurring distinctions between and within countries, or else taken up its development in one region and generalizing trends in production and management practices globally. Hall (2004) noticed that variation between or within countries has received little analysis. Such analyses will be useful in finding broad approaches to improving sustainability in this industry.

The response to the growth of shrimp farming has raised controversy in both shrimp producing and shrimp importing countries. Public opinion in importing countries, and in certain exporting countries, is being influenced by concerns over environmental impacts such as ecological consequences of mangrove conversion to shrimp ponds; salinization of groundwater and agricultural land; pollution of coastal waters from pond effluents; use of fish meal and oils in shrimp feeds and biodiversity issues that arise from the collection of wild shrimp seed (Ling *et al.* 1999). More recently the introduction and spread of exotic species such as *Litopenaeus vannamei* to Asia and other species including associated pathogens has also emerged as an issue for sustainability of this industry.

The social impacts of shrimp culture, include food security issues such as the diversion of local food resources for export, general conflicts with other stakeholders and concentration of the industry in the hands of a few entrepreneurs. These impacts combined with pollution and subsequent disease outbreaks are symptoms common to rapid shrimp expansion and poor site selection. These general failures in managing development and farm design have created considerable debate regarding the long-term sustainability of shrimp farming practices (Naylor *et al.* 1998).

Mollusks

Bivalve mollusks, e.g. gastropods; snails and bivalves; clams, mussels and oysters are good sources of inexpensive, and high quality protein. More than half of the world's mollusk production comes from aquaculture, which has for the most part been steady at around 23% of total aquaculture production (Table 2.6) for the past 5 years (FAO 2004). Cultured bivalves lead the world in weight of products.

Table 2.6 Average percent growth (in %) of production for major mollusk sub-groups (FAO 2004).

Taxa	1950-59	1960-69	1970-79	1980-89	1990-99	2000-03
Clams	6.6	17.7	11.7	11.1	17.3	8.5
Mussels	7.8	9.7	6.9	6.1	3.2	2.5
Oysters	10.2	2.8	4.0	4.4	12.1	4.8
Scallops	-	-	-	24.0	14.9	5.9
Other mollusks	17.3	10.1	27.2	23.9	26.8	0.7
Total mollusks	9.4	5.2	6.0	7.4	11.6	4.9

About 50% of the world-wide mussel harvest comes from Europe, with the main yield of Atlantic mussels coming from Spain, the Netherlands and Denmark, while the Mediterranean production predominantly comes from Italy. Production in these traditional areas has stabilized since the 1970s, and Europe's share of the world production has decreased due to increased production outside Europe, i.e., in Chile and Peru (O'Sullivan 2006). Mussel production is based on extensive operations and depends for the most part on natural resources for food, spat and space. In the main European culturing areas, production using existing techniques seems to have reached carrying capacity (FAO 2004).

Plants and Algae

FAO 2004 statistics, on aquatic plant mariculture, ranks plants first among total production worldwide with 12.5 million t in marine and brackish water (Table 2.1), with 99% of this production in China. Most of these locally consumed aquatic plants, which supply wholesale markets, are commonly produced in integrated culturing systems across southern Asia (Alveal *et al.* 1995). Plants such as water spinach and water mimosa are commonly grown and require limited knowledge of production techniques and preparation methods for marketing. Abundant nutrients are needed, however, to support the rapid growth of these plants. An ingenious traditional method for using wastewater and in the context of a reuse system, integrated with the farming facilities, is often used (Alveal *et al.* 1995).

2.2.3 Production by species

In 2003, 337 different farmed species and species groups were reported to FAO for statistical purposes. Of these, 76 were 'unspecified' groups, which is equivalent to 12.0 million t or 21.9% of total aquaculture production (Table 2.3). Production reported at species level consists of 242 species, of which more than 60% (158 species) are produced in marine and brackish water culture. This includes 70 finfish species, 54 mollusk species, 19 crustacean species, 13 plant species, and 2 'miscellaneous' species (FAO 2004).

2.2.4 Undefined groups (aka nei)

The non-specified groups most of which refer to groups "not elsewhere included" (nei) range from genera such as abalones (*Haliotis* spp) to classes such as in "Marine fish nei" and phyla "Invertebrates nei" (FAO 2004). It is imperative that, for any comprehensive sustainability assessment of aquaculture, information on these groups should be better resolved.

Throughout the FAO reported period of 1950-2003, there have been 95 different non-specific associations when a reporting country, at one point or another, had not provided sufficient statistical information. Some of these undefined groups have disappeared, but more have been added throughout this period as new species move from development stages into production stages. Nine of these, which comprise larger more general taxa, are more or less permanent (marine finfish nei, invertebrates nei, etc.); furthermore the total amount of nei groups has increased to over 21% of all reported aquaculture production (Table 2.7).

Table 2.7: Trends in production (million t) and percentage of total production from aquaculture of 'not elsewhere included' (nei) groups from 1970 to 2003.

	1970	1980	1990	2000	2003
Number of nei groups	29	34	62	78	77
Production (million t)	0.29	0.64	2.29	8.83	12.0
% of total aquaculture	8.1	8.8	13.6	19.3	21.9

Based on FAO (2004), China seems to have reported in 2003, for the first time its finfish mariculture production not exclusively as 'marine finfish nei', but as consisting of three species of marine finfish (Cobia, Large yellow croaker and Red drum). However, instead of one single large 'nei group', China now has 6 new aggregated 'nei' species groups (Amberjacks nei, Flatfish nei, Groupers nei, Percoids nei, Porgies/Seabreams nei and Puffers nei). More importantly, China reported a decline in finfish mariculture for the first time since 1984. Whether this decline is coincidental with China's new 2003 reporting classification or that the limited availability of new marine areas for expanding marine culture, having reached maximum levels, and the fact that China's policies are increasingly shifting towards imports (China is now the largest importer of fishmeal in the world), is unclear. Since China is the largest producer of aquaculture (including mariculture), any improvement of the Chinese aquaculture statistics will impact on global assessments of aquaculture sustainability.

2.2.5 Culturing environments

Aquaculture has developed in the three primary water environments: freshwater, brackish and marine. Based on FAO (2004), by 2003 global freshwater aquaculture production topped 24.2 million t or 44.2% of total aquaculture production, while mariculture makes up 27.7 million t or 50.6 %. Lastly, brackish culture was 2.9 million t or 5.2% of total aquaculture production (FAO 2004). While freshwater production may represent 40% of total global aquaculture, this is centered mainly in China, and is focused on three main finfish groups, (i.e., catfish, carp and tilapia species), a wider array of invertebrates (mainly mollusks such as freshwater clams and snails) and aquatic plants such as water lettuce, etc. Since I focus on a global assessment of mariculture, freshwater aquaculture is not discussed further.

Brackish

Brackish water culture showed the highest growth in 2003, with an annual percent growth rate of 18.2% (Table 2.8), followed by mariculture and freshwater culture, with 5.7% and 5.6% respectively. Brackish water systems are used to culture a range of plants, invertebrates and fin fish.

There are two classes of brackish water environments in aquaculture: natural systems such as lagoons, mangroves and saltwater wetlands, and man-made systems such as ponds, raceways and tanks. Natural systems are very dynamic due to seasonal climate and coastal influences. Therefore, their fluctuations influence production, as well as determining the species, technologies and culturing practices that can be used. The increasing recognition of the ecological and socio-economic value of intact coastal ecosystems now limits how much of these areas can be developed solely for culturing systems and can create conflict between users of these coastal areas and resources (Bardach 1997: Naylor *et al.* 1998; Kay and Alder 2005). This recognition has driven the development of man-made brackish water systems in inland areas or in areas that have no other productive potential (e.g. desert areas).

Table 2.8 Difference in the market value (USD/kg) of aquaculture species raised in different environments, 2000-2003. Based on FAO (2004).

Environment	2000	2001	2002	2003
Brackish culture	31.30	15.98	16.94	13.92
Mariculture	6.75	6.42	5.75	5.16
Mariculture + Brackish culture	8.84	7.27	6.69	5.97

In natural systems, there is a high diversity of species cultured, ranging from plants to finfish, with low establishment and operating costs relative to man-made systems. However, there are higher risks associated with natural systems, including higher disease prevalence, vulnerability to coastal disturbances (e.g. cyclones) and conflicts with other users due to absent or weak property rights. These low establishment and operating costs provide low-income coastal communities with the potential to develop income generating activities to help address the issue of poverty and food security. However, the history of shrimp culture in coastal areas throughout Asia and Latin America has raised questions over its ecological, economic and social sustainability (Naylor *et al.* 1998).

Man-made systems are more expensive to run, i.e., they have higher fixed and operating costs. However, in these systems, some diseases are easier to control, and risks of predation, theft and natural disasters are reduced as well. In some areas, these systems also have less of an environmental impact, especially where recycling and re-circulating technologies are used (Piedrahita 2003). Because so much of the operating environment is controlled, these systems are often used to culture a single species; therefore, globally, only a few species are cultured in man-made systems. Technically, there is no reason why a polyculture could not be established in such a system and be sustainable, but the high investment cost tends to drive production goals towards intensive monoculture systems using high-value and proven species. This has resulted in crustacean species, especially Whiteleg shrimp *Litopenaeus vannamei* dominating production in man-made brackish water systems. However, for many low-income coastal communities, these systems are often beyond their financial resources.

Marine (Mariculture)

Marine water systems are used for culturing plants, invertebrates and finfish (Table 2.9). Like brackish systems, culturing can take place in natural systems (e.g. bays and coasts with net pens and racks, open ocean with cages), and man-made systems (tanks). Overall, in both systems, the species cultured are larger and require bigger culturing facilities, such as nets and pens. Natural marine systems are just as dynamic as brackish water systems, and the environmental conditions also determine the species, technologies and culturing practices. These systems also have the same benefits in culturing species and are vulnerable to the same suite of risks. However, the proportion of the ecosystem that is used in marine systems is much less than in brackish water systems, and therefore in these systems, there is a lower perceived risk from impacts such as disease outbreaks. They are therefore perceived as more sustainable (Bardach 1997).

In natural marine system, there is also a relative high diversity of species cultured compared to man-made marine systems. The infrastructure such as nets, cages and feeding systems required for natural marine systems imposes a higher cost to establish and maintain these systems compared to brackish water systems. Therefore, investment tends to focus on a few species that are proven and high-value, such as salmon, turbot and ornamental fish. The higher costs of establishing and operating marine systems can be a barrier to poor coastal communities investing in the industry (Donaldson 1997).

While brackish water culture corresponded only to 5.2% of all current aquaculture production and 10.2% of total value (on average equivalent to US $14/kg), mariculture contributed 50.6% of aquaculture production and 36.9% of total value, equivalent to US$ 5.16/kg (FAO 2004). Nevertheless, these values have been declining since 2000 (see Table 2.4). The reasons for such apparent declines in value lie primarily with lower trophic species common to mariculture (e.g. mussels, clams etc.) showing increasing trends of production in response to a growing demand for seafood and more competitive marketing, resulting in lowering price trends. If we take an even closer look at the production values and remove the Chinese and aquatic plant production (Figures 2.4 and 2.5), trends in production and value indicate a change in mariculture production (again together with brackish water culture) showing an annual growth rate of 11.4%, equivalent to 6.9 million t in 2003.

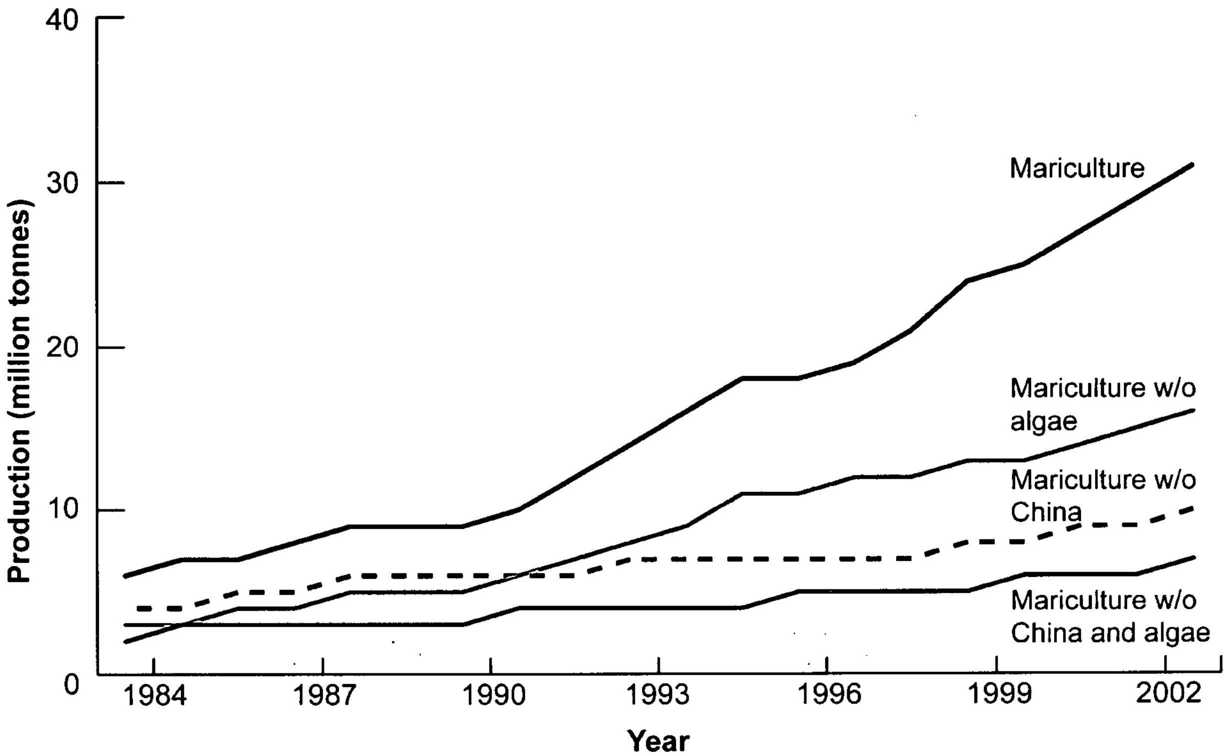

Fig 2.4 FAO Production by environment 1984-2003 (adapted from FAO 2004)

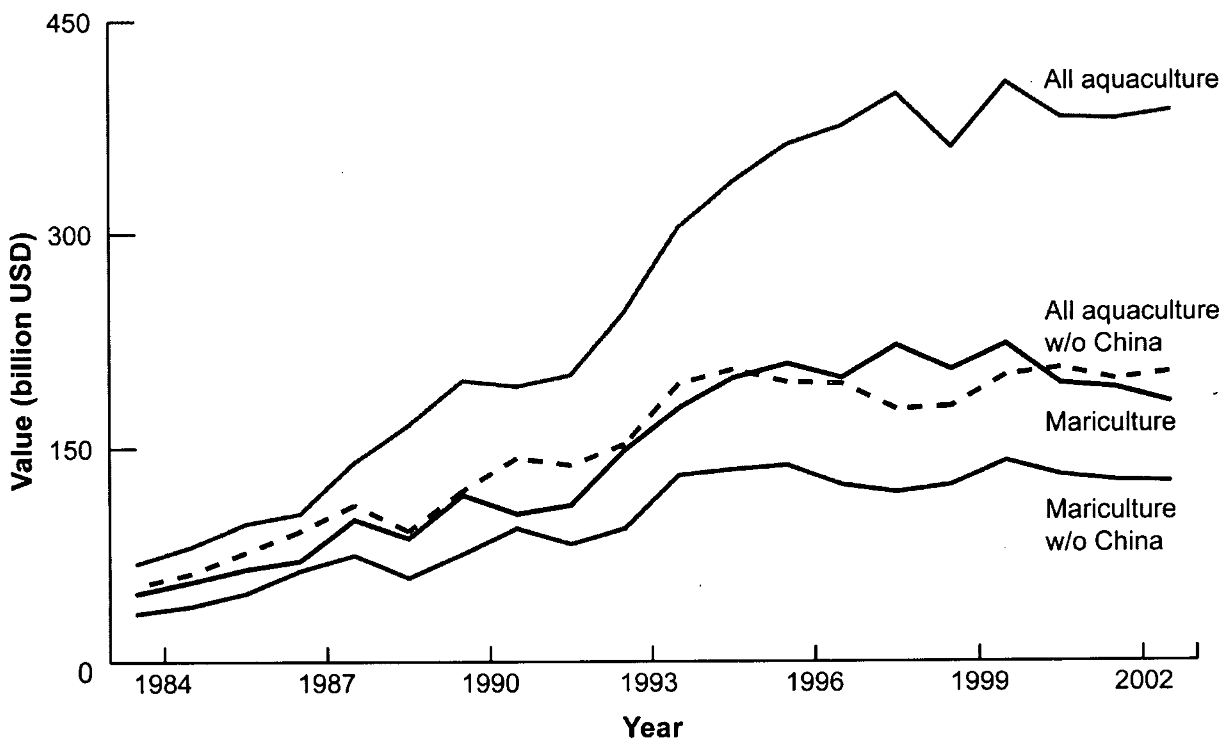

Fig 2.5 FAO Value by environment 1984-2003 (adapted from FAO 2004)

2.3 Aquaculture production technologies

The development of aquaculture would not be possible without some major advances in the technology of fish culturing, including, breeding animal husbandry, optimal harvest and post harvesting (Bardach 1997) protocols and performance. Technological and scientific research has also enabled a greater number of species to be cultivated. Consequently mariculture production and development is taking diverging paths from common mainstream traditional farming, examples are the discrepancies between different shrimp species e.g. *Litopenaeus vannamei vs. P. monodon* culturing techniques (Naylor *et al.* 1998).

A detailed description of the technological advances in these areas is beyond the scope of this thesis and the sections below provide an overview of current technologies only as they relate to environmental or socio-economic sustainability of this industry. The technology of aquaculture is often described in terms of its energy inputs (Roth *et al.* 2002) or culturing production systems as described in the following section.

2.3.1 Partial systems

Culturing technologies may take full control of all stages and requirements of a particular species and its life cycle (as in animal husbandry). This may include assisting in reproduction, incubation and in early life stages such as breeding, larval and seed rearing. It may also include providing the necessary energetic requirements, such as feeding throughout the ontogeny of the species; providing enclosures that will prevent their escape and provide protection from diseases and predators. These forms of control are often described as partial culturing.

Two technologies are prevalent in partial culturing: 'sea ranching and seed collection'. Sea ranching is the culture of a given species beginning at its earliest phase, until a more advanced juvenile (e.g. fingerling) stage is reached for release into the wild. The final stages of development are attained naturally with limited or no control, and the species is harvested later through conventional fishing methods. This technology used by fisheries managers when the objective is to replenish commercially or recreationally viable fishing stocks (stock enhancement), such as important salmonid species in the Northwest of the United States and red sea bream in Japan. According to FAO (2004) and other authors (Mustafa and Rahman 2000; Mustafa 2003) sea ranching or ocean ranching is distinct from mariculture, as the latter implies some form of intervention in the rearing process that leads to increased production. If so, the distinction between systems is a matter of scale and time, with marine ranching arguably similar to animal husbandry since some environmental controls are implemented and field improvements made (Fujiya 1999).

The second partial culturing technology is the rearing of juveniles or adults, which are obtained from wild juvenile, (*i.e.,* seed collection) or adult stage. They are for the most part fattened or maintained alive until the organisms reach a marketable size or an optimal market price. Again, this is seen in sea ranching and more specifically as a harvest type (Fujiya 1999). This technology is commonly used throughout Asia, where traditionally one or two fish are caught from the wild then confined in rudimentary wooden cages in rivers and coastal marine systems until they are consumed or sent to market. This combination of optimized fishing and mariculture has grown to industrial levels, as seen in tuna ranching. This is arguably a production system of doubtful sustainability since it relies on captured juvenile tuna, and small pelagic fishes as feed. Nevertheless, it is growing rapidly in the Mediterranean (Basurco and Lovatelli 2004) and in Pacific waters, mainly in Australia (Love and Langenkamp 2003)

2.3.2 Culturing systems

Stocking densities which reflects energy inputs may vary within and among culturing production systems. A few major categories of these systems include:

- Water-based systems (cages and pens, inshore/offshore);
- Land-based systems (rainfed ponds, irrigated or flow-through, tanks and raceways);
- Recycling systems (high control enclosed systems, more open pond based recirculation);
- Integrated systems (e.g. livestock-fish, ponds for growing fish and plant crops).

Mariculture technologies are primarily classified by production system based on the energy input levels, and primarily by one important measure, stocking density. Stocking density may range from extensive (low density) farming, semi-intensive, intensive and hyper-intensive cultures which until recently were limited to prototypes production systems, now moving out of the laboratory (Roth *et al.* 2002). Because there are no clear distinctions between and among culture types, characterization of system types must be defined as part of a continuum of levels of intensification (Funge-Smith and Phillips 2001).

2.3.3 Stocking densities

Extensive

Extensive aquaculture, involves the farming of finfish or shellfish in a 'natural' habitat with little or no supplementary inputs (food, fertilizer etc.) and low stocking densities with minimum impact on the environment (Tacon 1998; Naylor *et al.* 2000). Shellfish cultures mainly clams and mussel and some forms of oyster cultures are examples of extensive farming.

The advantages of this type of stocking rate are lower disease incidence and lower cost. However, these also imply low return and profit. For some species with higher operating costs, such as pearl oysters, low densities are also used. Extensive systems are often sustainable environmentally, but the socio-economic sustainability of the systems is variable with profit levels depending on the species farmed, its operating costs and farmgate price (Pullin and Sumaila 2005). Questions still remain whether the lower production rates will limit production thus requiring more farms for food supply creating stress on coastal zoning and its different users.

Semi-Intensive

Semi-intensive systems are often integrated with other agricultural production systems. Semi-intensive systems are distinguished from extensive systems by increased stocking rates and the requirement of some level of input, such as food, fertilizer, chemicals, etc. Integrated systems, as seen in China, incorporate fish production with the rearing of swine (where excreta are used to fertilize ponds), ducks (which churn sediment and assist in nutrient turnover), plants (which may be used as food), etc. (Kent 1995). Some integrated cultures and polyculture systems using omnivorous fish, i.e., vegetarian and omnivorous carp with rice paddy. Some recent shrimp cultures that stock at lower densities can be considered semi-intensive (Rosenthal 1985).

The environmental risks associated with high stocking densities may differ from species to species and from tropical to temperate systems. Common problems from high stocking densities include water nutrient changes; in some situations, nutrient levels in the water column may increase with higher stocking levels. In other situations; nutrient levels may decrease when bivalve mollusks are cultured extensively and over a large area. In China, some traditional integrated pond systems that may be viewed as extensive, relied on a fine balance of biological, physical and chemical processes. When such ponds are transformed to semi-intensive systems, major changes take place, including increased disease susceptibility and pond eutrophication (Li 2003).

Intensive

Intensive production systems are typified by the need for total control over the production cycle. Examples of intensive aquaculture include pond culturing of shrimp, cage and pen cultivation of salmon, pond production of channel catfish, microalgal cultivation and rearing of crocodiles and alligators. Intensive aquaculture generally demands providing all the food consumed by the farmed organism, as well as chemicals, fertilizers, etc. They may also require sophisticated interventions: control of reproduction, larval rearing, vaccination and so forth. Intensive production aims to maximize production and minimize infrastructure costs and requirements, but it has more often than not failed. For example, in the Philippines, shrimp disease outbreaks increased when the traditional extensive practices were replaced to semi-intensive and intensive practices (Naylor *et al.*, 1998).

Considering the tradeoff between production and risk is in line with the industry's growing concern growing for its economic sustainability (Pullin and Sumaila 2005). However, the pull of international markets is so high that minimizing costs through under-funding operations and using quick and dirty techniques is prevalent, as seen for example in rural India where brackish water shrimp farms using intensive culturing practices dominate the sector, but there is also a high failure rate due to disease (Rout and Bandyopadhyay 1999)

Intensive systems often result in large-scale conversion of habitats as described above. The loss of coastal habitats has long term implications for sustainability, because a range of ecosystem services from water quality to providing the broodstock that is used to stock the farms are compromised (Agardy and Alder 2005). Extensive systems are at great risk of disease, with potentially wide-reaching impacts, since disease outbreaks often spread quickly. In developing countries, such losses can be devastating for many small-scale farmers and can have long-term affects on the social and economic sustainability of communities.

Hyper-intensive

Hyper-intensive cultures are at the limit of what the present technology can do for maximizing production. In the best-case scenario, hyper-intensive cultures operate completely closed systems. The systems are characterized by small enclosures and shorter farming stages, so that returns of investment are high. Continued investment in this technology will probably lead to biotechnological breakthroughs, increasing the predominance of these hyper-intensive systems. For example, extensive shrimp culture can produce only 100 to 200 kg per ha per crop cycle, one or two orders of magnitude less then hyper-intensive systems, which are capable of producing over 10,000 kg per ha per crop cycle.

Hyper-intensive closed systems have the potential to reduce impacts on ecosystems, because they can be constructed on less productive land, which implies less conflict with other sectors, and eliminates the need to convert productive or protected land. The technology also exists to treat discharges prior to release. However, these systems are very expensive to develop (Shang and Tisdell 1997), and they marginalize small-scale farmers and poor coastal communities, who are unable to invest and benefit from this technology directly. They may benefit indirectly, however, through employment in production, post-harvesting and marketing, depending on local conditions.

Firms that sell or lease such planned hyper-intensive enterprises are multiplying and are targeting countries with economies in transition, such as Ecuador and Peru (Aladi 2002). However, these firms do not fully master the technology, resulting in many failures. These enterprises are best described as 'boom-bust' operations that operate in the short-term by establishing the enterprise, quickly making a profit and then translocating before environmental damage appears to be irreparable. This mismatch between theory and practices raises question on the ecological and socio-economic sustainability of such systems.

Mariculture operations can also be categorized by another important attribute: feeding type and strategy (Tacon 1998). These are vital traits for cultured species, which reflect their predisposition to adapt or adjust to diverse diets and feeding regimes that often differ from their natural diets and feeding habits. The ability to adapt thus has long-term implication on the sustainability of cultured species. When differentiating feeding strategies and stocking densities among the same species, fish cultures, as does terrestrial husbandry, depends on the level of technology and social acceptance of the farm site. Metabolic versatility of a given species in this aspect and for other traits (oxygen demand, maximal stocking density, etc.) may assist in determining future candidate species with culturing potential.

2.4 Sustainability challenges in mariculture

2.4.1 General overview

Ensuring that the aquaculture sector is sustainable and can continue to develop presents challenges to the industry itself. These challenges include:

1) Determining areas for development and expansion. In some areas, available coastal land is a limiting factor as seen in Europe for mussel cultures (FAO 2006). Habitat modification that results from converting productive land to aquaculture occurs in South East Asia, where mangrove deforestation is no longer deemed acceptable, as it disrupts the essential mangrove-fishery link (e.g. shrimps– milkfish; Barbier and Sathirathai 2004). When this link is damaged, the risk of coastal subsistence fishers losing their resource base is increased;

2) Supplies of inputs such as fishmeal and fish oil. Demand for trash fish or low-value fish has steadily increased with continued expansion of mariculture. Present trends in production can be maintained only if the proportion of fishmeal and fish oil obtained from capture fisheries is increased (Delgado *et al.* 2003; FAO 2004; Tacon 2003; Alder and Pauly 2006);

3) Addressing the risk represented by indiscriminate use of antibiotics, pesticides and other chemicals. This use may cause health problems, including antibiotic resistance and harm non-target species (Husevag and Lunestad 1991; Naylor *et al.* 2000; Cabello 2006);

4) Managing organic pollutants. Dissolved and solid waste discharges and outputs contribute to nutrient loading and eutrophication (Sather *et al.* 2006);

5) Controlling biological pollutants through the introduction of species, parasites and diseases. These weaken, hinder or alter ecosystem functions and equilibrium (Hindar 2001).

The implications for sustainability vary with each culturing technology and species. They are discussed below.

2.4.2 Capture fisheries and mariculture

Many fish stocks traditionally preferred for direct human consumption are presently overfished (Pauly *et al.* 2002; Worm *et al.* 2006). Indeed, the reported landings of global fisheries are declining by about 500,000 tonnes per year since the late 1980s when they peaked at approximately 90 million t (Pauly *et al.* 2002). The demand for fish is driven by increasing human population, increasing economic purchasing power as seen in emerging economies such as China and India, and increasing awareness of health benefits from fish consumption (Tacon 2001). In response to this demand, fisheries are also increasingly capturing fish of low trophic levels and low economic value as the catches of large fish declines. Nevertheless the demand for fish continues to grow globally and, as fish become scarce, the demand for these low value fish increases. Some people have called for the expansion of aquaculture to meet this increasing demand. However, much of the increase in recent seafood demand has been for carnivorous (e.g. salmonids) or omnivorous (e.g. shrimp) species that are grown on compound aquafeeds, and thus contributing to the increasing demand for small pelagic fish (anchovies, sardines, mackerels, etc.) which are the major input to aquafeeds (Naylor *et al.* 2000).

2.4.3 Poverty relief and food security

At the World Commission on Environment and Development (WCED) in 1987, the 'Brundtland Commission' advocated aquaculture as one of the measure that would help attain sustainable development in developing countries (WCED 1987). Questions regarding whether the present mariculture systems can contribute to sustainability, food security, locally and abroad, were not addressed. Since then, questions on what forms of cultures are more sustainable than others within and among species, culture techniques and regions still need to be answered.

As mentioned above, efforts to solve food security dilemma in the developing world in the 1980s led to many governments opening the door to any potentially promising development. This open-door policy extended to the aquaculture sector and paid little attention to the environment and coastal communities. What mattered was private and international aid, or investments. The introduction of foreign species, as was the case for shrimp culture in India, Philippines and Ecuador, as well as salmon farms in Chile (Ibáñez and Pizarro 2002) are just a few examples of these unsustainable policies that affected coastal communities.

The likelihood of sustainably meeting the increasing demand for seafood, even with supplementing production from mariculture is minimal (Naylor *et al.* 2000). Present day seafood preference has increased the demand for farmed high-priced marine fish such as tuna and salmon. A considerable proportion of sardines, anchovies and other small pelagics are diverted to feed other fish, thus compromising food security in many countries (Alder and Watson 2007). Small pelagic fish are a traditional food source for poor communities who cannot afford increasingly expensive pelagics (Alder and Pauly 2006) which make up less than 5% (4.5 million t) of total capture fish production. However, maintaining current supplies of tuna at around 4 - 5 million t is technically possible, but would be entirely dependent on the progress and continuous expansion of offshore tuna mariculture ventures and continued diversion of small pelagic fishes as feed for this industry.

Sustainability has been the stated goal behind the promotion of modern aquaculture; the inputs required by a growing mariculture sector imply the diversion of resources away from animal husbandry, in addition to the diversion of small pelagics from direct human consumption. The future of mariculture, therefore, will be determined largely by consumers and their ability to pay, and with investors seeking economic opportunities and investment, and sustainability and long-term food security are likely to take the back seat.

2.4.4 Others

A synthesis of the previous sections highlights the ecological, social and economic challenges the industry faces in meeting global sustainability objectives. Ecological issues such as habitat conversion, nutrient loading into coastal environments, the use of antibiotics, diseases, introductions of new species threatening biodiversity and the use of fishmeal and fish oil as feed, all threaten the coastal ecosystems and the industry that depend on its services. Some of these challenges can be addressed through technological developments, while others require changes in management practices. Similarly, there are social and economic challenges for the industry, which are primarily addressed through policy changes, and the development of partnerships with communities and industry, which develops income generating opportunities directly through jobs, or indirectly through new business opportunities.

The large-scale industrial sector has additional needs to ensure its operations remain profitable, notably productivity increases and consistent quality standards (Funge-Smith and Phillips 2001). Consequently, the requirements for sustainable aquaculture development will need to include technological, economic and social aspects that effectively meet human needs, and provide for economic well-being while maintaining productive ecosystems.

Addressing these challenges is not an easy task. Indeed, it may take considerable time to build consensus within government and industry on how to implement the necessary changes to ensure sustainability. Any change, however, will be a trade-off between the level of ecosystem sustainability, social benefits and profitability. How to measure the trade-off and who benefits has yet to be defined at global and regional scales. However, the question still remains on how to measure sustainability especially for mariculture, the focus of this thesis. The next chapter provides a framework to address this question.

Chapter 3

3.1 Assessing the sustainability of mariculture

The previous chapter argued that the aquaculture industry and governments realize that, for long-term growth, they must regard sustainability as a key component of all of their operations, despite the challenges this poses. The aquaculture industry, including the mariculture sector, has guidance on how to achieve environmentally-friendly practices as well as ecological and social-economic sustainability. This comes from various sources: industry itself, governments, academia, NGOs and consumers, and from other sectors involving animal husbandry. Industry, NGOs and governments have responded to the need for sustainability by developing a suite of guidelines, codes of practice and protocols; some of these are discussed below. As suggested previously, the long-term sustainability of mariculture relies on maintaining ecosystem services, building social capital and contributing to economic growth. Therefore in assessing the sustainability of the mariculture sectors, the broad aspects of maintenance of ecosystems, and continuing social and economic growth need to be included in any assessment.

Indeed, the growing concern over sustainable aquaculture, in particular mariculture, has prompted reviews of particular aspects of the industry for example aquafeeds (Tacon 1993, 1998: FAO 2004). However, there are no overall industry-wide reviews other than the recent FAO State of Aquaculture Report (FAO 2006), which is very comprehensive, although it fails to include an overall quantitative or qualitative indication of progress towards sustainability at the global, regional or species-specific levels.

There are many approaches to assessing the sector's sustainability such as the Pressure-State-Response Model (Linster and Fletcher 2001) or the Conceptual Framework of the Millennium Ecosystem Assessment (2003). Some approaches are highly complex and data intensive such as the Conceptual Framework, but provide a comprehensive picture of the state of the system(s) assessed. At the other end of the assessment spectrum is the use of a well-defined, suite of indicators such as the ecological footprint (Wackernagel and Rees 1996), which requires a number of standardized data sets, or the Marine Trophic Index, MTI, (Pauly and Watson 2005) which is based primarily on a single database of fish landings and estimate of trophic level of the fish landed. The indicators approach is often much simpler to apply and it is easier for policy makers and society to understand how the indicators reflect changes in the system and the significance of changes in the value of the indicators (e.g., declining MTI = declining marine health of the ecosystem). In some situations, indicators will help direct and steer policy makers on determining the type and level of development and management of a given aquaculture sector, including mariculture.

While there are codes of practice, guidelines and recommended protocols within the aquaculture industry to minimize its impact on the environment, the ability of the industry or government to assess progress toward meeting sustainable management or development objectives is weak at best. Given the growing awareness of consumers of the long-term benefits of sustainable production, and growing demand by wholesalers to meet the demand based on this awareness, it is imperative that a set of indicators be developed to assess the sustainability of aquaculture, similar to the Marine Stewardship Council's (MSC 1998) guidelines for the sustainable fishing or the World Wildlife Fund's "*Fish 'Yes' List*" (WWF 1998).

This chapter first describes the terms and the general approach used to assess sustainability, and reviews the criteria and indicators used in other agricultural and natural resource sectors, along with species-specific guidelines and codes of practices for marine and brackish water culture (mariculture). While some of the guidelines for freshwater aquaculture will no doubt overlap with those for mariculture, freshwater aquaculture indicators are outside the scope of this thesis. This chapter then describes the criteria used to select mariculture indicators, and defines and describes the selected indicators of countries' mariculture performance.

3.2 Assessment definitions

Measuring the state of a resource, sector or process including mariculture requires three steps: a) defining the criteria on which to identify and assess indicators meant to reflect sustainability in the mariculture sector; b) determining the boundaries of the indicator (quantitative or qualitative) that reflects the level of sustainability; and c) either collecting the data or undertaking studies to measure or to quantify the indicator relative to the boundaries previously defined (Esty *et al.* 2005). The relationship between criteria, indicator and sustainability are illustrated in Figure 3.1.

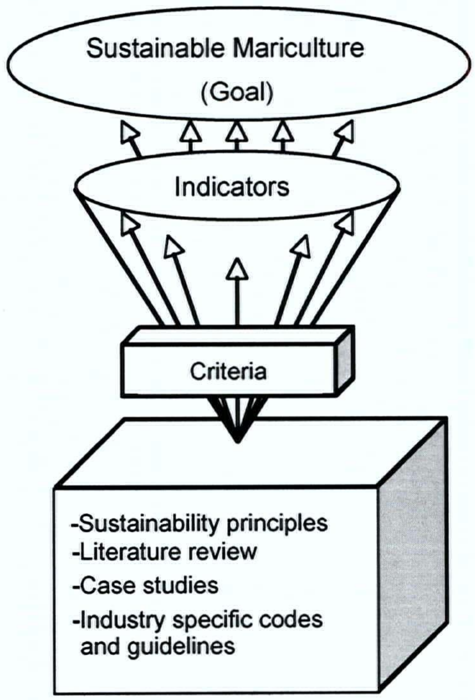

Figure 3.1 Relationship between indicators, criteria and the underlying framework.

In some studies, thresholds are specified so that the state of resources or process is clearly defined. For example, when less than 10% of biomass remains (the threshold) a fishery is considered overfished (Hilborn and Walters 1992). In some studies, the indicators are aggregated into a single or set of indices that provide an overall assessment of the system or process such as the Human Development Index (UNDP 2006). In this thesis, the following definitions are used:
Criterion (plural: criteria): "A standard, a rule, or test on which a judgment or decision can be based" Merriam-Webster's collegiate dictionary 10th ed. (1993)

Indicator: "A measure used to determine, over time, the performance of functions, processes, and outcomes" Merriam-Webster's collegiate dictionary 10th ed. (1993)

Criteria

In the context of an assessment, there are a number of possible criteria and, for the assessment to be robust, the criteria used to identify and select the indicators should also reflect the principles of sustainability and good mariculture management practices. Also they should be acceptable to the industry, government, concerned consumers and the local community. In this thesis, criteria were developed or modified in the light of these concerns.

Indicator

Indicators can provide the qualitative and/or quantitative measures against which we assess a given sector. If the criteria are well defined and have the features discussed above, this will allow for the identification and selection of indicators that will also be robust, relevant and acceptable. It should also be possible to express the indicators quantitatively (e.g. score between 1 and 10) or qualitatively (e.g. high, medium, low).

This study uses several criteria to guide in the selection of the most appropriate indicators for assessing sustainable mariculture. There are general criteria, often described as Specific, Measurable, Achievable, Relevant and Time-bound or SMART (GEF 2005) which can be applied to any indicator:

Specific: The indicator captures the essence of the desired result by clearly and directly relating to achieving an objective, and only that objective, and in this study it is mariculture sustainability;

Measurable: The indicators are unambiguously specified so that all parties agree on what the system covers and there are practical ways to measure the indicators and interpret the results;

Achievable and Attributable: The indicators can measure the changes that are anticipated as a result of an intervention such as a policy or improved farming practice, and whether the changes are realistic. The indicator is clearly defined and measured so that changes in the indicator can be linked to the intervention;

Relevant and Realistic: The type of indicator can be achieved in a practical manner, and that reflect the expectations of stakeholders;

Time-bound, Timely, Traceable, and Targeted: The indicator can be tracked in a cost-effective manner at desired frequency for a set period, with clear identification of the particular stakeholder group to be impacted by the project or program (modified from GEF 2005).

The reliability of a specific 'diagnostic' indicator for a selected standard of sustainability must be subjected to continuous scrutiny. Because indicators often reflect the views and values of society at a certain temporal and spatial scale, they could lose their relevance. Thus there is a need to identify indicators that will be useful over long time frames.

There are also criteria that are specific to the sustainability of ecosystems, and socio-economic conditions that can be applied in the aquaculture sector. The development of indicators in other natural resource sectors can also provide criteria to select a suite of indicators. While criteria may be specific or applicable to the mariculture sector, in this study, criteria that are globally applicable (spatially and species-independent) are used.

3.3 Sustainability assessment framework

3.3.1 Background

A search of peer-reviewed and industry-specific literature failed to identify any widely accepted criteria or indicators to assess the sustainability of aquaculture as defined in Chapter 2 of this thesis. As noted previously, there are published mariculture guidelines and codes of practices such as those for shrimp (Boyd 1999) and the Canadian Department of Fisheries and Oceans (DFO 2001) for salmon guidelines. Nevertheless these guidelines do not provide indicators on how to measure their impact on sustainability. Fortunately, the work in developing indicators in the fisheries, agriculture and forestry sectors provide considerable information, approaches and frameworks upon which to develop the necessary criteria and indicators for the mariculture sector. They are reviewed in the following sections.

3.3.2 Natural resources sustainability indicators

A definition of sustainable mariculture has yet to be developed, but authors such as Costa-Pierce (2002) have described forms of sustainable and ecologically appropriate aquaculture as integral parts of modern aquatic resources management. Nevertheless, proper indicators are still lacking; however, they can be derived from other sectors where sustainability indicators have reached some level of acceptance. In the fisheries, agriculture and forestry sectors, significant progress has been made in establishing indicators for sustainable use of fish, land and forest resources. The criteria for indicators used in these sectors provide examples and lessons learned on which to develop indicators for mariculture.

Some of the criteria and indicators in these sectors, while not being a direct measure of sustainability, can still provide a basis for developing a set of indicators. In addition, many of these indicators cover ecological, economical and social conditions as noted in Section 3.1. Also operational details in these documents can often be translated into criteria or indicators. In addition, the definition of sustainable aquaculture and the codes of conduct and guidelines highlighted in Chapter 2 cover the fundamentals of sustainability for the industry, and can provide models to develop sustainability criteria and indicators for mariculture. The following sections outline sustainability and some indicators that are used and applicable to aquaculture.

3.3.3 Capture fisheries indicators

The crisis in the capture fisheries sector has prompted international, regional and national governments to move towards sustainable fisheries practices. In some areas, the shift has included a requirement to assess the sustainability of stocks and to consider the effects of the industry on marine ecosystems. For example, the Fisheries Department of South Australia has developed sustainable management plans for its major fisheries with objectives and indicators. The shrimp fisheries in this state are assessed using biological (e.g. exploited biomass), environmental (e.g. bycatch levels), economic (e.g. gross value of catch) and social (e.g. number of public meetings) indicators (Primary Industries and Resources South Australia 2003).

Another example is the B.C. herring roe fishery managed by Fisheries and Oceans Canada, which uses five indicators (Table 3.1) considered to be "fundamental to biologically sustainable fisheries management" (Wallace and Glavin 2003).

Table 3.1 B.C. Herring roe fishery indictors (Wallace and Glavin 2003).

Indicators	**Score**
Knowledge of species' life history	B
Stock assessment and sustainable quota determination	B
Management system: Accurate and timely catch information	B
Ecosystem considerations	C
Precautionary measures and long-term sustainability	C
Overall Grade	B

This report card approach is an example of a simple indicator approach. This overall assessment, while presenting a 'passing' grade is only as good as the framework on which the scoring is based, and will only be relevant if current standards or performance indicators are current and updated to reflect sustainability criteria. Thus, in this report card example, a biodiversity criterion (recently been deemed of primary importance to ecosystem function and sustainability) should be stated as a separate performance indicator, which would no doubt change the overall score.

3.3.4 Agricultural indicators

In agriculture, the common criterion for sustainable agriculture resides on 'permanence' which means adopting techniques that maintain the soil fertility indefinitely, so that an agricultural area can be used in perpetuity, although this diminishes the land's capacity to be used by other organisms (e.g. wildlife). The U.K.'s Department for Environment Food and Rural Affairs uses 35 indicators to assess agricultural sustainability. These indicators cover the ecological (e.g. land committed to conservations), economic (e.g. income from farming) and social (e.g. age distribution of farmers) dimensions of sustainability (Department for Environment, Food and Rural Affairs 2001).

3.3.5 Forestry indicators

Habitat loss and declining biodiversity are major drivers of sustainable forestry. The issue here is whether the use and appropriation of goods and services will detract from or degrade the use of the forests by other organisms. Biodiversity, productive capacity, ecosystem health, socio-economic benefits and governance frameworks are key criteria for determining sustainability in the forestry sector (Oliver *et al.* 2001). Based on these criteria, several indicators are used, such as relative forest area by type, timber volume and occurrence of invasive species.

3.3.6 Aquaculture codes of conducts and guidelines

Codes of conduct and operational guidelines for the aquaculture sector are often focused on mariculture and aimed at addressing sustainability issues (and issues discussed in Chapter 2) such as biodiversity, ecosystem conservation, nutrient discharges, employment, use of pharmaceuticals, among others. While these guidelines do not provide benchmarks on which to gauge if the industry is meeting its sustainability objectives, they do provide a framework can be used to develop appropriate indicators. Over the last decade, numerous codes or guidelines have been developed for aquaculture, ranging from supporting particular stages of culturing to industry-wide guidelines applying to feed manufacturing (Hassard and Tacon 2001). The FAO Code of Conduct for Sustainable Fishing (FAO 1995) and the Jakarta Mandate (CBD 1997) are the two most relevant codes for guiding the identification and selection of indicators for mariculture.

One of the most well known codes is the FAO Code of Conduct for Responsible Fishing, which covers the sustainable use of aquatic resources, including guidelines for sustainable aquaculture. The Code promotes responsible aquaculture practices that include distributing benefits equitably, participation of stakeholders in development of best practices through appropriate feeds and feeding regimes, safe use of drugs and other chemicals, safe disposal of wastes and production of food that is safe for human consumption.

The International Council for Exploration of the Sea (ICES) developed a Code of Practice on the Introductions and Transfers of Marine Organisms with recommendations regarding procedures and practices to reduce the negative risks involved in the intentional introduction and transfer of marine and brackish water organisms (ICES 1995). More recent ICES publications have come up with 10 categories of recommendations centered on issues that should be carefully addressed before and after the introductions of organism, as well as considerations on the use of Genetically Modified Organisms (Beardmore 2003).

Past initiatives, such as the Jakarta Mandate on Marine and Coastal Biological Diversity, an outcome of one of the conferences of the parties for the Convention on Biological Diversity (CBD 1997) have taken into account the relationship between fishing activities (including aquaculture) and the conservation and sustainable use of marine biodiversity. The Mandate is the first all-inclusive global consensus on marine biodiversity conservation. It describes case studies for mariculture as well as promoting best practices. The case studies cover diverse topics in mariculture including feed systems, coastal management, social and financial aspects and the best practices associated with these case studies that relate to biodiversity conservation and sustainable use of marine resources (UNEP 2001).

Some important outcomes of the Jakarta Mandate are the Ad Hoc Technical Expert Group on Mariculture, the SBSTTA 8 (CBD 2001) where it was recommended that parties adopt the use of specific methods and practices in aquaculture to avoid adverse biodiversity-related effects. These included practices such as the completion of environmental impact assessments, effective site-selection methods, effluent and waste control, use of native species and subspecies and other techniques for protecting genetic, species and ecosystems diversity. These recommendations and decisions provide guidance on the scope and nature of sustainability indicators.

3.4 Mariculture sustainability

Previous sections and chapters have noted that indicators should reflect the need to balance biodiversity with the productive capacity of the system, maintain ecosystem health, provide for equitable distribution of social and economic benefits and operate within a sound governance framework. They should be culturally appropriate, relevant to their geographic locality and cost effectiveness. How much these criteria will influence sustainability indicators depend on the context in which they are used. The indicators should also be SMART (see above), irrespective of system, species or location. However, this study attempts to assess mariculture sustainability at the global level. Therefore, it uses indicators that are culturally, spatially and ecosystem independent. Using such indicators will make global and regional comparisons possible and contribute to a globally accepted set of standards.

Codes of conduct and aquaculture industry guidelines, as well as species-specific indicators, also provide input into developing more globally appropriate indictors for mariculture. When this information is combined with what has been learned in the other sectors a robust set of indictors meeting ecological, economic and social criteria emerge (Figure 3.2).

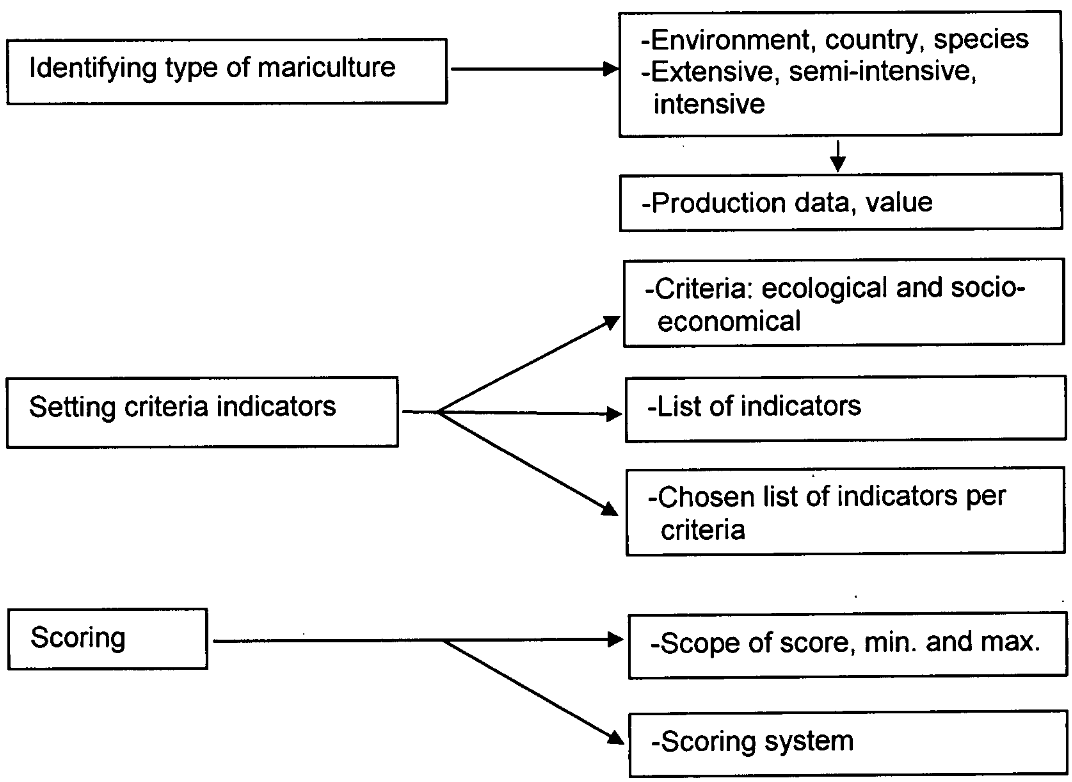

Figure 3.2 The approach for criteria and indicator selection and application with its linkages between criteria, indicator and its application in mariculture.

Based on the literature related to mariculture practices as reviewed in Chapter 2, sector developments and interactions, and the above criteria, the following set of sustainability indicators (ecological and socio-economic) were identified and described below.

3.4.1 Indicators in general

Potential Ecological Indicators:

- Species introduction versus native/local (regional);
- Fishmeal usage in diet; carnivorous versus non-carnivorous species;
- Fishmeal substitution in carnivorous species diet, (i.e., usage of blood meal, feather meal etc.);
- Intensity of production;
- Aquatic versus inland farm sites; open versus closed system;
- Hatchery usage versus wild seed provenance;
- Habitat alteration;
- Waste water treatment.

Potential socio-economic indicators:

- Market destination; foreign export or local domestic market;
- Nutrition value of species produced;
- Code of practice implementation;
- Pharmaceutical usage;
- Use of molecular/genetic manipulation linked to cultivated species or its feed;
- Conflicts with surrounding systems;
- Traceability;
- Employment;
- Toxicity control;

3.4.2 Ecological

Many of the ecological indicators below were selected and adapted from Costa-Pierce (2001), the recommendations and decisions resulting from the Jakarta Mandate and from the FAO Code of Conduct. These studies provided key information on managing ecosystems and also on the addressing issues within the sector including sustainability. This information was used to define the six ecological indicators used in this study (Table 3.2)

Table 3.2 Ecological indicators chosen for this study and their performance with regards to ecological criteria.

Potential indicator	Criteria					Main source/references
	A	B	C	D	E	
Native or introduced	√	√		√	√	CBD (2004); Costa Pierce (2001).
Use of fishmeal and derivatives.		√	√		√	Tacon (1993); Tacon (2003).
Stocking density	√		√		√	Bardach (1997).
Larvae & seed provenance	√			√	√	Kautsky and Folke (1991); Folke and Kautsky (1992).
Habitat impacts	√		√	√	√	Costa-Pierce (2001); Folke and Kautsky (1992).
Waste treatment	√	√	√		√	Costa-Pierce (2001); Rosenthal (1985).

Four of the six criteria for ecological aquaculture identified by Costa Pierce (2001) provide the framework of aquaculture-specific criteria. The first three are based on ecologically sustainable theory:

A) Preserving the form and functions of natural ecosystems;

B) Optimizing trophic level efficiency, that is, optimal efficiency is realized when plants or herbivorous organisms are cultured;

C) Practicing nutrient management by not discharging any nutrients or causing chemical pollution, and not using chemicals or antibiotics harmful to human or ecosystem health;

D) Using native species/strains and not contributing to 'biological' pollution; but if exotic species/strains are used, ensuring that complete escapement control and recovery procedures are in place.

The first three criteria may be deemed ecologically conservative whereas the 4th point stands out by implying that exotic species may be used as long as there is full control of escapement. This involves costly investments, such as fully integrated water recycling and recirculating systems and waste treatment. Moreover, depending on specific ontogenetic stages, control requirements may extend to hatchery, and other rearing and maintenance stages. For example, trials on the feasibility of culturing freshwater catfish such as the catfish *Clarias* sp in Cuba and the Australian freshwater crayfish *Cherax* sp. in Chile, required isolated conditions where connecting water ways were impeded. In the case of the crayfish, ponds were created in extreme hot desert habitats to ensure that escaped crustaceans would not survive. Such scenarios are not profitable on a commercial scale. Escarpments have also been reported recently for both species (Arthington and McKenzie 1997; E. Diaz, CIM University of Habana, 2005 pers. comm.).

The fourth criterion (D), requires more than physical boundaries; genetic manipulation such as tetraploidy has been implemented to lessen the risk of escapement. Yet genetically modified organisms are in the forefront of the debate over the reliability of their sterile and their potential to transfer disease.

The first three criteria are considered essential for achieving sustainable aquatic resource management. These ecological criteria also provide the basis upon which all current aquatic husbandry practices have been accepted (at least in theory), and from which indicators can be derived. The habitat impact and wastewater treatment indicators were derived from these criteria. Industries that fulfil these three criteria may not necessarily achieve sustainability.

The fourth criterion (D), identified by Costa Pierce (2001), suggests that introduced species can be pests: a subject that becomes contentious in many areas of the world, and which shows how the evolution of criteria and guidelines and technological developments will alter what is considered a requirement for sustainability. An invasive species can cause harm to ecosystems, and to the commercial, agricultural, or recreational activities dependent on these ecosystems (CBD 2004). Non-native shrimp, oysters and Atlantic salmon in the Pacific

Northwest, are just a few examples of non-native mariculture species that have generated concern over disease and other impacts that might arise from their escape (CBD 2004)

Based on the above analysis; ecological indicators were selected based on:

A: Effects on the form and functions of the surrounding natural ecosystems;

B: Trophic level efficiency, e.g. food conversion ratio (FCR);

C: Nutrient management, i.e., outputs, such as organic and chemical pollutants;

D: Biodiversity issues, including the use of native species and subspecies;

E: SMART = Specific, Measurable, Accurate, Realistic, Time-Bounded.

These criteria were applied to the potential indicators presented above, with most indicators meeting 3 of the 5 criteria (Table 3.2).

These six indicators were therefore considered acceptable for the analysis and are described in detail below and in (Table 3.3).

Native versus introduced

The ICES Code of Practice (ICES 2005) stresses that all introductions and transfers of marine organisms carry risks associated with target and non-target species. Furthermore, FAO (1995a) contends that introductions cannot meet the Precautionary Principle, because their impacts are irreversible and unpredictable. Indeed, introductions can result whenever live organisms are moved, regardless of the original intent (ICES 2005). Therefore the origin and natural distribution of species used for farming is crucial when determining risks and levels of environmental and socio-economic impact. Farming activities that involve non-native species pose inherently a higher risk due to the potential negative effects. Furthermore these risks can differ depending on the extent (or lack) of measures implemented by the farm (e.g. fully closed re-circulating systems; open net pens, etc.)

Table 3.3: Detailed description of ecological indicators for mariculture.

Ecological criteria	Description of practice and score scheme
Native or introduced	Native species score the highest (10), rather than foreign and introduced species (1) on the premise of potential impacts to local biodiversity if they escaped. Use of native but non-local species where scored intermediately. Genetic biodiversity impacts may be of a native origin when larvae, spats or seeds are from poorly managed hatcheries, vulnerable to out-breeding depressions and/or genetic bottlenecks.
Use of fishmeal, and derivatives.	Fish protein and oil inclusion in the diet at any stage of development must be considered; herbivore species will score 10, and carnivorous (piscivorous) organisms will score closer to 1, depending on the level of feed supplied.
Stocking density	The three intensity levels (intensive, semi-intensive and extensive) score 1, 5 and 10, respectively. Variations due to polyculture or feed requirements at different ontogenetic stages will modify the score accordingly.
Larvae and seed provenance	Hatcheries are major providers of larvae, fry and seeds. Broodstock origin and strain will also affect the score. Wild seed collection and its importance contribute to a low score due to bycatch and other effects on non-target species.
Habitat impacts	Farm site location and selection, surface area, impact on the surrounding ecosystem, biodiversity impacts are considered with low impacting species (e.g. mussels) scoring high (10) and high-impact species (e.g. shrimp in coastal areas) scoring low (1).
Waste treatment	Water exchange, output destinations, recycling and filtering implementations open water discharge or closed system reuse systems. Systems that are closed score high (10), while open systems without waste treatments score low (1)

Farmed species that are released into the environment, accidentally or on purpose, constitute a direct threat to ecosystem biodiversity if those organisms are not retrieved in time and produce offspring that are able to survive and adapt in their new environment (ICES 2005). The majority of these events may not be reversible or quantifiable in terms of damage (e.g. salmon farms in southern Chile). Other releases may be reversed, but at great expense (e.g. Whiteleg shrimp and Tiger prawns, seabreams and mullets). Nevertheless, steps in determining the full cost of such events must be undertaken. Transferring species to closed rearing systems will always be associated with a potential risk for escapement (e.g. accidental slippage, flooding, etc.). Even complete isolation of an exotic species entails risks, as the probability of accidental release is not zero.

Feed and food use

Autotrophic organisms are arguably the least demanding organisms to produce, in terms of feed cost. Yet, they are also less valuable, in terms of financial returns, than carnivorous species such as tuna and salmon. With few exceptions, it is mainly omnivorous and carnivorous species that are the top market drivers of non-plant mariculture production, and they are often the most profitable. The demand by developed countries and the wealthy class of developing countries continues to grow for these species. Despite their reliance on fishmeal, which is a major source of increasing costs, they continue to fetch top dollars. The dilemma of feeding fish to fish is the opportunity cost lost by turning fish into aquafeed; this is certainly true when fish, which are perfectly suited as direct food, are destined to aquafeed (A. Tacon, Hawaii Institute of Marine Biology, 2006, pers. comm.).

Stocking densities

Harmful discharges and transfers from mariculture farms have been directly correlated with stocking densities, regardless of development stage and culture (CBD 2004). Fish farm discharges into the environment include organic and inorganic wastes, uneaten feeds, mortalities, residual vaccine, antibiotics and other chemicals. Other potential transfers to marine systems such as potential illness and stress susceptibility are inherent in aquaculture. Limits on stocking densities which minimize the impacts of discharges and transfers are related to the carrying capacity of the farming system and subsequent carrying capacity of the surrounding ecosystem, which itself defines the true thresholds, and thus stocking limits to any farming enterprise (Bardach 1997).

Larvae and seed provenance

Farming activities often require juvenile stages for stocking purposes, such as seed and larvae, i.e., cannot produce their own and they may be dependant on wild fry collection. Depending on the species reproductive strategies and ecosystem sensitivity, harvesting of wild seeds may impact wild stocks and cause local population changes, as is the case for milkfish in Indonesia (Chua 1997). Hatchery and brood stock development can mitigate some of the negative effects that result from wild seed harvesting. Nevertheless genetic biodiversity may still be at risk in the medium and long term when hatchery stock is used and better management practices are still preferred.

Secondary habitat impacts

Environmental impacts from marine aquaculture operations can also be caused by poor site selection, construction phase impacts such as material transportation, road construction, housing, feed storage and inappropriate farm expansions. These are some examples of secondary impacts that need to be considered in any sustainability assessment, since they can affect ecosystems as well as coastal communities. These impacts tend to be overshadowed by more contentious and direct impacts such as pollution, chemical contamination, etc. Impacts caused by previous uses, e.g. agriculture or past aquaculture industries, should also carry some weight on the level of impact since they will influence future activities.

Waste treatment

Effluent waste and its management differ among and within farmed species, feed type, and culture method. Husbandry parameters and consequential drug and chemical discharges are dependent on local biotic and abiotic conditions along with infrastructure, e.g. human resources or government support services. Mitigating initiatives through better management and technological improvements such as re-circulating systems will for the most part contribute to waste reductions, but when the resulting benefits lead to increases of production, the effluent reduction achieved can be offset by production increases. This often results in no net changes from previous effluent levels.

3.4.3 Socio-economic indicators

The intent of sustainable production systems is not only to consider environmental aspects of the production process, but also the economic and social aspects, especially in the case of 'fair trade'. Countries striving to increase their economic development through trade, are often faced with a dilemma of importing 'food' versus exporting high-value food. In theory, if the economic benefits generated by exports are high, they can be used to meet local demands. However, in fisheries, this is often not the case, and trade has generated food insecurity in some countries (Alder and Watson 2007). The reasons for this failure are often due to unfair trade practices and corruption. Costa-Pierce (2001) supports exports, but also highlights the need to market locally to support community development.

Based on the concepts and guidelines previously defined and the need for fair trade and equitable distribution of the economic benefits gained from developing a mariculture industry, the following criteria were used to evaluate potential performance indicators (Table 3.4):

A: Fair trade and equity standards for production and market;

B: Employment standards;

C: Chemical and pharmaceutical use in final product;

D: Code of Practice existence, implementation and degree of impact;

E: SMART = Specific, Measurable, Accurate, Realistic, Time-Bounded.

Table 3.4 Socio-economic indicators chosen for this study and their performance with regards to socio-economic criteria.

Potential indicator	Criteria					Main source/references
	A	B	C	D	E	
Product destination	√	√			√	Naylor *et al.* (1998).
Chemical and pharmaceutical use	√		√	√	√	Folke and Kautsky (1992).
Genetic manipulation			√	√	√	Beardmore and Porte (2003)
Code of practice usage	√	√	√	√	√	FAO 1995; FAO (1999).
Traceability	√			√	√	Moretti *et al.* (2003).
Employment	√	√		√	√	Costa-Pierce (2001).
Nutrition; protein ratio			√	√	√	Tacon (2004).

These criteria were applied to the potential indicators presented above, with most indicators meeting 3 of the 5 criteria (Table 3.4). These seven indicators were therefore considered acceptable for the analysis (Table 3.5) and are described in detail below.

Benefit distribution

What, where and who is to farm? Aquaculture development, as stated before, has and still is, promoted as a relief option for food security deficits in developing nations and communities. The outcome of certain mariculture sectors have shown that benefits do not always trickle down, and that the sector often benefits only a few farmers or investors. Therefore, social benefits for any mariculture venture will be determined by local income distribution. Fair trade, which encompasses profit sharing, poverty alleviation efforts, food security standards and class discrimination also influences the distribution of social and economic benefits and needs to be considered in national assessments. When mariculture production aims to satisfy domestic or export demand, it should have clear social benefits, either as an affordable commodity for locals or as a source of foreign currency, which is then used to supplement domestic food supplies.

Use of chemicals and pharmaceuticals

Concern over antibiotic overuse, residual pesticides and piscicides, indiscriminate hormone and vaccine usage by the mariculture industry have all been widely reported (Naylor *et al.* 1998) and are indicative of overstocking and poorly managed mitigation measures. The drug levels and chemicals used in mariculture overlaps with ecological indicators in some areas. However, from a human health and food security perspective, it is an appropriate socio-economic indicator with less chemical and antibiotic use being better

Table 3.5: Potential socio-economic indicators of the sustainability of mariculture.

Socio-economic criteria	Description of practice and score scheme
Product destination	Culture is to satisfy international (1) or domestic demand (10).
Use of chemicals and pharmaceuticals	Indiscriminate use of antibiotics, pesticides, disinfectants, antifoulants, hormones and vaccines (1) or no use of chemicals or pharmaceuticals (10).
Genetic manipulation	Production of genetically modified organisms (e.g. fertile tetraploids) and transgenic species fall low in the scoring scheme (1). Well managed, sterile animals may or may not qualify for better management practices, but score > 1.
Code of practice usage	Certification, up to date set of standards and principles, i.e., FAO Code of Conduct (FAO 1995, 1999), or Eco-labeling are scored high, while no certification or similar scheme scores low (1)
Traceability	Food safety related to a specific geographical origin, slaughtering or processing facility, down to the batch of fish can be identified scores high (8-9). If the origin and preparation of feed used in the farmed sector is included then scores high (10).
Employment	Jobs created or strong community focus scores high (8-10); and where jobs are lost to the farming operations, or weak local community focus, score is low (1-3).

Genetic manipulation (Biosafety issues)

Farming genetically modified species (GMOs) or the use of modified strains of a species in all or any phase of the production cycle, including use of genetically manipulated feed, requires further analysis with regards to biosafety. Biological impacts have been documented with hybrid species (CBD 2004) but many more risks have not been properly studied yet. Given the uncertainties associated with GMOs, the lower the use of these organisms, the less risk there is to human health and higher the socio-economic sustainability. Nevertheless there is potential to manage these risks through further research on consequence of using GMOs in the ecosystem, and as a source of food for humans.

Use of code of practices

A measure of the extent an operation or species-specific industry complies with the objectives of sustainable value chain management provides an indication of socio-economic sustainability. Capitalizing on value chain management is an inherent part of the basic concept of sustainable production. It has the potential to enhance economic sustainability of all members of the value chain, making it an appropriate indicator (FAO 1999).

Traceability

The sustainable food chain management enhances the welfare and health of people and animals. However, if there is no oversight of the phases and the steps in production, processing, marketing and the final destination, then economic sustainability is at risk, since failure (e.g. food unsafe to eat) of any of the steps has a domino affect on participants further down the chain. Tracking of post harvest activities is imperative to food safety and food quality (Moretti *et al.* 2003). Nevertheless, the specific traceability analyzed here concerns only the productive phase of the mariculture industry. Therefore, only partial traceability is considered here, i.e., the production cycle before reaching the wholesaler.

Employment

When mariculture is planned as a highly integrated community-based local operation, employment opportunities and the potential for positive community impacts increase greatly (Costa-Pierce 2001). The ability of the specific mariculture enterprise to create economic niches, generate employment and to provide local sources of high quality foods is highly desired to meet socio-economic sustainability goals. When alternatives such as grow-out, feedlot concept operations are the norm, few benefits to communities are provided.

Nutritional value (protein content)

There are different types of protein and fats with different benefits to human health found in fish and invertebrates (Tacon 2004). However, determining the level of each protein was not possible and so it was decided that a simpler approach: total protein content per 100 grams of product. This indicator reflects levels of food security in different countries.

3.5 Scoring scheme

The scoring scheme, using a scale from 1 to 10 for each ecological and socio-economic indicator, was developed by examining the range of data values (minimum to maximum), practices (worst to best) and impacts (negative, neutral, and positive) for each indicator based on published literature. A minimum value of 1 was assigned to reflect a completely unsustainable situation, and a maximum value of 10 was used to reflect the ideal case for sustainability. The intermediate values were distributed to reflect the number and distribution of values, practices or impacts for each indicator (Appendix 1). The indictors based on discrete or continuous variables were standardized to values between 1 and 10. The 1 to 10 scale for all indicators is based on absolute numbers and avoids using relative scores. This approach using a 1 to 10 scale is simple without losing the resolution of the data so that the key characteristics of sustainability are evident and comparisons between country-species combinations now and in the future are possible.

In this study, an overall score of less than 6 [or 7 if, of the 13 indicators were less than 6] was considered unsustainable, between 6 and 8 as approaching sustainability and greater than 8 sustainable. This scheme for rating sustainability is similar to the Marine Stewardship Council approach for scoring capture fisheries.

3.6 Data sources and processing

The data used in this study (Appendix 2), came mainly from primary publications, i.e., official national (e.g. Canadian Department of Fisheries and Oceans) and international publications (e.g. Food and Agriculture Organization of the United Nations), internationally recognized websites with databases (e.g. the website of the Sea Around Us Project; www.seaaroundus.org) and academic research reported in peer-reviewed journals (Table 3.6).

The prices used in this study were extracted from the FAO FishStat database for each country-species combination. Anomalies were found in the dataset with extremely high values, and experts in the trade of seafood were queried about these prices (A. Tacon, Hawaii Institute of Marine Biology, 2006, pers. comm.). The spurious prices often were orders of magnitude higher than the price of related groups, and could be corrected straightforwardly.

Given the indicators identified in the previous section, a search of available and reliable data provided a number of datasets to quantify the indicators in Table 3.2. The datasets selected were for species that are commercially produced and that make up approximately 95% of total global mariculture production, and hence do not include species with very low production levels. The data were extracted from these datasets on a case-by-case basis and checked to ensure: the information was current and generated within the last 10 years; consistency, by ensuring data were within the likely range of possible values; and validity, by comparing the values obtained with other studies or reports. If these three criteria were met, the data was checked to make sure the value for the species was applicable throughout the country. Where more than one culture practice was evident for a species in the country, the proportion of production was estimated, and the data was adjusted accordingly. The data expressed in a decimal grade between 1 (worst-case) and 10 (best case/the perfect practice) were used to assign a value for each indicator.

Table 3.6 Type and source of data used to quantify ecological and social indicators.

Indicator	Data description	Sources	Comment
Native or introduced	Two way response (native or none native)	-State of the environment -Sea Around Us Project database. -FAO publications -FishBase -Other NGO publications	Country of origin and distribution is readily obtained from these sources, yet regional or within-region translocations are not.
Fishmeal use	-Use or no usage, and if so how much of it -Farm diet information -Industrial feed composition information	-Nutrition Journals -FAO publications -Field work -National statistical synthesis e.g. (SERNAP Chile) -Personal communications	Prevalent diet make-ups are not readily available; technological and economical issues will vary type and season when first and last used.
Stocking density	-Stocking capacity Better practice protocols, and maximum production carrying capacity	-Aquaculture Journals -Reports on best practices -NGO reports	Maximization of production capacity may be unknown. Practices differ from farm to farm, species to species
Seed and larvae origin	Origin, provider, hatchery implementation	-FAO publications -FishBase Aquaculture journals	Number of hatcheries per farm, unknown importation of larvae from outside
Habitat impacts	Direct and indirect effects on the surrounding environments; biodiversity change biomass changes, eutrophication etc.	-NGO publications -FAO publications -Environmental impact assessments -Scientific journals	Full knowledge of the effects is less common in developing and more remote areas.
Waste treatment	Use of filter system waste disposal implementation, re-use recycling systems.	-NGO publications -Field work -Scientific journals	Updated data is required for accurate estimations
Product destination	Destination market and secondary markets	-Scientific journals -FAO publications -Globefish -Personal communications	Market watch, under the scrutiny of market and economical forces and policies make the whereabouts of one product change from one day to the next
Chemical and drug use	Usage and how much	-Scientific journals -NGO publications	Seasonal changes in disease outbreaks and control may vary
Genetic manipulation	Use of GMOs species, feed, derivatives	-Scientific journals -FAO publications	Banned use for direct human consumption, non genetically altered species are key
Code of practice	Implementation or not and of which code and standards	-Scientific journals -FAO publications	Reports based on national policy may vary with current activity
Traceability	Market and product control and monitoring	-Scientific journals -FAO publications -NGO publications -Personal communication	Great void in developing and more remote areas.
Employment	Equity, fair trade, number of employees per farm	-Scientific journals -NGO publications -FAO publications -Personal communication	Accessibility problems and lack of interest for smaller productions may harbor poor working conditions
Nutrition, protein ratio	Protein content	Nutrition and Diet Journals	The type of protein was not taken in account in this study

The values were entered into a Microsoft Access database and, where required, used to construct spreadsheets for further analyses or for import into a statistical program. For each country-species combination a 'case', additional details on the country, species, organism category, FAO coastal zone and habitat were also recorded. Data was collected for 60 countries spanning all continents except Antarctica, covering the world's main coastal ecosystem types, and the diverse group of cultured species.

Some data sources provided data that could be used directly as an indicator e.g. native vs. introduced, or stocking density. Other data sources were combined to jointly provide quantitative measures for an indicator e.g. direct and indirect employment, fish diet and food conversion ratio. Where data were not used directly, and required some form of processing, the process is outlined below and described in detail in Appendix 3.

3.7 Data quality

Data from primary sources were preferred since they are generally more reliable, consistent and well documented. When they were insufficient, secondary publications and sources were investigated. However, consistency was maintained to ensure their comparisons across species and countries could be made. If no data was available, a similar and adjacent country that produced the same species was used to estimate the corresponding value. The data used applied to the period between 2000 and 2003.

When a guesstimate for an indicator in one country was issued using neighbouring country information, the final score could not be inferior to the score used in the first place. Another point of concern was the species group consisting of more than one species, which is the case for 'nei' groups. Other sources of information were used to determine what would be the likely species in that group and then 50% of the score would be allocated to that group and 50% to the score on the remaining nei groups. This was meant to leave the benefit of doubt to the non-specific group, but, as well, tax the country that does not specify the composition of their aquaculture production. Examples include 'cephalopods nei' or 'sturgeons nei', where at least two species are known to be produced. In these cases, the ratio or the extent of one over the other set the estimate for the score.

3.8 Data analyses

The values of the 13 indicators derived from the data described above were analyzed using a correlation matrix to check the level of association between indicators, and the extent of co-linearity, consistency and reliability. Correlation coefficients were also used to check for consistency between the overall ecological and socio-economic indicators.

Principal component analysis (PCA) was used to examine the importance of the indicators to overall sustainability (Manly 1998). PCA is a multivariate statistical method that reduces multi-dimensional systems to a few dimensions generally 4 or less (Manly 1998). The reduction of the dataset to a smaller number of factors is often expressed as eigenvalues: the greatest variance of the dataset is in the first component, the next greatest amount of variance is in the second component, and so on, until the number of components equals the number of original factors. In this case, the 13 indicators accounts for all of the variation, i.e., 1.0 (Table 4.3a). The number of components to use in the analyses is based on the amount of variation in the eigenvalues. For each component, eigenvectors (Z1 and Z2) were also derived and were used to map the cases onto the principle components, generally in the first (Z1) and second dimension (Z2) (Table 4.3b). The eigenvectors were used to calculate the individual Z1 and Z2 scores in two dimensions to explore differences between species groups and countries (see Figures 5.1 and 5.2). The scoring coefficients (Table 4.3c) were calculated to determine if one or more indicators dominated the assessment. Scoring coefficients can be considered as correlation coefficients between the original indicators and the extracted principle components, with high values reflecting high association between the original indicators and components, and a negative value indicating an inverse association. STATA, version 8, was used for the correlation and PCA analyses (StataCorp 2005).

A mariculture sustainability index (MSI) was calculated for each country-species combination using the average of the 13 indicators with values ranging from 1 to 10. The MSI was weighted using total production for the period from 1994 to 2003 to account for differences in annual production between species, as well as the differences in production between countries and the differences in the species produced. Production in the period 1994 to 2003 was used to weight the MSI to account for differences in performance between operations that were operating for a longer time (more weight) than more recent or emerging operations (less weight). This enabled comparisons between species and countries as well as the calculation of ecological, socio-economic and overall mariculture sustainability indices to be made. These indices were compared to other sustainability indices such as the Environmental Sustainability Index (ESI; Esty *et al.* 2005) and the Human Development Index (HDI; UNDP 2006), as well as low-income food deficit countries (LIFDC; FAO 2002) were also compared.

Chapter Four

4.1 Introduction

This chapter presents the analysis results of testing the coherence and robustness of the 13 indicators presented in Chapter 2, applying those indicators to a range of countries and comparing the results to other indices of sustainability. The scores based on these indicators and the mariculture sustainability index (MSI) are presented, and summarized by country, species group and taxa. The production and prices paid are also discussed for species with high MSI scores (where a high score, e.g. 10, equals high sustainability) and for a range of developing countries, in particular those with low incomes and a food deficit.

4.2 Indicator scores

This assessment generated a total of 361 cases (country – species combinations) and associated MSIs covering 60 countries and 86 species or species groups (Appendix 2) for the period from 1950 to 2003, with focus on the last 10 years. The possible MSI ranged from 1 (low sustainability) to 10 (high sustainability). The highest MSI was 8.4 with seaweed grown in Chile and the lowest score was 1.7 for Whiteleg shrimp farmed in Thailand. A score of less than 6 was considered unsustainable, since it implies that (based on a weighted average for the country or species) the combined score (MSI) was less than 6, or the majority of indicators scored less than 6. A score of between 6 and 8 was considered as approaching sustainability. A score greater than 8 was considered sustainable. In this analysis, 13 cases were greater than or equal to 8 (sustainable), 112 cases were between 6 and 8 (approaching sustainability) and 236 cases were less than or equal to 6 (not sustainable). The average score for each indicator ranged between 4.5 and 7.6 (Table 4.1).

Table 4.1. Summary statistics for the 13 indicators of mariculture sustainability.

Indicator	Average	Std. Dev.	Min	Max
Native/introduced	7.3	3.63	1	10
Export levels	4.5	1.87	1	10
Fishmeal use	5.2	3.62	1	10
Stocking intensity	4.8	2.63	1	10
Nutrition	7.6	2.46	2	10
Hatchery use	5.0	1.84	1	10
Antibiotic use	5.2	3.40	1	10
Habitat modification	5.0	2.04	1	10
GMOs	6.4	1.78	2	10
Code of Conduct compliance	5.2	1.44	1	9
Traceability	5.5	1.87	1	10
Employment	5.4	1.26	3	8
Waste management	5.4	3.08	1	10

The number of farmed species in this study varied by country, ranging from a minimum of 1 in a number of countries to a maximum of 19 in Taiwan. In approximately 40% of the cases, there was incomplete data to estimate the MSI. However, it was usually only one indicator that was missing and in most instances, it was a socio-economic indicator. For these records, the missing score was estimated based on information from adjacent countries, secondary sources or personal communications.

The correlation matrix of the 13 indicators (Table 4.2) resulted in significant correlations between fishmeal, stocking intensity, nutrients and habitats. However, on closer examination, these significant correlations were not directly related or were not from the same core dataset, but reflected the logic of how specific culturing practices relate to each other (e.g. a high fishmeal score implies herbivorous organisms such as bivalves, which score low for protein, and therefore have a significant negative correlation). A correlation analysis was also used to look at the relationship between the total ecological score and socio-economic score (Figure 4.1), which indicated a positive and significant relationship.

Table 4.2: Correlation matrix of the 13 indicators of mariculture sustainability, high positive numbers indicate a strong association while high negative numbers indicated a strong but inverse association.

Indicators	Indicators												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
1. Native/introduced	1.00												
2. Export	0.02	1.00											
3. Fishmeal	-0.17	-	1.00										
4. Intensity	-0.13	0.20	0.80	1.00									
5. Nutrition	0.21	0.26	-0.84	-0.76	1.00								
6. Hatchery	-0.15	0.24	0.34	0.40	-0.38	1.00							
7. Antibiotic	-0.14	0.21	0.87	0.82	-0.84	0.44	1.00						
8. Habitat	-0.13	0.25	0.74	0.74	-0.78	0.55	0.83	1.00					
9. GMO	0.17	0.05	0.38	0.43	-0.28	0.01	0.42	0.32	1.00				
10. Code of conduct	-0.18	0.25	0.42	0.45	-0.50	0.51	0.57	0.60	0.05	1.00			
11. Traceability	-0.09	0.20	0.38	0.44	-0.46	0.58	0.53	0.59	0.19	0.65	1.00		
12. Employment	0.06	-0.17	0.18	0.23	-0.25	-0.05	0.26	0.13	0.01	0.19	0.09	1.00	
13. Wastes	-0.15	0.26	0.76	0.71	-0.78	0.49	0.81	0.81	0.27	0.49	0.47	0.17	1.00

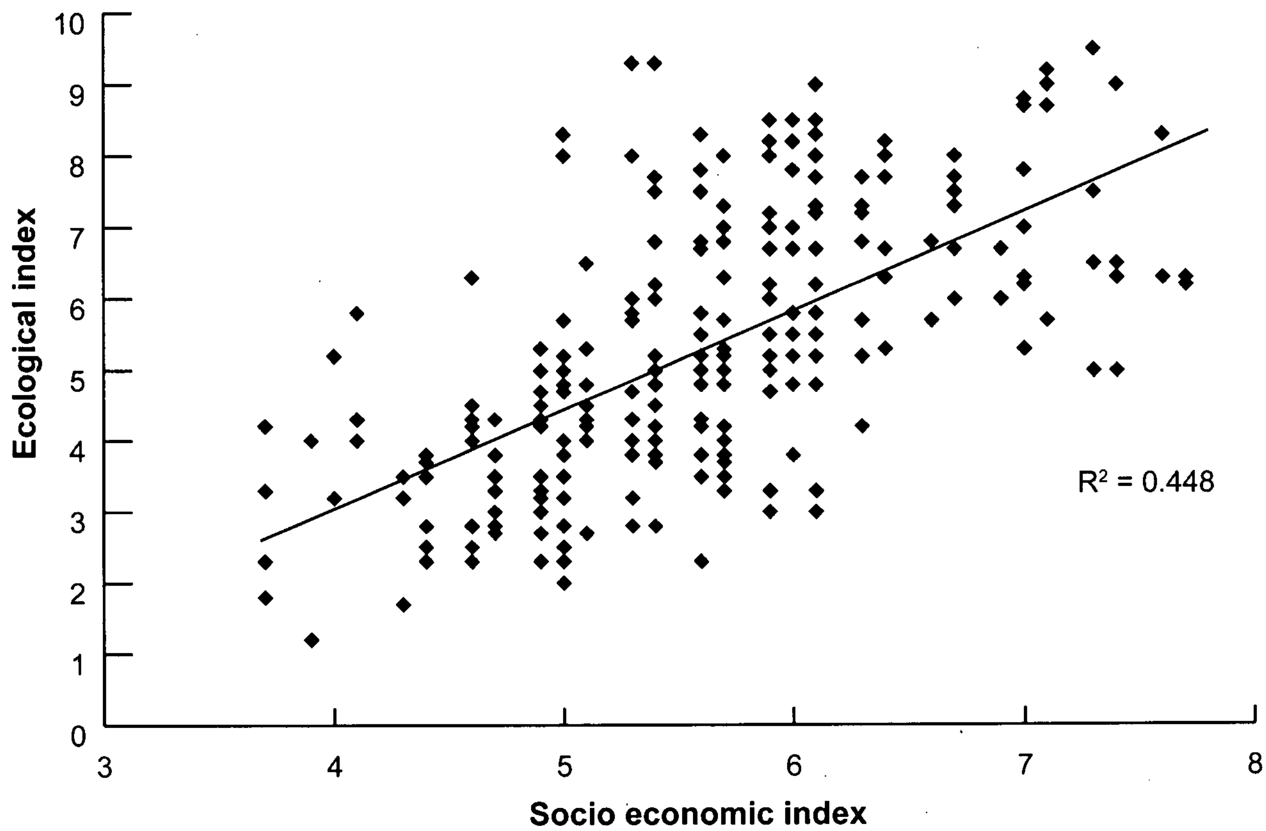

Figure 4.1 Correlation between ecological (x-axis) and socio-economic (y-axis) indicators of mariculture sustainability for 361 cases.

The principle component analysis of the 13 indicators (Table 4.3) suggests that two to four components account for the overwhelming bulk of the variability (see Section 3). The first two components account for 60% of the variation in the 13 indicators (Table 4.3a). The coefficients for the first two components (Z1 and Z2) of the analysis are presented here (Table 4.3b) and used later to explore the effect of country and species (see Section 5.2). The scoring coefficients, which provide a relative measure of the degree of association between indicators, ranged from -0.34 to 0.373 (Table 4.2c) with 4 coefficients (native/foreign, domestic/exports, GMOs and employment) having absolute values less than 0.25 and therefore not considered to be highly associated with the first component. Nutrition (protein content) was associated with the first component, but negatively.

Table 4.3 Results of principal component analyses a) eigenvalues in the 13 components and the proportion of variance explained, b) the eigenvectors Z1 and Z2 used to estimate the Z1 and Z2 values used to map the cases onto the components, and c) the scoring coefficients for the 13 indicators.

a)

Component	Eigen value	Difference	Proportion	Cumulative prop.
1	6.29	4.821	0.484	0.484
2	1.469	0.269	0.113	0.597
3	1.201	0.175	0.092	0.689
4	1.026	0.231	0.079	0.768
5	0.795	0.194	0.061	0.829
6	0.601	0.16	0.046	0.876
7	0.44	0.136	0.034	0.909
8	0.304	0.035	0.023	0.933
9	0.27	0.074	0.021	0.954
10	0.196	0.028	0.015	0.969
11	0.168	0.022	0.013	0.981
12	0.146	0.05	0.011	0.993
13	0.096	----	0.007	1

b)

Indicator	Component	
	Z1	Z2
Native/introduced	-0.076	0.274
Export levels	0.117	-0.309
Fishmeal use	0.345	0.21
Stocking intensity	0.344	0.171
Nutrition	-0.35	-0.149
Hatchery use	0.236	-0.453
Antibiotic use	0.373	0.146
Habitat modification	0.363	-0.029
GMOs	0.151	0.438
Code of Conduct compliance	0.271	-0.324
Traceability	0.264	-0.314
Employment	0.089	0.332
Waste management	0.348	0.031

c)

Indicator	Scoring co-efficient
Native/introduced	-0.076
Export levels	0.117
Fishmeal use	0.345
Stocking intensity	0.344
Nutrition	-0.35
Hatchery use	0.236
Antibiotic use	0.373
Habitat modification	0.363
GMOs	0.151
Code of Conduct compliance	0.271
Traceability	0.264
Employment	0.089
Waste management	0.348

4.3 Mariculture Sustainability Index (MSI)

The ten highest performing countries, based on a weighted index (MSI weighted by production), consisting of ecological and socio-economic indicators, were: Germany, The Netherlands, Spain, Japan, Russian Federation, North Korea, South Korea, Ireland, France and Argentina (Table 4.4). Six of these top ten countries are developed and European, while the remaining countries are considered to be economies in transition except North Korea which is a developing country. There is no consistency between countries that score high for the ecological indicators and countries scoring high for socio-economic indicators as seen in Iceland which was ranked 13th with an MSI of 6.2 overall but ranked 22nd for ecological (score of 5.4) and 2nd for socio-economic (score of 7.1).

The ten lowest scoring countries are: Guatemala, Cambodia, Bangladesh, Honduras, Myanmar, Belize, Chile, Norway, Brazil and Faeroe Islands (Table 4.4). Eight of the 10 countries are developing and spread across Latin America and Asia. The remaining two countries are European. Most of these countries scored low for both ecological and socio-economic indicators. The 60 countries evaluated and their respective MSI scores are depicted in Figure 4.2.

4.3.1 Ecological indicators

Four of the top five performing countries based on a weighted index composed of the six ecological indicators were European: Germany, Netherlands, Spain, Japan and the Russian Federation (Table 4.5). Most of the countries scored high for limiting introduced species, their use of fishmeal and their treatment of waste and water. The countries cultured a mix of bivalves and fish, with the Russian Federation also culturing marine plants.

The majority of the lowest scoring nations (Table 4.6) for ecological sustainability are highly dependant on aquafeeds that are rich in fishmeal and fish oil, and which were essential for many of the species produced through 1994 to 2003. Low scores for stocking density and insufficient waste treatment were also common for the lowest scoring nations. Low scores of these indicators suggest a higher risk on impacting surrounding habitat, especially, when these farms are open system cultures.

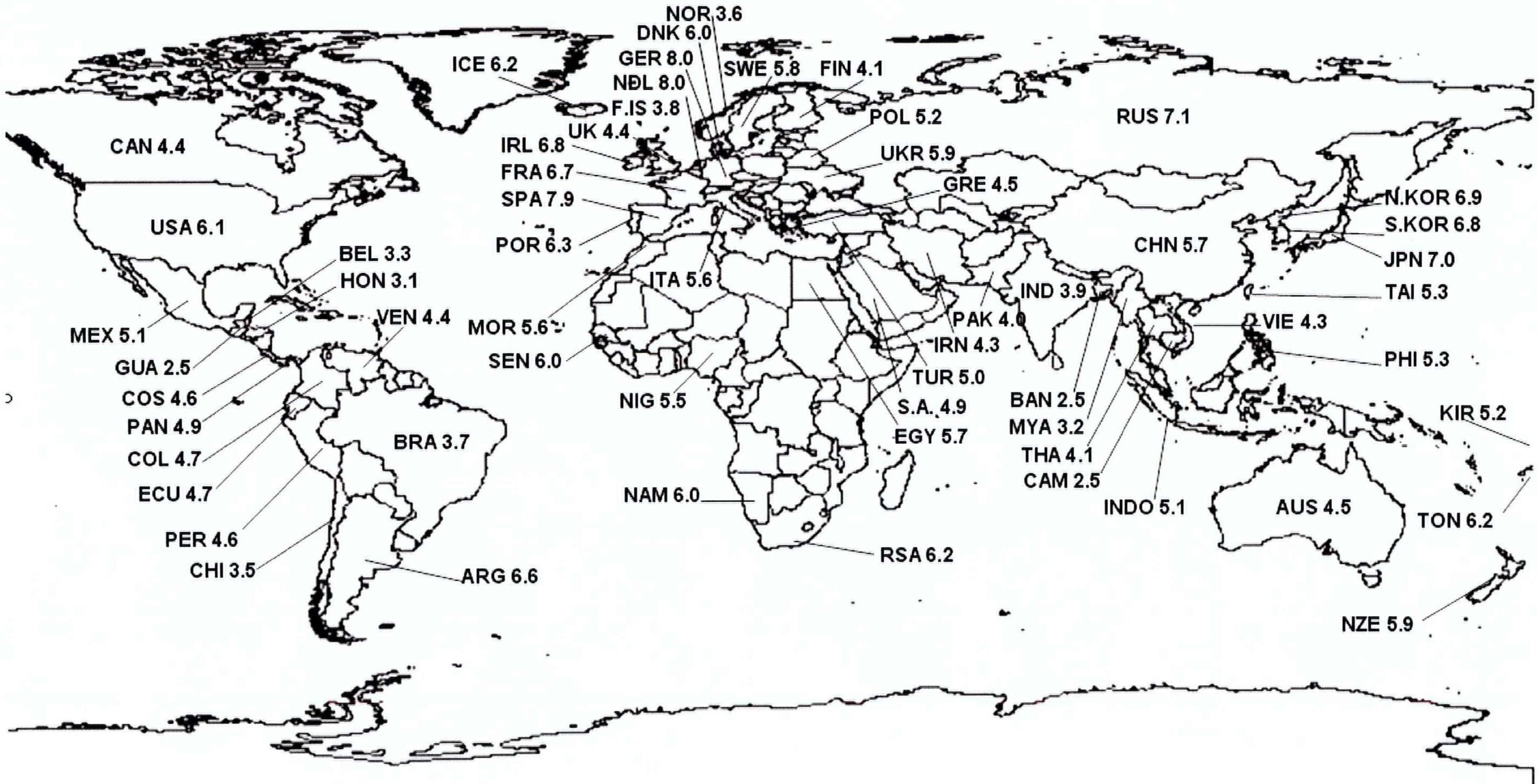

Figure 4.2 The resulting MSI of the 60 countries analyzed in this study

Table 4.4 Rankings and weighted MSI (top and bottom 10) and ecological and socio-economic scores by country; 10 indicate high sustainability and 1 is low sustainability of mariculture.

Country	Rankings			Scoring		
	Ecological	**Socio-eco**	**MSI**	**Ecological**	**Socio-eco**	**MSI**
Germany	1	1	**1**	9.0	7.1	**8.0**
Netherlands	2	2	**2**	9.0	7.1	**8.0**
Spain	3	3	**3**	8.7	7.1	**7.9**
Japan	5	6	**4**	7.5	6.5	**7.0**
Russian Federation	4	27	**5**	8.4	5.4	**6.9**
Korea, North	6	8	**6**	7.4	6.4	**6.9**
Korea, South	10	9	**7**	7.1	6.4	**6.8**
Ireland	7	12	**8**	7.4	6.1	**6.8**
France	14	5	**9**	6.4	7	**6.7**
Argentina	8	17	**10**	7.4	5.9	**6.6**
--	-	-	-	-	-	-
India	54	39	**50**	2.8	5.0	**3.9**
Faeroe Islands	40	56	**51**	4.5	3.0	**3.8**
Brazil	57	46	**52**	2.5	4.8	**3.7**
Norway	50	53	**53**	3.5	3.7	**3.6**
Chile	53	51	**54**	2.9	4.1	**3.5**
Belize	56	52	**55**	2.7	3.8	**3.3**
Myanmar	55	54	**56**	2.8	3.7	**3.2**
Honduras	52	57	**57**	3.2	3.0	**3.1**
Bangladesh	58	58	**58**	2.3	2.7	**2.5**
Cambodia	59	59	**59**	2.3	2.7	**2.5**
Guatemala	60	60	**60**	2.3	2.7	**2.5**

Table 4.5 Ecological scores for the 5 highest scoring countries; number in brackets is the total weighted ecological sustainability score for each species in that country. The 6 indicators used are: *Native vs. Introduced* (**Nat. vs. Int.**), *Fish meal/oil* (**F. meal**), *Intensity* (**Int.**), *Hatchery vs. Wild seed* (**H. vs. W.**), *Habitat Impact* (**H. Impact**), *Waste treatment* (**W. treat.**).

Country	Species	Indicator (10 indicates high sustainability and 1 is low/non sustainable)					
		Nat. vs. Int.	**F. meal**	**Int.**	**H. vs. W.**	**H. Impact**	**W. Treat.**
Germany	Blue mussel	10	10	9	8	7	10
	European seabass	10	3	5	7	5	7
	Pacific cupped oyster	1	10	10	5	7	1
Netherlands	Blue mussel	10	10	9	8	7	10
	Cupped oysters nei	5	10	7	7	9	10
	European flat oyster	10	10	7	5	7	10
Spain	Atlantic salmon	10	1	2	3	3	1
	Blue mussel	10	10	9	8	7	10
	Cupped oysters nei	5	10	10	7	8	10
	European eel	10	3	3	3	6	7
	European flat oyster	10	10	7	5	7	10
	European seabass	10	3	5	5	5	5
	Flathead grey mullet	10	3	5	5	5	5
	Gilthead seabream	10	1	1	3	3	1
	Kuruma prawn	1	3	5	5	5	7
	Pacific cupped oyster	1	10	7	5	7	10
	Tuna-like fishes nei	10	1	3	1	5	1
Japan	Coho (=Silver) salmon	10	1	1	5	3	5
	Flathead grey mullet	10	3	5	5	5	5
	Kuruma prawn	10	3	5	5	4	7
	Laver (Nori)	10	10	7	5	7	7
	Pacific cupped oyster	10	10	7	3	5	10
Russian Federation	Atlantic salmon	1	3	3	6	3	4
	Brown seaweeds	10	10	10	8	8	10
	Flatfishes nei	5	3	4	5	4	5
	Marine fishes nei	5	3	4	5	4	5
	Mediterranean mussel	10	10	7	6	7	8
	Mullets nei	5	5	5	5	4	5
	Sea mussels nei	5	10	7	5	7	8
	Sea trout	10	3	3	6	3	5
	Sea urchins nei	5	5	7	5	7	5
	Silver carp	10	5	3	6	4	5
	Sturgeons nei	5	5	6	6	4	5
	Yesso scallop	10	10	7	7	7	7

Table 4.6 Ecological scores for the 5 lowest scoring countries; number in brackets is the total weighted ecological sustainability score for each species in that country. The 6 indicators used are: Native vs. Introduced (**Nat. vs. Int.**), Fish meal/oil (**F. meal**), Intensity (**Int.**), Hatchery vs. Wild seed (**H. vs. W.**), Habitat Impact (**H. Impact**), Waste treatment (**W. treat.**),

Country	Species	Indicator (10 indicates high sustainability and 1 is low/non sustainable)					
		Nat. vs. Int.	F. meal	Int.	H. vs. W.	H. Impact	W. Treat.
Norway	Atlantic cod	10	1	3	3	3	1
	Atlantic salmon	10	1	1	5	3	1
	Blue mussel	10	10	9	8	7	10
	European flat oyster	10	10	7	5	7	10
	Pacific cupped oyster	1	10	7	2	7	10
Thailand	Barramundi (=Giant seaperch)	10	1	1	3	3	1
	Blood cockle	10	10	7	3	5	7
	Cupped oysters nei	5	10	7	5	6	10
	Giant tiger prawn	10	1	1	1	1	1
	Groupers nei	9	1	5	5	3	4
	Penaeus shrimps nei	5	3	1	3	1	2
	Whiteleg shrimp	1	3	1	3	1	1
Chile	Abalones nei	1	10	1	7	3	3
	Atlantic salmon	1	1	1	1	1	2
	Coho (=Silver) salmon	1	1	1	5	1	2
	Gracilaria seaweeds	10	10	10	7	10	10
	Pacific cupped oyster	1	10	7	5	7	1
India	Giant tiger prawn	10	1	1	3	1	1
Myanmar	Giant tiger prawn	10	1	1	3	1	1
Belize	Whiteleg shrimp	1	3	3	5	1	3
	Cupped oysters nei	7	10	7	7	7	10
Brazil	Groupers nei	9	1	5	5	5	4
	Whiteleg shrimp	1	3	3	5	1	1

4.3.2 Socio-economic indicators

Germany, The Netherlands, Spain, Iceland and France are the five highest scoring countries for socio-economic indicators (Table 4.7). They all emphasize production of carnivorous species such as finfish and crustaceans, and yet they are also top bivalve producers, which provide high sustainability scores via the socio-economic indicators.

Table 4.7 Five highest scoring countries for socio-economic sustainability; 10 indicates high sustainability and 1 is low sustainability, the 7 indicators are: Export vs. Domestic (**Ex vs. Do**), Nutrition-Protein content (**Prot**), Antibiotic and drug use (**Drug**), Genetically modified organism use (**GMO**), application of Code of Practice (**CoP**), Traceability (**Trace**), Employment (**Emp**).

		Indicator (10 indicates high sustainability and 1 is low/non sustainable)						
Country	**Species**	**Ex vs. Do**	**Prot**	**Drug**	**GMO**	**CoP**	**Trace**	**Emp**
Germany	Blue mussel	7	5	10	10	5	7	6
	European seabass	5	9	5	5	7	7	5
	Pacific cupped oyster	5	4	10	7	9	9	6
Netherlands	Blue mussel	7	5	10	10	5	7	6
	Cupped oysters nei	5	4	10	3	7	7	7
	European flat oyster	5	4	10	7	7	5	7
Spain	Atlantic salmon	1	9	1	5	3	4	3
	Blue mussel	7	5	10	10	5	7	6
	Cupped oysters nei	5	4	10	3	7	7	7
	European eel	7	9	5	7	5	5	7
	European flat oyster	5	4	10	7	7	5	7
	European seabass	5	9	3	5	5	7	7
	Flathead grey mullet	5	9	4	7	5	7	5
	Gilthead seabream	3	9	1	5	5	7	7
	Kuruma prawn	7	9	1	5	5	7	3
	Pacific cupped oyster	3	4	10	7	6	7	6
	Tuna-like fishes nei	5	10	5	10	3	1	5
Iceland	Abalones nei	1	8	7	9	7	10	5
	Arctic char	5	9	9	7	7	10	5
	Atlantic cod	5	9	8	9	7	10	5
	Atlantic halibut	5	9	8	9	8	10	5
	Atlantic salmon	5	9	8	7	7	10	5
	Atlantic wolffish	1	7	10	9	7	10	5
	Blue mussel	10	5	8	7	8	10	5
	European seabass	5	9	8	8	7	10	5
	Haddock	5	8	8	9	7	10	5
	Rainbow trout	5	10	8	7	7	10	5
	Spotted wolffish	5	7	8	9	7	10	5
	Turbot	5	8	8	8	7	10	5
France	Atlantic salmon	1	9	4	5	5	5	5
	Blue mussel	7	5	10	10	5	7	6
	Coho (=Silver) salmon	3	9	4	3	5	5	5
	European eel	7	9	5	7	5	5	7
	European flat oyster	5	4	10	7	7	5	7
	European seabass	5	9	3	5	5	7	5
	Gilthead seabream	1	9	1	5	5	7	7
	Kuruma prawn	7	9	4	5	5	7	3
	Pacific cupped oyster	5	4	10	7	8	8	7

The five lowest scoring countries were Myanmar, Honduras, Bangladesh, Cambodia and Guatemala (Table 4.8). They are all developing countries and intensively farm shrimps. Low scoring developed countries are European with high tonnage of Atlantic salmon. Pharmaceutical use and the export orientation of these two main species groups were common across developing and developed countries for many of the species cultured.

Table 4.8. Eight lowest scoring countries for socio-economic sustainability; 10 indicates high sustainability and 1 is low sustainability, the 7 indicators are: Export vs. Domestic **(Ex vs. Do)**, Nutrition-Protein content **(Prot)**, Antibiotic and drug use **(Drug)**, Genetically modified organism use **(GMO)**, apply Code of Practice **(CoP)**, Traceability **(Trace)**, Employment **(Emp)**.

Country	Species	Indicator (10 indicates high sustainability and 1 is low/non sustainable)						
		Ex vs. Do	**Prot**	**Drug**	**GMO**	**CoP**	**Trace**	**Emp**
Norway	Atlantic cod	7	9	1	8	5	7	3
	Atlantic salmon	1	9	1	5	5	5	5
	Blue mussel	7	5	10	10	5	7	6
	European flat oyster	5	4	10	7	7	5	7
	Pacific cupped oyster	5	4	10	7	8	8	7
Myanmar	Giant tiger prawn	1	10	1	7	4	3	6
Finland	Atlantic salmon	1	9	1	6	7	5	5
Faeroe Islands	Atlantic salmon	1	9	1	7	6	5	5
Honduras	Penaeus shrimps nei	5	10	1	5	2	2	3
Bangladesh	Penaeus shrimps nei	5	10	1	6	4	1	5
Cambodia	Penaeus shrimps nei	5	10	1	6	4	1	5
Guatemala	Penaeus shrimps nei	5	10	1	5	1	1	3

The environmental sustainability index (ESI) and the human development index (HDI) are not closely associated with the ecological and socio-economic indices, that comprise the MSI indicator (Table 4.9). The closest association was between the HDI and the socio-economic indicator, with many of the higher ranking MSI countries also having relatively higher ranking HDI scores.

Table 4.9 The top 10 countries and their Mariculture Sustainability Index MSI (along with it's two major sustainability components; Ecological index 'ECO' and Socio-economic Index 'Soc-Eco') are compared to their respective ranks in both Environmental Sustainability Index "ESI" (146 countries) and the Human development Index "HDI" (177 countries).

		Ecological dimension		**Socio-economic dimension**	
Country	**MSI rank**	**ECO index**	**ESI rank**	**Soc-Eco index**	**HDI rank**
Germany	1	1	31	1	21
Netherlands	2	2	40	3	10
Spain	3	3	76	4	19
Japan	5	5	30	7	7
Russian Federation	4	4	33	27	65
Korea, North	6	7	n/a	8	n/a
Korea, South	7	10	n/a	9	26
Ireland	8	6	21	12	4
France	9	14	36	5	16
Argentina	10	8	9	17	36

The MSI for low-income food deficit countries (LIFDC) was low except for North Korea, which farms high-value yet sustainable abalone, and Morocco, which farms relatively sustainable bivalves. Overall, LIFDC countries generally receive high prices for cultured species, averaging over > 1 USD/kg for their farmed seafood. The exceptions are Senegal and Pakistan where prices are lower than 1 USD/kg (Table 4.10). Prices were not available for cultured species in North Korea and Nigeria.

Table 4.10 MSI and Average price USD per kilo for low-income food deficit countries (LIFDC); prices are averaged over all species farmed and sources from FishStat (FAO 2004).

LIFDC Country	Country MSI	Average 2001-2003 USD per kilo
Bangladesh	3.5	3.4
Cambodia	3.5	5.4
China	5.5	2.1
Ecuador	4.6	6.2
Egypt	4.9	3.6
Honduras	3.6	6.0
India	3.9	6.3
Indonesia	4.3	4.4
Kiribati	5.5	1.4
Korea, North	7.1	N/A
Korea, South	5.9	15.2
Madagascar	4.0	5.0
Morocco	6.0	2.1
Nicaragua	4.8	4.7
Nigeria	4.9	N/A
Pakistan	4.3	0.5
Philippines	4.8	2.5
Senegal	5.5	0.6
Sri Lanka	3.8	10.2

4.4 Culturing environment

Mollusk culturing was the highest scoring form of farming based on a weighted score in culturing environments (Table 4.11), especially in marine waters. In brackish water, finfish was the highest scoring animal culturing system and crustacean culturing was lowest overall, with a combined MSI of 3.9 (Table 4.11). Cultured crustaceans are primarily shrimp and prawns and account for much of the annual average growth rate in mariculture over the last decade. However, much of this growth is from intensive farm operations, which are low-scoring systems.

Table 4.11 Average MSI per environment and taxonomic group.

	Major taxa		
Environment	**Crustaceans**	**Finfish**	**Mollusks**
Brackish water culture	3.8	5.7	4.7
Mariculture	4.3	3.9	6.0
Combined	3.9	4.3	6.0

Plants have the highest weighted score of all the major taxa, especially in brackish water, where their score is 8, twice as high as for crustaceans in brackish water. There is minimal difference in scores between brackish water and mariculture for non-plant organisms.

4.5 Cultured species

The highest MSI scoring species are presented below. As mentioned above, cultured crustaceans in general fail to reach a passable sustainability level, since the scores are less than 5 for Kuruma prawn, Indian white prawn and Banana prawn. Finfish species peak at an MSI of 7 for Rainbow trout, Halibut and Wolfish. Nevertheless, these are smaller and isolated productions in countries with a small share of the global aquaculture market. However, species such as milkfish scored just above 5 in both brackish water and mariculture, while better-known brackish water species such as mullet, and mariculture species such as Atlantic salmon failed to reach the top 10 species, according to the MSI. On the other hand, mollusk (more precisely bivalves) scored very well. This applies to species such as Blue mussel, flat oysters and Grooved carpet shell. The latter is also featured in brackish cultured environment along with cupped oysters and European flat oysters, scoring above 7 in the MSI index.

4.6 Stocking density

The two species of crustaceans (Whiteleg shrimp) and finfish (Milkfish) that are cultured extensively score low on the weighted sustainability score (Table 4.12). In this study, there are less than 10 species of crustaceans that are farmed semi-intensively, and more than 10 extensively. Natantian decapods and Baltic prawns are the exception to the generally low scores assigned to crustaceans (Table 4.12). A combination of low socio-economic scores (e.g.

traceability, export driven), poor waste management and limited regulatory guidelines accounts for the remaining species scoring low on sustainability.

The single species of Milkfish that is farmed extensively (*Chanos chanos*) was scored lower than many semi-intensively and intensively farmed finfish (Table 4.12). This is due to limited traceability, poor waste management, larvae and dependence on wild capture fisheries for seed requirements. Overall, semi-intensively cultured finfish score higher than those intensively cultured (Table 4.12). Most finfish are intensively cultured using aquafeeds with open systems. In addition, most of these fish are exotics.

The few mollusks that are cultured intensively scored between 5 and 8, which is within the range of scores for semi-intensively cultured mollusks (Table 4.12). The exception to this is the Pacific cupped oyster, which is an introduced species in many areas. There was little variation between scores for semi-intensively cultured mollusks, which ranged from 6.9 to 7.3; this is because they do not require aquafeeds.

Table 4.12 Lowest MSI scoring species and species groups in culturing environments.

Extensive	MSI
Crustaceans	-
Whiteleg shrimp	4.6
Finfish	-
Milkfish	5.9
Mollusks	-
n/a	n/a
Plants	-
Aquatic plants nei	6.9
Brown seaweeds	7.3
Gracilaria seaweeds	6.9
Laver (Nori)	6.9

Semi-intensive	MSI
Crustaceans	-
Natantian decapods nei	7.3
Kuruma prawn	5.4
Indian white prawn	4.5
Whiteleg shrimp	4.3
Giant tiger prawn	4.0
Penaeus shrimps nei	3.5
Baltic prawn	7.3
Finfish	-
Mullets nei	8.8
Spotted wolffish	7.7
Atlantic wolffish	7.4
Atlantic halibut	7.0
Rainbow trout	7.0
Arctic char	6.9
Turbot	6.9
Haddock	6.9
Silversides(=Sand smelts) nei	6.0
So-iuy mullet	5.9
Mollusks	-
Mediterranean mussel	7.4
Razor clams nei	7.4
Smooth mactra	7.3
Perlemoen abalone	7.2
Pullet carpet shell	7.0
Common cuttlefish	7.0
Gasar cupped oyster	7.0
Yesso scallop	7.0
Marine mollusks nei	6.9
Blood cockle	6.9

Intensive	MSI
Crustaceans	-
Baltic prawn	5.2
Marine crustaceans nei	4.7
Indian white prawn	4.6
Kuruma prawn	4.6
Banana prawn	4.5
Giant river prawn	4.0
Giant tiger prawn	3.6
Whiteleg shrimp	3.5
Finfish	-
Blackchin tilapia	6.6
Trouts nei	6.0
European eel	5.9
Common sole	5.8
European seabass	5.4
Turbot	5.3
Sea trout	5.3
Rainbow trout	5.2
Freshwater fishes nei	5.0
Seabasses nei	4.8
Mollusks	-
Common edible cockle	8.1
Octopuses nei	7.3
Mediterranean mussel	6.7
Pacific cupped oyster	5.5

4.7 Trends in production

4.7.1 Unsustainable production

In both analyses of the overall sustainability MSI, culturing environment and stocking density for Atlantic salmon was scored low relative to other species. The production of Atlantic salmon has been steadily increasing over the last 10 years, and overall tonnage (> 100 thousand tonnes) has been much higher than other species (Figures 4.3), with low sustainability scores. The low scoring species are shown in Figure 4.3 without the high values of Atlantic salmon that would otherwise dwarf their production numbers. The production of Coho salmon, shrimp and seabass has also been increasing, but slowly; for Barramundi, production has been constant over the last 10 years.

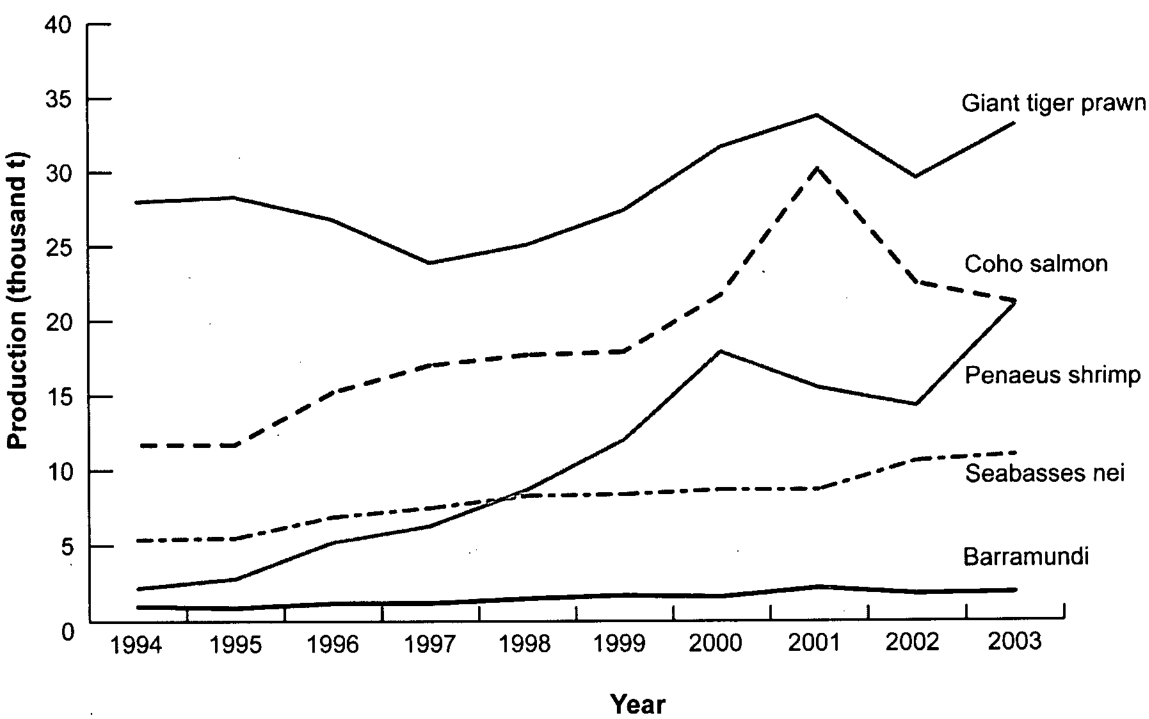

Figure 4.3: Trends in production (thousand t) without Atlantic salmon (for the years between 1994 and 2001 inclusive) of the most unsustainable practices in mariculture species production, (i.e., Atlantic salmon [not shown], Coho salmon, Barramundi and seabass and as for crustaceans; Giant tiger prawn and penaeid shrimps).

4.7.2 Sustainable production

The species with the highest MSI scores are shown in the following graph (figure 4.4) throughout 1994 to 2003 period, excluding blue mussels (*Mytilus* sp.) which showed high levels of production relative to other species with high MSI scores. When blue mussel production is excluded, declines in production in the last years are evident. These years coincide with minor El Niño Southern Oscillation (ENSO) index between 1998 and 2001, which affected the seasonal nutrients input and temperature range required for adequate productions used for plants (seaweeds) and filter feeding bivalves (Gonzalez *et al.* 2000; Figueroa *et al.* 2006).

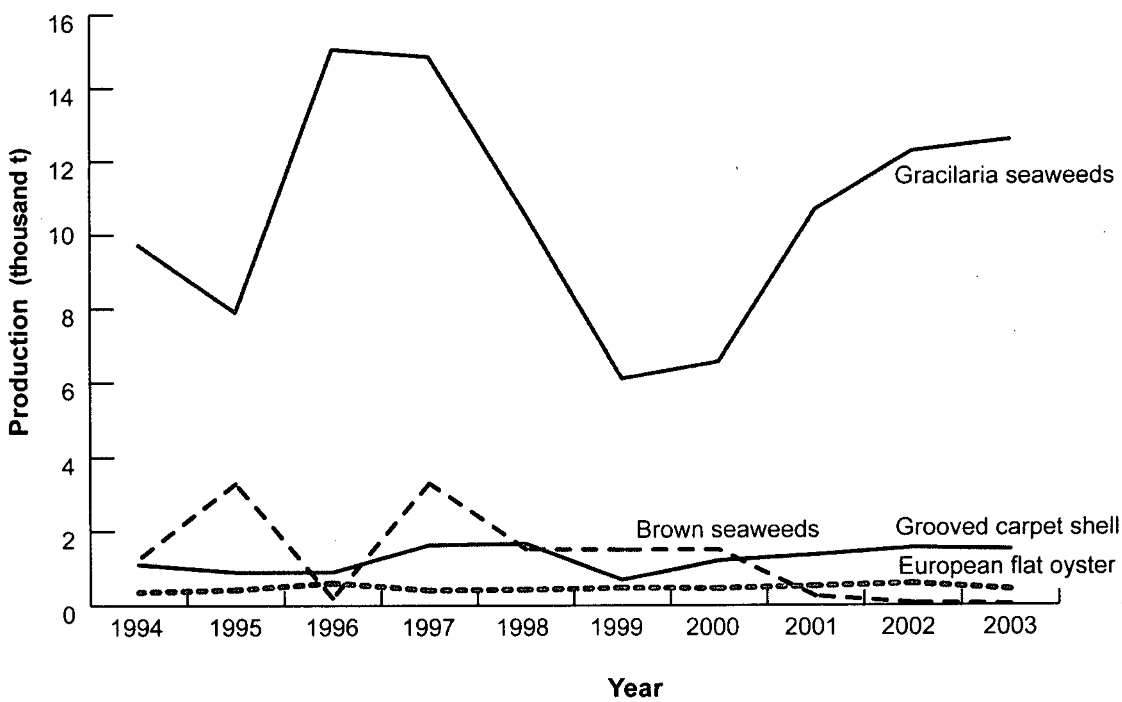

Figure 4.4: Trends in production (thousand t) for the most sustainable cultured species (excluding Blue mussels) from 1994 to 2003, i.e., Brown seaweeds, European flat oyster, Gracilaria seaweed and Grooved carpet shell.

4.7.3 Sustainability and value

The cultured species price based on FAO Fishstat (FAO 2004) ranged from USD 60/kg (Korean abalone) to USD 0.10/kg (Gracilaria). For some cultured species, there were differences in price between LIFDC and non-LIFDC (Table 4.14). There was no association between the MSI by species and the fob price in USD of farmed species (Figure 4.5). However, when the prices for the top- and bottom-scoring species are examined, a weak inverse association appears (Figure 4.6).

Table 4.13 A comparison of prices paid (USD/kg) based on the average price from 2001 to 2003 of mariculture taxa for 'low income-food deficient countries' LIFDC and non-LIFDC, along with their difference ratio (based on FishStat FAO 2004).

	Price		
Taxa	**Non LIFDC**	**LIFDC**	**Price ratio**
Laver (Nori)	13.2	0.4	33.0
Gracilaria seaweeds	0.8	0.1	8.0
Banana prawn	5.3	2.2	2.4
Pacific cupped oyster	2.5	1.2	2.1
Gilthead seabream	4.4	2.9	1.5
Penaeus shrimps nei	3.5	2.7	1.3
Milkfish	1.2	1.1	1.0
Whiteleg shrimp	5.8	5.3	1.1
Barramundi (Giant seaperch)	2.8	2.8	1.0
Flathead grey mullet	2.4	2.8	0.9
European seabass	4.9	5.7	0.9
European eel	6.5	7.6	0.9
Marine fishes nei	2.8	4.0	0.7
Giant tiger prawn	4.4	6.7	0.7
Mediterranean mussel	0.8	1.5	0.5
Groupers nei	5.1	11.0	0.5
Blood cockle	0.3	1.6	0.2

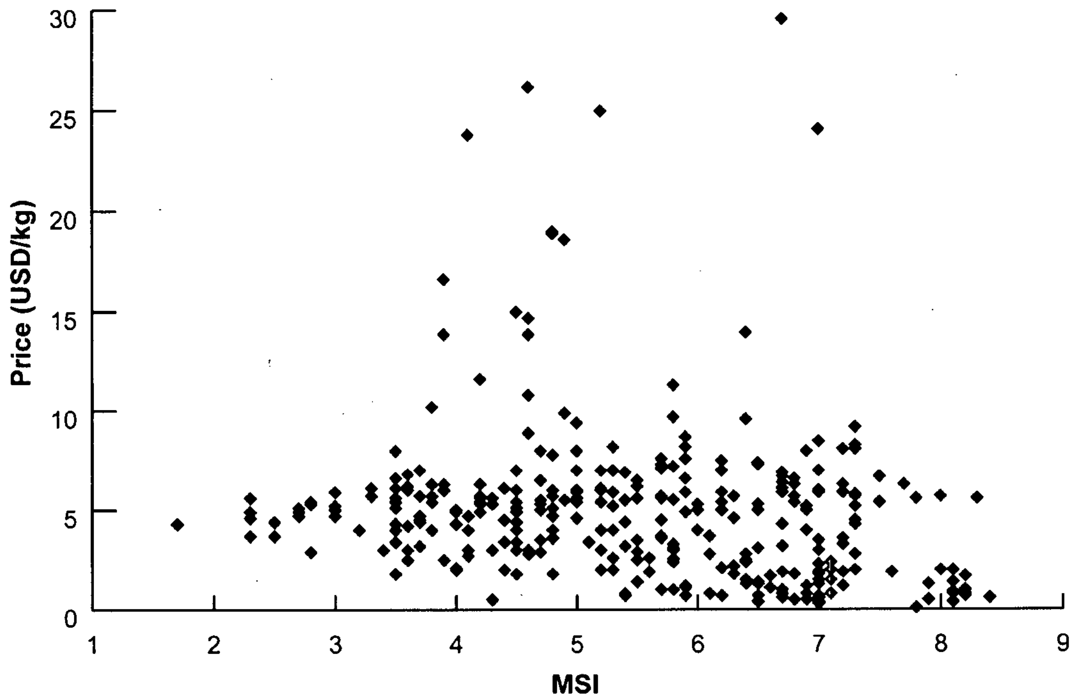

Figure 4.5: Interaction between the MSI for all species and prices paid (USD/kg) for these farmed species based on the average price from 2001 to 2003 (source: FishStat FAO 2004).

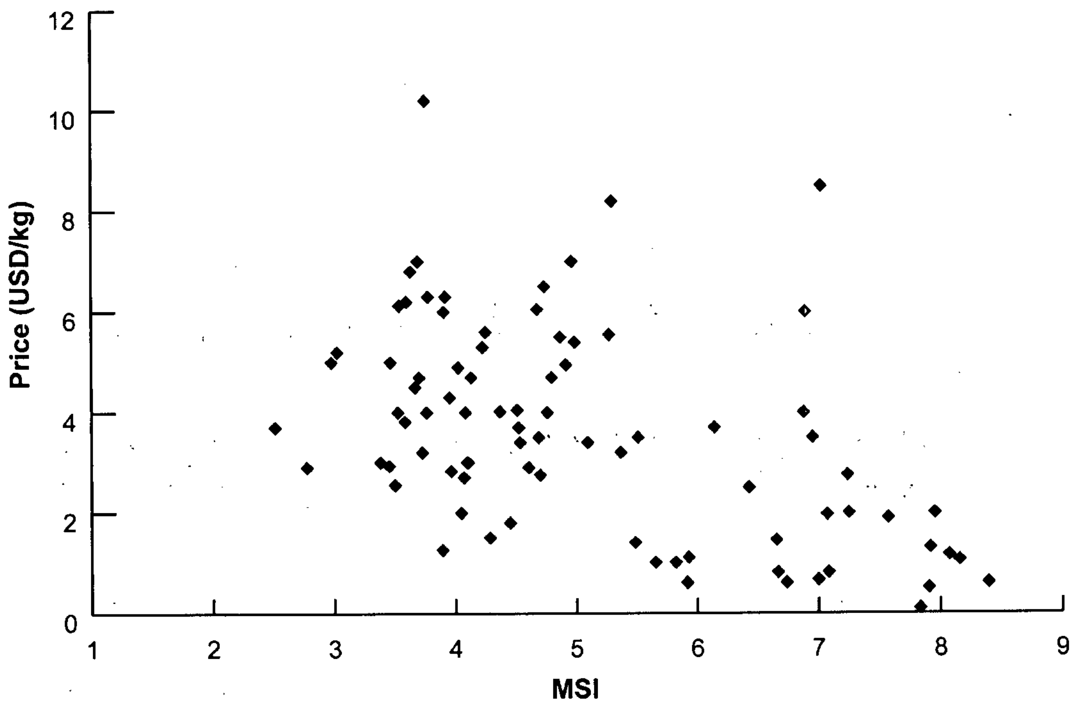

Figure 4.6: Interaction between the MSI for the highest and lowest scoring species and prices paid (USD/kg) for these farmed species, based on the average price from 2001 to 2003 (source: FishStat FAO 2004).

Chapter 5

5.1 Introduction

The aquaculture industry is developing at a rapid rate, perhaps too rapidly. This particularly applies to mariculture, which is diversifying and growing as new technologies become practical and new species become available (Costa-Pierce 2001; Naylor *et al.* 2000). However, uncontrolled growth and development may cause serious environmental degradation and unforeseen economic, social and cultural impacts on its surrounding communities (Corbin and Young 1997). If the industry is to be sustainable in the long-term, it must be able to recognize its impacts and be able to mitigate them as well as track its progress toward sustainability. This study defined 13 indicators to measure mariculture sustainability in ecological, economic and social dimensions, and assessed 60 countries against these indicators. The implications of the results of this assessment and subsequent conclusions and recommendations are presented below

5.2 Indicator validity

The validity of the indicators in reflecting the state of mariculture in the 60 countries assessed was investigated using correlation and principal component analyses. These analyses are based on 361 case studies, covering a range of countries and species cultured and therefore a robust test of the validity of the 13 indicators. The correlation matrix of the 13 indicators did not reveal co-linearity among the indicators (Table 4.1); further investigation of significant correlation coefficients could be explained by the interactions of multiple practices as described in Section 4.2.

The principal component analyses (PCA) in this study also suggest that the indicators are valid. More than 60% of the variation in the indicator values can be explained by two dimensions and 77% variation by four dimensions. All the scoring coefficients were less than 0.37 and two were negatively associated. This suggests that the indicators are measuring the different dimensions in the data and that no one indicator is driving the assessment (Table 4.2). Analyses of species groups (Figure 5.1) and countries (Figure 5.2) illustrates that the indicators are capable of differentiating between high and low sustainability practices. While 4 indicators were less than 0.25 suggesting a weak association, the remaining 9 indicators were only marginally stronger in their association with the first component. Three of the weak indicators were from the socio-economic group, reflecting the challenge in defining indicators that effectively assess the social and economic dimensions of sustainable mariculture. The difference in the strength between ecological and socio-economic indicators is due in part to the ecological aspects of mariculture being directly associated with mariculture production or specific practices, (i.e., easily measured) relative to social and economic aspects, which are usually measured using proxies.

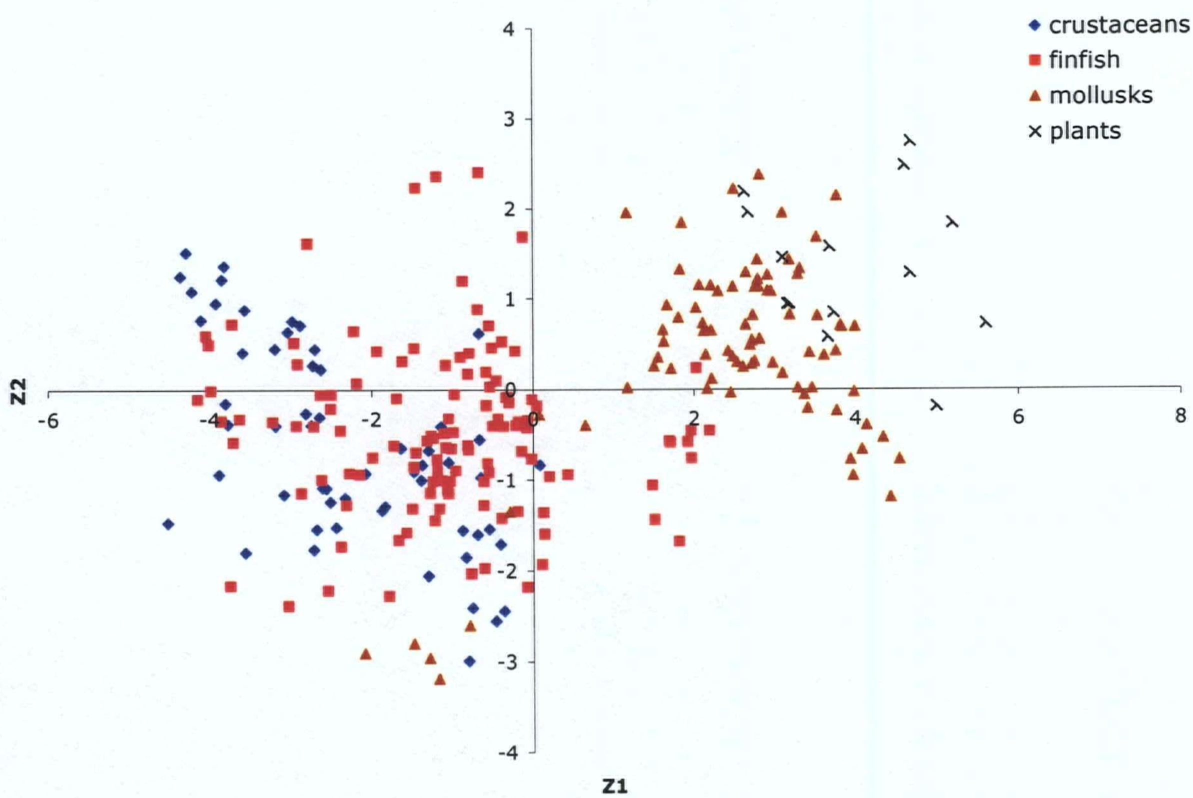

Figure 5.1: Distribution of component scores in 2 dimensions (Z1 and Z2) for the 361 cases based on taxa.

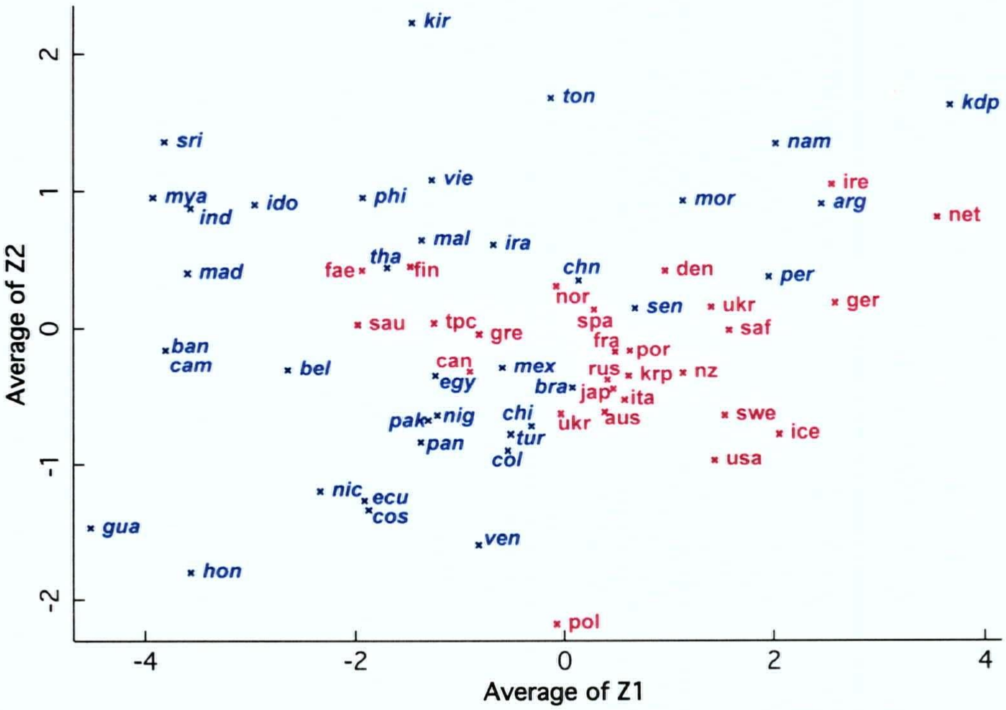

Figure 5.2: Distribution of average component scores for developed (red) and developing (blue) countries.

While 361 cases presents a substantial dataset to test the indicators, there are many more combinations of country-species-environments that exist within the mariculture sector. This study may not have captured the total range of combinations and therefore have limited application. However, the species-country combination used in this assessment represents over 95% of global mariculture production and can be considered a good representation of the industry. The underlying data may also bias the results since much of it was obtained from FAO datasets (FAO 2004). While every effort was made to ensure the data was reliable and accurate, there may be reporting biases within specific countries as seen in the capture fisheries sector, where countries such as China have misreported wild capture fisheries landings (Watson and Pauly 2001). The other source of inaccuracy is missing data, which were interpolated in some cases. However, in these instances, it was often only one indicator that was interpolated and usually in the socio-economic dimension. Nevertheless, the 13 indicators used in this study are robust, relevant and easily measured for application at the global and regional scales and independent of species and place.

5.3 Country ranking

The top ranking countries for MSI were primarily developed countries (Table 4.3), the exceptions being the Russian Federation and Argentina, which are emerging economies, and the North Korea, a developing country. Five of the developed countries are European, which is in part a reflection of the demand by Europeans for sustainable seafood products and their concerns for pollution and GMO free products (Beardmore and Porte 2003). Japan and Korea are the other two high-ranking countries and the scores reflect their demand for high quality seafood products (Bridger and Costa-Pierce 2001). These two countries also produce substantial amounts of mollusks and plants (Table 4.4), which are relatively more sustainable that crustaceans and finfish. However, the rankings of many of these countries would decline if they themselves produced some of the seafood they import and consume, such as Atlantic salmon and shrimp. For example, Spain is a significant importer of seafood including salmon and shrimp, much of it sourced from mariculture in developing countries (FAO 2004).

The lowest ranking countries for MSI are Guatemala, Cambodia, Bangladesh, Honduras, Myanmar, Belize, Chile and Norway (Table 4.3) and the first five almost exclusively culture shrimp (Table 4.5), while Chile and Norway are the top two producers of Atlantic salmon globally (Ibáñez and Pizarro 2002). They all score low on sustainability due to their semi-intensive to intensive production practices and use of fishmeal/oil in production. The developing countries in this list also score low for environmental management of waste. Many policy makers promote the expansion of aquaculture for improving the economies of developing countries including the creation of employment opportunities. However, this analysis suggests that this is not a sustainable strategy due to the externalization of environmental costs. The future of the industry in developing countries in the short-term (next 2 to 3 decades) will be a tradeoff between socio-economic development and sustaining ecosystems. However, the impacts of this tradeoff can be minimized implementing best management practices (FAO 2006).

It is worth noting that USA (ranked 15), Canada (43), Australia (40) and New Zealand (19) were not in the top or bottom ranking countries based on the MSI. The USA and New Zealand are currently not significant mariculture producers by world standards. Much of the US aquaculture production is in freshwater. In New Zealand much, of their production is mollusks, and their finfish culturing industry is emerging. As in the top ranking countries, if imports were included in the assessment, the rankings would be lower. Canada and Australia are large producers of finfish, and Australian is also a producer of crustaceans. They culture high tropic level species requiring fishmeal/oil.

The countries ranked high in the MSI were not necessarily ranking high when measured against an overall environment sustainability index such as the ESI (Table 4.8). Even when the combined ecological score is compared to the ESI there are very few similarities. This difference is due to the ESI encompassing a wider range of environmental sustainability indicators such as land, air and freshwater (Esty and Levy 2006). Currently it does not include a marine component that includes fish, making direct comparisons difficult.

The countries ranked high in the MSI did not necessarily rank high when measured against an overall socio-economic index such as the HDI (Table 4.8). There is a closer association of the combined socio-economic indicator when measured against the HDI (Table 4.8). This is due in part to the broader definitions of the socio-economic indicators in both indices.

Approximately 60% of the developing countries in this study are also low income and food deficit countries (LIFDC) and their corresponding MSI is also low (Table 4.9). The average non-weighted MSI for the 19 LIFDCs in this study was 5.1 and ranged from 7.1 (North Korea) to 3.5 (Bangladesh). Only two countries exceed a score of 6, i.e., were approaching sustainability. This implies that these countries are risking their food security from marine sources and the long-term sustainability of their marine ecosystems to provide for short-term benefits.

5.4 Environment and wild capture fisheries

The literature review in Chapter 2 highlighted the growth of aquaculture in marine and brackish water environments, especially for crustaceans and finfish. This growth was reflected also in the low rankings and scores for the culturing of crustaceans and finfish in both environments (Tables 4.10 and 4.11), where the combined MSI was 3.9 and 4.3, respectively. Crustaceans are cultured primarily in the coastal zone in brackish water and marine areas (Table 2.1), and often involve the conversion of land and high inputs of nutrients, which all score low in terms of sustainability. The consistent growth of crustacean culture continues to put coastal ecosystems at risk for long-term sustainability (Costa-Pierce 2002). Plants, followed by mollusks have the highest rankings in brackish water and marine ecosystems (Figure 4.2), but their production has been steady over the last decade (see Table 2.1).

Although bivalves were often ranked high for sustainability, they can impact negatively on the ecosystems depending on the locality and local environmental conditions (e.g. Deal 2003). The necessary indicators to assess these impacts are level of habitat alteration for bivalve farming, changes in biotopes and nutrient levels, which are outside of the scope of the 13 indicators. Nevertheless, it is important to consider the impact of bivalves in normal ecosystem functions.

Eutrophication is the most pressing issue related to aquaculture and environmental management (Bardach 1997), and much of it originates with the culturing of crustaceans and finfish. However, this issue can be addressed by implementing best management practices. These include controlling nutrient loading into surrounding water environments and siting farms in suitable locations that avoid areas with poor flushing and shallow waters (Rosenthal 1985). The first solution is technologically feasible and only limited by the cost of implementing the necessary technology. The second solution is best addressed through coastal planning and management, which is more problematic. Integrated coastal management requires building consensus with stakeholders with differing perspectives, wants and needs on how the coast should be managed (Kay and Alder 2005). In particular, conflicts with other users such as agriculture, fisheries, urban expansion and tourism need to be solved. In some cases, the introduction of aquaculture, especially semi-intensive or intensive stocking densities of higher trophic level organisms requiring aquafeeds can add significantly to the current nutrient loading and exacerbates degrading water quality (Bardach 1997). This has been shown in Chile where the cumulative effect of agriculture, urban development and aquaculture degraded water quality in several regions (Ibáñez and Pizarro 2002).

The long-term future of mariculture should be independent of aquafeeds, broodstock, seed and fry from wild capture fisheries. However, this does not preclude the development of synergies between mariculture and capture fisheries, as seen in the growing interest in developing viable systems where mariculture can contribute to sustainable fisheries. For example, in Japan the wild capture fishery for red sea bream and Japanese flounder and is enhanced by the release of hatchery-reared juveniles (Kitada and Kishino 2006).

5.5 Species culturing

The choice of the species to culture plays a critical role in determining the MSI of that species. Whether it is non-endemic to the area, requires aquafeeds and the stocking density influence the MSI. In this study, many of high ranking species are low-trophic level with the exception of a rainbow trout operation which was farmed in Iceland and which was highly sustainable manner until 2003, when it ceased operations (Table 4.11). In this case, it was fed on fish processing wastes and other non-fish protein such as worms. Most species are also cultured in the areas where they are in closed systems. In open systems, they usually are endemic and farmed within the carrying capacity of the ecosystem, which is known and taken into account.

Not all endemic species are appropriate for culturing either because there is no local or international demand, difficulties in culturing, high operating costs or low profitability. When native species are not appropriate for mariculture, tradeoffs are made with the introduction non-endemic species when communities decide to capitalize on the opportunity mariculture offers for economic development. The introduction of non-endemic species increases the risk of introducing diseases, parasites and displacement of native species with consequential risk for the ecosystem (Costa-Pierce 2002). These risks can be reduced by strict quarantine regulations for importing, testing the viability of non-endemic species reproducing due to escapements prior to commercial production and preferably using closed systems (Naylor *et al.*, 2000; Costa-Pierce 2002). However, implementing these measures are too expensive for most developing countries.

Species that are cultured can be herbivorous, omnivorous or carnivorous. However, carnivorous species cannot be sustainable unless they are fed on protein that cannot be consumed in any form by humans, such as fish-processing wastes. There are presently no forms of aquaculture based solely on such forms of protein. Rather, existing aquafeeds are either based on capture fisheries, or on wastes from fish processing or other forms of animal protein and each form has different impacts and limits on sustainability, with wild capture fisheries the most limited. Because the issue of compound aquafeeds links with the issue of 'food versus feed' (Tacon 1993), many producers are investigating other options for aquafeeds. An example of an alternative to fishmeal and oil is growing fish on a vegetarian diet (Tacon 1993, 2001; Tacon and Forster 2003). There is considerable experimental work underway for dietary requirements such as vegetable-based protein and oil substitutes (Appendix 3.2).

5.6 Traceability

One of the most important indicators, and yet one most commonly overlooked, is traceability. Traceability is an operational process documenting all the stages of production and distribution that food products go through (FAO 2002), or as defined by the International Organization for Standardisation (ISO 8402:1994), as "the ability to trace the history, application or location of an entity by means of recorded identification." The enforcement of traceability implies the development of systems giving information on the entire life cycle of food products, 'from the farm -or the sea- to the fork'.

This food control indicator provides a measure of reliability, transparency and accountability, which are concerns that are of increasing importance among seafood traders, as demonstrated in recent US actions to ban imports of Chinese seafood products (Cherry 2006). Consumers expect farmed seafood to be safe, high quality and if certified, the certification is maintained and products accurately labeled (Jacquet and Pauly 2006). If the traceability practices are not implemented, ecological and socio-economic sustainability are at risk (Moretti *et al.* 2003). Following the outbreak of Bovine Spongiform Encephalopathy (BSE) and the awareness of the health impacts of dioxin and PCB in farmed animals, concern over food quality has grown. The concept of traceability in food products became an issue of primary concern among European policy makers and scientists e.g. the E.U. Tracefish Project, when such outbreaks were identified.

5.7 Value

Results from this study indicate that there is, at best a weak, inverse relationship between price and MSI (Figure 4.6), suggesting that low ranking species are more valuable and potentially more profitable. These results also suggest that developing countries, including LIFDC, are investing in high-value species, often for export. This policy can risk food security if the benefits of exporting are not used to either supplement food supply or invested back into the country to assist in developing the economy and creating livelihood opportunities for coastal communities. The exponential growth of the Chilean salmon industry has brought economical and urban development to remote areas in Southern Chile. Nevertheless the industry's growth has not 'trickled down' accordingly to the labor force or at the regional level. In the past decade, workers' salaries participation in the industry's added aggregated value, fell from 8.4 to 3.6%, while the industry's net earnings grew by 11.9% for the same period (Ibáñez and Pizarro 2002). Externalizing costs to the coastal communities and the environment must be reflected in the value of the cultivated species and industry must be held accountable to it.

The range in the price of cultured species is wide, ranging from 0.10 USD/kg to 60.00 USD/kg, and for some species, developing countries also receive a lower price than developed countries. These differences may be due to quality, production costs, transportation costs and market inequities. Much of these products is exported to developed countries where demand is high, but mariculture production is low (Figure 5.3). Therefore the price of farmed fish and crustaceans is highly sensitive to consumer preferences and world supply, as seen in the price of Atlantic salmon which has dropped by more than 50% in the past 10 years, corresponding to the same period of increasing production and export of farmed salmon. The declining price of farmed Atlantic salmon has affected the price of wild capture salmon in the same way (Pullin and Sumaila 2003).

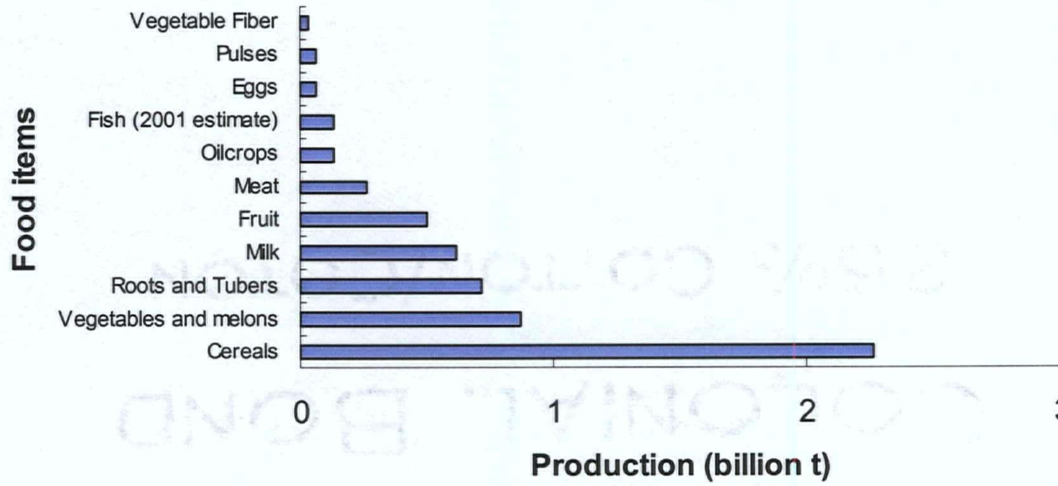

Fig 5.3 Global production (million t) of major food items

5.8 Conclusions

5.8.1 Indicator validity

Tests show that the thirteen indicators identified in this study are valid and can be used as a basis for assessing mariculture sustainability at the global and regional scale. They are defined broadly, so that they are species and locality independent. More importantly, they are based on data that is easily accessed and mostly current.

5.8.2 Country ranking

We find that overall, mariculture is not sustainable using current practices. Those countries ranking high are primarily from the developed world, but only because their imports of unsustainably farmed seafood are yet to be included in an assessment. Mariculture in the lowest ranking countries is not sustainable and much of the production consists of crustaceans. In many developing countries, shrimps are the species of choice, which is highly unsustainable and primarily for export in these countries. Indeed many of the countries with high seafood import levels also rank high in mariculture sustainability. Some developing countries may be risking their (marine) food security and the long-term sustainability of their marine ecosystem to produce food export.

The ESI and HDI are not closely associated with the MSI, this is due to the lack of a marine component in the ESI; as for the HDI, it does not reflect aquaculture practices or socio-economic features pertinent to mariculture.

5.8.3 Environment and capture fisheries

Many of the issues surrounding environmental degradation and other negative effects from mariculture can be addressed through technological improvements, best management practices and effective coastal planning and management. The first two solutions are limited by financial resources of operators and investors, while the third is much more difficult and requires more effort and consensus-building with other stakeholders.

Alternatives to basing aquafeeds on wild capture fisheries are needed if higher trophic species are to become candidates for sustainable aquaculture. Until alternative feeds are developed, the mariculture sector will continue to compete with other intensive animal productions systems. However, there is considerable research underway to develop alternative feeds that are competitive with fishmeal and fish oil.

5.8.4 Cultured species

There are limitations to what species can be cultured in a given environment. Producing non-endemic species in many countries, especially developing, will be a trade-off between ecosystem sustainability and socio-economic development due to the uncertainties associated with introducing non-endemic species to the ecosystem.

5.8.5 Value and traceability

The combination of perceived high quality product, growing consumer demand, increasing awareness of the benefit from seafood and declining prices are driving the expansion of mariculture today. Current low prices are only possible because the ecological and social costs of production are externalized. However, the ecosystems that are providing for this growth are at risk, as well as the coastal communities that have traded their ecosystem services.

Increasingly, consumers are considering these impacts and reflect their concern in paying more for sustainably produced seafood, which will in turn drive investors and producers to implement best management practices. This will require effective traceability systems so that the consumer can be confident in their choice of seafood.

In the 1970s aquaculture was promoted as a source of accessible and cheap protein for developing countries. It has yet to fulfill its potential. In mariculture, the focus has shifted to supplying the demand for high-value seafood to developed countries or the growing rich class in developing countries. Meeting this demand will require the industry to operate in a more ecologically, economically and socially sustainable ways, and to monitor and evaluate how well it is operating within a sustainability framework. This study has defined 13 indicators that will enable the industry to progress towards its sustainability goals.

5.9 Recommendation for industry and governments

1. Further research on socio-economic indicators should be funded. Indicators that directly measure social and economic impacts are needed to better assess these aspects within the mariculture sector;

2. Further development of the ESI and HDI to include mariculture (or aquaculture) should be supported. Ideally, the MSI could be incorporated into both indicators, or the relevant ecological and socio-economic indicators could be incorporated;

3. Further development of the sustainability indicators should also include the import of farmed seafood so that those countries that are externalizing ecological and social costs can be appropriately assessed;

4. Considerable support be given to developing countries so that policy and regulations for implementing best management practices are effected, enabling them to respond more efficiently to the current rapid growth of mariculture. This includes increased funding for monitoring of impacts on ecosystems, economies and communities, and increased strategic planning of the industry to include best management practices, especially within a coastal management framework;

5. Increase awareness among the consumers who are driving the demand for shrimp and salmon. They should be at least aware of the benefits in choosing sustainably produced seafood. This in turn will raise awareness among investors to implement best management practices and this can be done through instruments such as certification schemes and other economic incentives;

6. Further research funding to develop models for public-private partnerships so that mariculture systems are sustainable, profitable and ensure local communities benefit from private investment and minimizes the government and the community subsidizing industry development;

7. The industry reduces its dependence of fish-based aquafeeds through supporting the research on reducing fish protein content in feeds. In addition to technological solutions, other options include developing integrated mariculture and polyculture systems for a range of species, especially crustaceans and finfish;

8. Standardize and promote traceability among producers including self-regulation of traceability standards with NGOs potentially taking an external party monitoring role.

9. Further develop the indicators so they can be applied on a finer scale, specifically for use at the species-level or at the farm-level with a defined locality.

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Appendix 1. Detailed scoring scheme.

Ecological criteria	**Scoring scheme**
Introduced	1= non native, introduced; 3= native to country, locally introduced recently; 5= native and risk of similar non native species to an unknown ratio (e.g., nei); 7= native, with risk of local introductions; 10= native to local ecosystem
Fish meal, oil use	1= usage; 3= relatively less usage; 5= usage and non fish based diet substitute used; 7= almost no usage; 10= none.
Intensity level	1= hyper and intensive stocking; 3= mostly intensive stocking; 5= intensive/semi intensive stocking; 7= semi-intensive and extensive stocking; 10= extensive stocking
Hatchery vs wild	1= indiscriminate wild capture with depleting consequences; 3= indiscriminate wild capture when population is stressed; 5= unknown origin when but hatchery production and/or larvae importation exist; 7= mostly hatchery stocking with somewhat unknown seed/larvae provenance; 10= predominantly hatchery stocking with adequate wild broodstock provenance
Habitat alteration	1= practice is detrimental to surrounding habitat and ecosystem; 3= serious concerns of impacts on habitat and ecosystem; 5= occasional cases of adjacent habitat impact and certain unknown cases; 7= non impacting farming with minor effects on surrounding ecosystems; 10= as friendly as it gets
Waste water treatment	1= high discharges with no waste treatment whatsoever; 3= high discharges with some waste treatment; 5= moderate treatment operating at carrying capacity, 7= adequate treatment or none needed with minor seasonal variations; complete isolation of waste discharge and more than adequate treatment implementation, or no treatment needed.

Socio-economic criteria	**Scoring scheme**
Export vs. domestic	1= exclusive for export; 3= mostly for export; 5= both markets; 7= mostly local consumption; 10= local consumption
Nutrition	<5 = under 10 ppm of nutritional protein content; 7= between 10 and 13 ppm of protein content; >9= above 20 ppm of protein
Antibiotic and drug use	1= indiscriminate use; 3= poorly regulated use; 5= occasional use with implemented pre-harvest drug free period; 7= almost no use; 10= drug free
GMO	<3= gonadic underdevelopment ; 5=sex selection (e.g., polyploidy); 7= minor selectivity at the non molecular level; 10= No GMO
Code of practice	<3= Non use or ignorance of regulations; 5= minor implementations or locally non-binding; 7= updated and current use and followed rigurosly; 10= beyond the regulation forfront and benchmark implementations
Traceability	1= unknown 3= grey areas in provenance and farming stages; 5= cases of incomplete provenance; 7= appropriate tracing with certain cases of uncertain sources of feed or species combinations; 10= fully traceable
Employment	<3= unfair, insecure and exploitative working conditions; 5= seasonal, marginal employment in job sensitive areas; 7= adequate and locally involved industry reflected in working conditions; 10= optimal work and working conditions

Appendix 2. Ecological and socio-economic scores, and human development and environmental sustainability indices in each country-species combination.

Country	Sp.	Native Introduced	Fish meal usage	Intensity level	Hatchery vs wild	Habitat alteration	Waste water Treatement	Ecological	MSI	ESI	HDI
Argentina	Blue mussel	10	10	7	5	7	10	8.2	7.1	62.7	0.863
Argentina	Pacific cupped oyster	3	10	5	7	7	10	7.0	6.4	62.7	0.863
Argentina	River Plata mussel	7	10	7	5	7	10	7.7	7.0	62.7	0.863
Australia	Atlantic salmon	1	1	1	3	5	3	2.3	3.7	61.0	0.957
Australia	Barramundi	5	3	1	5	5	1	3.3	4.0	61.0	0.957
Australia	Cupped oysters nei	5	10	7	7	9	10	8.0	7.1	61.0	0.957
Australia	Flat oysters nei	5	10	7	7	7	9	7.5	7.4	61.0	0.957
Australia	Giant tiger prawn	10	1	1	5	5	1	3.8	4.9	61.0	0.957
Australia	Giant tiger prawn (br)	10	1	1	5	5	1	3.8	4.9	61.0	0.957
Australia	Kuruma prawn	10	1	5	4	5	5	5.0	5.0	61.0	0.957
Australia	Pacific cupped oyster	1	10	10	10	7	10	8.0	7.2	61.0	0.957
Australia	Pacific cupped oyster (br)	1	10	8	10	7	10	7.7	7.0	61.0	0.957
Australia	Southern bluefin tuna	10	1	1	1	3	1	2.8	4.1	61.0	0.957
Bangladesh	Penaeus shrimps nei	5	3	1	3	1	1	2.3	3.5	44.1	0.530
Belize	Whiteleg shrimp	1	3	3	5	1	3	2.7	3.7	-	0.751
Brazil	Cupped oysters nei	7	10	7	7	7	10	8.0	7.1	62.2	0.792
Brazil	Groupers nei	9	1	5	5	5	4	4.8	5.2	62.2	0.792
Brazil	Whiteleg shrimp	1	3	3	5	1	1	2.3	4.0	62.2	0.792
Cambodia	Penaeus shrimps nei	5	3	1	3	1	1	2.3	3.5	50.1	0.583
Canada	Atlantic bluefin tuna	10	10	5	1	3	1	5.0	5.0	64.5	0.950
Canada	Atlantic cod	10	1	3	3	3	3	3.8	4.7	64.5	0.950
Canada	Atlantic salmon (Atl)	10	1	1	3	5	1	3.5	4.1	64.5	0.950
Canada	Atlantic salmon (Pac)	1	3	2	3	3	2	2.3	3.4	64.5	0.950
Canada	Blue mussel	10	10	9	8	8	10	9.2	8.2	64.5	0.950
Canada	Coho(=Silver)salmon	10	2	1	5	3	3	4.0	4.1	64.5	0.950
Canada	Pacific cupped oyster	1	10	1	5	7	10	5.7	6.1	64.5	0.950
Chile	Abalones nei	1	10	1	7	3	3	4.2	3.9	53.6	0.859
Chile	Atlantic salmon	1	1	1	1	1	2	1.2	2.5	53.6	0.859
Chile	Coho(=Silver)salmon	1	1	1	5	1	2	1.8	2.8	53.6	0.859
Chile	Gracilaria seaweeds	10	10	10	7	10	10	9.5	8.4	53.6	0.859
Chile	Pacific cupped oyster	1	10	7	5	7	1	5.2	5.6	53.6	0.859
China	Blood cockle	10	10	7	3	5	7	7.0	7.0	38.6	0.768
China	Groupers nei	9	1	5	5	5	4	4.8	5.3	38.6	0.768
China	Laver (Nori)	10	10	7	5	7	5	7.3	6.8	38.6	0.768
China	Pacific cupped oyster	1	10	7	5	5	1	4.8	5.4	38.6	0.768
China	Red drum	1	1	2	5	4	5	3.0	4.4	38.6	0.768
China	Whiteleg shrimp	1	3	1	5	3	3	2.7	3.9	38.6	0.768
Colombia	Cupped oysters nei	5	10	7	7	7	10	7.7	6.9	58.9	0.790
Colombia	Whiteleg shrimp (Atl)	10	3	3	5	3	3	4.5	4.7	58.9	0.790
Colombia	Whiteleg shrimp (Pac)	10	3	3	5	3	3	4.5	4.7	58.9	0.790
Costa Rica	Whiteleg shrimp (Pac) (br)	10	3	1	5	3	5	4.5	5.0	59.6	0.841
Denmark	Atlantic salmon	10	3	1	5	5	7	5.2	5.5	58.2	0.943
Denmark	Blue mussel	10	10	9	8	7	10	9.0	8.1	58.2	0.943
Denmark	European eel	10	3	3	3	6	7	5.3	5.9	58.2	0.943
Ecuador	Red drum	1	1	3	5	5	5	3.3	4.5	52.4	0.765
Ecuador	Whiteleg shrimp	10	3	5	5	1	3	4.5	4.7	52.4	0.765
Egypt	European seabass	10	3	5	5	5	5	5.5	5.8	44.0	0.702
Egypt	European seabass (br)	10	3	5	5	5	5	5.5	5.8	44.0	0.702
Egypt	Flathead grey mullet	10	3	5	5	5	5	5.5	5.8	44.0	0.702
Egypt	Flathead grey mullet (Med)	10	3	5	5	5	5	5.5	5.8	44.0	0.702
Egypt	Gilthead seabream	1	1	1	5	3	1	2.0	3.5	44.0	0.702
Egypt	Gilthead seabream (br)	1	1	1	5	3	1	2.0	3.5	44.0	0.702
Egypt	Penaeus shrimps nei	5	1	5	5	3	3	3.7	4.0	44.0	0.702
Faeroe Ils.	Atlantic salmon	10	3	1	5	3	5	4.5	4.7	58.2	0.943
Finland	Atlantic salmon	10	3	2	5	3	7	5.0	4.9	75.1	0.947
France	Atlantic salmon	10	3	2	5	5	3	4.7	4.8	55.2	0.942
France	Blue mussel	10	10	9	8	7	10	9.0	8.1	55.2	0.942
France	Coho(=Silver)salmon	1	3	1	5	5	3	3.0	3.9	55.2	0.942
France	European eel	10	3	3	3	6	7	5.3	5.9	55.2	0.942
France	European flat oyster	10	10	7	5	7	10	8.2	7.3	55.2	0.942
France	European seabass	10	3	5	7	5	5	5.8	5.7	55.2	0.942
France	European seabass (br)	10	3	5	7	5	5	5.8	5.7	55.2	0.942
France	Gilthead seabream	10	1	1	5	3	1	3.5	4.3	55.2	0.942
France	Kuruma prawn	1	3	5	5	5	5	4.0	4.9	55.2	0.942
France	Pacific cupped oyster	1	10	10	5	5	1	5.3	6.2	55.2	0.942
France	Pacific cupped oyster (Med)	1	10	10	5	5	1	5.3	6.2	55.2	0.942

Appendix 2. Continued

Country	Sp.	Native Introduced	Fish meal usage	Intensity level	Hatchery vs wild	Habitat alteration	Waste water Treatement	Ecological	MSI	ESI	HDI
Germany	Blue mussel	10	10	9	8	7	10	9.0	8.1	56.9	0.932
Germany	European seabass	10	3	5	7	5	7	6.2	6.2	56.9	0.932
Germany	Pacific cupped oyster	1	10	10	5	7	1	5.7	6.4	56.9	0.932
Greece	European eel (br)	10	3	3	3	6	7	5.3	5.9	50.1	0.921
Greece	European eel	10	3	3	3	6	7	5.3	5.9	50.1	0.921
Greece	European flat oyster	10	10	7	5	7	10	8.2	7.3	50.1	0.921
Greece	European seabass (br)	10	3	5	5	5	1	4.8	5.0	50.1	0.921
Greece	European seabass	10	3	5	5	5	1	4.8	5.0	50.1	0.921
Greece	Flathead grey mullet (br)	10	3	5	5	5	3	5.2	5.7	50.1	0.921
Greece	Flathead grey mullet	10	3	5	5	5	3	5.2	5.7	50.1	0.921
Greece	Gilthead seabream (br)	10	1	1	3	3	1	3.2	4.1	50.1	0.921
Greece	Gilthead seabream	10	1	1	3	3	1	3.2	4.1	50.1	0.921
Greece	Kuruma prawn	1	3	5	5	5	5	4.0	4.6	50.1	0.921
Guatemala	Penaeus shrimps nei	5	1	3	3	1	1	2.3	3.0	44.0	0.673
Honduras	Penaeus shrimps nei	5	1	5	5	1	2	3.2	3.6	47.4	0.683
Iceland	Abalones nei	3	7	7	7	7	5	6.0	6.4	70.8	0.960
Iceland	Arctic char	10	3	5	8	6	5	6.2	6.9	70.8	0.960
Iceland	Atlantic cod	10	4	5	8	6	5	6.3	7.0	70.8	0.960
Iceland	Atlantic halibut	10	3	5	8	7	5	6.3	7.0	70.8	0.960
Iceland	Atlantic salmon (br)	1	5	5	8	6	5	5.0	6.1	70.8	0.960
Iceland	Atlantic salmon	1	5	5	8	6	5	5.0	6.1	70.8	0.960
Iceland	Atlantic wolffish	10	3	5	8	7	5	6.3	6.7	70.8	0.960
Iceland	Blue mussel	7	10	7	8	8	10	8.3	8.0	70.8	0.960
Iceland	European seabass	5		5	8	7	5	5.0	6.2	70.8	0.960
Iceland	Haddock	10	3	5	8	7	5	6.3	6.9	70.8	0.960
Iceland	Rainbow trout	10	5	5	8	6	5	6.5	7.0	70.8	0.960
Iceland	Spotted wolffish	10	3	6	8	7	5	6.5	6.9	70.8	0.960
Iceland	Turbot	10	3	6	8	7	5	6.5	6.9	70.8	0.960
India	Giant tiger prawn (East)	10	1	1	3	1	1	2.8	3.9	45.2	0.611
India	Giant tiger prawn	10	1	1	3	1	1	2.8	3.9	45.2	0.611
Indonesia	Banana prawn (India)	10	4	4	3	3	3	4.5	4.5	48.8	0.711
Indonesia	Banana prawn	10	4	4	1	3	3	4.2	4.4	48.8	0.711
Indonesia	Barramundi (br)	10	3	1	1	3	1	3.2	3.6	48.8	0.711
Indonesia	Barramundi	10	3	1	1	3	1	3.2	3.6	48.8	0.711
Indonesia	Giant tiger prawn (India)	10	1	1	3	1	1	2.8	3.8	48.8	0.711
Indonesia	Giant tiger prawn	10	1	1	3	1	1	2.8	3.8	48.8	0.711
Indonesia	Groupers nei	9	1	5	5	3	4	4.5	5.0	48.8	0.711
Indonesia	Milkfish	10	7	10	3	3	3	6.0	5.9	48.8	0.711
Iran	Indian white prawn	1	3	6	2	6	4	3.7	4.5	39.8	0.746
Ireland	Atlantic salmon	10	3	3	5	5	5	5.2	5.4	59.2	0.956
Ireland	Blue mussel	10	10	9	8	8	10	9.2	8.2	59.2	0.956
Ireland	European flat oyster	10	10	7	5	7	10	8.2	7.3	59.2	0.956
Ireland	Pacific cupped oyster	1	10	7	5	7	10	6.7	6.8	59.2	0.956
Italy	Cupped oysters nei (br)	5	10	10	10	9	10	9.0	7.6	50.1	0.940
Italy	Cupped oysters nei	5	10	10	10	9	10	9.0	7.6	50.1	0.940
Italy	European eel (br)	10	3	3	3	6	7	5.3	5.9	50.1	0.940
Italy	European eel	10	3	3	3	6	7	5.3	5.9	50.1	0.940
Italy	European flat oyster	10	10	7	5	7	10	8.2	7.3	50.1	0.940
Italy	European seabass (br)	10	3	5	5	5	5	5.5	5.5	50.1	0.940
Italy	European seabass	10	3	5	5	5	5	5.5	5.5	50.1	0.940
Italy	Flathead grey mullet (br)	10	3	5	5	5	5	5.5	5.8	50.1	0.940
Italy	Flathead grey mullet	10	3	5	5	5	5	5.5	5.8	50.1	0.940
Italy	Giant tiger prawn	1	1	3	5	5	3	3.0	4.6	50.1	0.940
Italy	Gilthead seabream (br)	10	1	5	5	3	1	4.2	4.9	50.1	0.940
Italy	Gilthead seabream	10	1	3	5	3	1	3.8	4.7	50.1	0.940
Italy	Gracilaria seaweeds	10	10	10	7	7	10	9.0	8.2	50.1	0.940
Italy	Kuruma prawn (br)	1	3	5	5	5	7	4.3	4.8	50.1	0.940
Italy	Kuruma prawn	1	3	5	5	5	7	4.3	4.8	50.1	0.940
Japan	Coho(=Silver)salmon	10	1	1	5	3	5	4.2	4.4	57.3	0.949
Japan	Flathead grey mullet	10	3	5	5	5	5	5.5	5.8	57.3	0.949
Japan	Kuruma prawn	10	3	5	5	4	7	5.7	5.5	57.3	0.949
Japan	Laver (Nori)	10	10	7	5	7	7	7.7	7.0	57.3	0.949
Japan	Pacific cupped oyster	10	10	7	3	5	10	7.5	7.1	57.3	0.949
Kiribati	Milkfish	10	7	5	1	3	3	4.8	5.5	-	0.515
Korea, Dem.	Gracilaria seaweeds	5	10	10	5	7	10	7.8	7.4	29.2	0.766
Korea, Dem.	Laver (Nori)	10	10	7	5	7	5	7.3	6.8	29.2	0.766

Appendix 2. Continued

Country	Sp.	Native Introduced	Fish meal usage	Intensity level	Hatchery vs wild	Habitat alteration	Waste water Treatement	Ecological	MSI	ESI	HDI
Korea	Abalones nei	10	5	3	7	5	5	5.8	5.0	43.0	0.912
Korea	Blood cockle	10	10	7	3	5	7	7.0	7.0	43.0	0.912
Korea	Flathead grey mullet	10	3	5	5	5	5	5.5	5.8	43.0	0.912
Korea	Groupers nei	9	1	5	5	5	4	4.8	5.2	43.0	0.912
Korea	Kuruma prawn	10	3	5	5	4	7	5.7	5.5	43.0	0.912
Korea	Laver (Nori)	10	10	7	5	7	7	7.7	7.0	43.0	0.912
Korea	Pacific cupped oyster	1	10	7	5	7	10	6.7	6.5	43.0	0.912
Madagascar	Giant tiger prawn	10	1	3	5	1	1	3.5	4.0	50.2	0.509
Malaysia	Banana prawn	10	4	3	3	3	2	4.2	4.4	54.0	0.805
Malaysia	Banana prawn	10	4	3	3	3	2	4.2	4.4	54.0	0.805
Malaysia	Barramundi (India)	10	1	1	1	3	3	3.2	3.6	54.0	0.805
Malaysia	Barramundi	10	1	1	1	3	3	3.2	3.6	54.0	0.805
Malaysia	Blood cockle (India)	10	10	7	3	5	7	7.0	7.0	54.0	0.805
Malaysia	Blood cockle	10	10	7	3	5	7	7.0	7.0	54.0	0.805
Malaysia	Cupped oysters nei (India)	5	10	7	5	6	10	7.2	6.7	54.0	0.805
Malaysia	Cupped oysters nei	5	10	7	5	6	10	7.2	6.7	54.0	0.805
Malaysia	Giant tiger prawn (India)	10	1	1	3	1	1	2.8	3.6	54.0	0.805
Malaysia	Giant tiger prawn	10	1	1	3	1	1	2.8	3.6	54.0	0.805
Mexico	Abalones nei	5	10	1	7	5	3	5.2	4.6	46.2	0.821
Mexico	Atlantic bluefin tuna	10	5	3	1	3	1	3.8	4.6	46.2	0.821
Mexico	Flathead grey mullet	10	3	5	5	5	5	5.5	5.8	46.2	0.821
Mexico	Pacific cupped oyster (Atl)	1	10	10	3	7	10	6.8	6.6	46.2	0.821
Mexico	Pacific cupped oyster	1	10	10	3	7	10	6.8	6.6	46.2	0.821
Mexico	Whiteleg shrimp (br)	10	3	3	5	3	5	4.8	5.0	46.2	0.821
Mexico	Whiteleg shrimp	10	3	3	5	3	5	4.8	5.0	46.2	0.821
Mexico	Yellowfin tuna	10	1	1	1	3	1	2.8	4.1	46.2	0.821
Morocco	Clams, etc nei	5	10	8	3	7	10	7.2	6.5	44.8	0.640
Morocco	European eel	10	3	6	5	4	5	5.5	5.7	44.8	0.640
Morocco	European flat oyster	10	10	7	3	7	10	7.8	6.9	44.8	0.640
Morocco	European seabass	10	3	4	5	4	5	5.2	5.4	44.8	0.640
Morocco	Gilthead seabream	10	3	4	5	4	5	5.2	5.5	44.8	0.640
Morocco	Marine fishes nei	5	4	5	5	4	5	4.7	5.3	44.8	0.640
Morocco	Mediterranean mussel	10	10	7	5	6	10	6.3	6.4	44.8	0.640
Morocco	Pacific cupped oyster	1	10	7	5	7	10	6.7	6.3	44.8	0.640
Morocco	Pacific cupped oyster (Med)	1	10	7	5	7	10	6.7	6.3	44.8	0.640
Morocco	Penaeus shrimps nei	5	3	3	5	4	5	4.2	4.9	44.8	0.640
Morocco	Yesso scallop	1	10	7	7	6	9	6.7	6.5	44.8	0.640
Myanmar	Giant tiger prawn	10	1	1	3	1	1	2.8	3.7	52.8	0.581
Namibia	Blue mussel	1	10	8	4	7	9	6.5	5.8	-	0.626
Namibia	Gracilaria seaweeds	10	10	7	4	9	10	8.3	6.7	-	0.626
Namibia	Pacific cupped oyster	1	10	7	4	7	9	6.3	5.5	-	0.626
Netherlands	Blue mussel	10	10	9	8	7	10	9.0	8.1	53.7	0.947
Netherlands	Cupped oysters nei	5	10	7	7	9	10	8.0	7.1	53.7	0.947
Netherlands	European flat oyster	10	10	7	5	7	10	8.2	7.3	53.7	0.947
New Zealand	Abalones nei	5	5	1	5	5	5	4.3	4.2	60.9	0.936
New Zealand	Pacific cupped oyster	1	10	10	3	7	10	6.8	6.7	60.9	0.936
Nicaragua	Whiteleg shrimp	10	3	1	5	3	3	4.2	4.8	50.2	0.698
Nigeria	Bagrid catfish	10	9	3	3	4	3	5.3	5.5	45.4	0.448
Nigeria	Freshwater fishes nei	5	5	5	3	5	3	4.3	5.0	45.4	0.448
Nigeria	Mullets nei	5	7	3	3	4	3	4.2	4.8	45.4	0.448
Nigeria	Snappers nei	5	7	3	3	4	3	4.2	4.9	45.4	0.448
Nigeria	Tilapias nei	5	5	3	3	4	3	3.8	4.8	45.4	0.448
Nigeria	Torpedo catfishes nei	5	5	3	3	4	3	3.8	4.6	45.4	0.448
Norway	Atlantic cod	10	1	3	3	3	1	3.5	4.6	73.4	0.965
Norway	Atlantic salmon	10	1	1	5	3	1	3.5	4.0	73.4	0.965
Norway	Blue mussel	10	10	9	8	7	10	9.0	8.1	73.4	0.965
Norway	European flat oyster	10	10	7	5	7	10	8.2	7.3	73.4	0.965
Norway	Pacific cupped oyster	1	10	7	2	7	10	6.2	6.6	73.4	0.965
Pakistan	Marine crustaceans nei	4	3	5	3	5	3	3.8	4.3	39.9	0.539
Panama	Whiteleg shrimp	10	3	1	5	5	5	4.8	5.3	57.7	0.809
Peru	False abalone	10	10	7	7	7	5	7.7	7.2	60.4	0.767
Peru	Gracilaria seaweeds	10	10	10	5	10	10	9.2	8.2	60.4	0.767
Peru	Pacific cupped oyster	1	10	10	5	7	10	7.2	6.5	60.4	0.767
Peru	Whiteleg shrimp	10	3	1	5	3	3	4.2	4.5	60.4	0.767

Appendix 2. Continued

Country	Sp.	Native Introduced	Fish meal usage	Intensity level	Hatchery vs wild	Habitat alteration	Waste water Treatement	Ecological	MSI	ESI	HDI
Philippines	Banana prawn (br)	10	4	5	3	3	1	4.3	4.5	42.3	0.763
Philippines	Banana prawn	10	4	5	1	3	1	4.0	4.3	42.3	0.763
Philippines	Barramundi	10	1	1	3	3	3	3.5	3.9	42.3	0.763
Philippines	Giant tiger prawn (br)	10	1	1	1	1	1	2.5	3.5	42.3	0.763
Philippines	Giant tiger prawn	10	1	1	1	1	1	2.5	3.5	42.3	0.763
Philippines	Gracilaria seaweeds	10	10	10	5	7	10	8.7	7.8	42.3	0.763
Philippines	Groupers, seabasses nei (br)	9	1	5	5	6	4	5.0	5.2	42.3	0.763
Philippines	Groupers, seabasses nei	9	1	5	5	6	4	5.0	5.2	42.3	0.763
Philippines	Milkfish (br)	10	7	7	1	3	3	5.2	5.7	42.3	0.763
Philippines	Milkfish	10	7	7	1	3	3	5.2	5.7	42.3	0.763
Philippines	Penaeus shrimps nei	5	3	5	3	1	1	3.0	3.9	42.3	0.763
Poland	Freshwater fishes nei	5	5	5	6	5	5	5.2	5.4	45.0	0.862
Portugal	Atlantic salmon	1	3	3	6	4	3	3.3	4.5	54.2	0.904
Portugal	Brill	10	5	3	6	4	6	5.7	5.7	54.2	0.904
Portugal	Common cuttlefish	10	5	5	6	7	7	6.7	6.5	54.2	0.904
Portugal	Common edible cockle	10	10	7	6	9	6	8.0	6.9	54.2	0.904
Portugal	Common sole	10	5	3	6	4	5	5.5	5.8	54.2	0.904
Portugal	European eel	10	5	3	6	4	5	5.5	5.8	54.2	0.904
Portugal	European flat oyster	10	10	7	6	8	6	7.8	6.9	54.2	0.904
Portugal	European seabass (br)	10	3	3	6	4	4	5.0	5.2	54.2	0.904
Portugal	European seabass	10	3	3	6	4	4	5.0	5.4	54.2	0.904
Portugal	Flat and cupped oysters nei	10	10	7	6	7	9	8.2	7.0	54.2	0.904
Portugal	Freshwater fishes nei	5	5	5	5	5	5	5.0	5.4	54.2	0.904
Portugal	Gilthead seabream (br)	10	3	3	6	4	3	4.8	5.1	54.2	0.904
Portugal	Gilthead seabream	10	3	3	6	4	3	4.8	5.3	54.2	0.904
Portugal	Grooved carpet shell (br)	10	10	7	7	8	9	8.5	7.2	54.2	0.904
Portugal	Grooved carpet shell	10	10	7	7	8	9	8.5	7.3	54.2	0.904
Portugal	Kuruma prawn	1	3	3	6	4	3	3.3	4.6	54.2	0.904
Portugal	Marine fishes nei	5	5	5	6	4	5	5.0	5.4	54.2	0.904
Portugal	Marine molluscs nei	5	5	5	6	4	5	5.0	5.3	54.2	0.904
Portugal	Mullets nei	5	5	5	6	4	5	5.0	5.4	54.2	0.904
Portugal	Octopuses nei	5	5	5	6	8	5	5.7	5.7	54.2	0.904
Portugal	Pacific cupped oyster	1	10	7	6	8	9	6.8	6.3	54.2	0.904
Portugal	Pullet carpet shell	10	10	7	6	8	9	8.3	7.0	54.2	0.904
Portugal	Razor clams nei	5	10	7	6	8	9	7.5	6.5	54.2	0.904
Portugal	Sargo breams nei	6	3	3	6	4	3	4.2	4.8	54.2	0.904
Portugal	Sea mussels nei	5	10	7	6	7	8	7.2	6.5	54.2	0.904
Portugal	Turbot	10	3	3	6	4	5	5.2	5.3	54.2	0.904
Russian Fed.	Atlantic salmon	1	3	3	6	3	4	3.3	4.1	56.1	0.797
Russian Fed.	Brown seaweeds	10	10	10	8	8	10	9.3	7.4	56.1	0.797
Russian Fed.	Brown seaweeds (Pac)	10	10	10	8	8	10	9.3	7.3	56.1	0.797
Russian Fed.	Flatfishes nei	5	3	4	5	4	5	4.3	4.6	56.1	0.797
Russian Fed.	Marine fishes nei	5	3	4	5	4	5	4.3	4.7	56.1	0.797
Russian Fed.	Mediterranean mussel	10	10	7	6	7	8	8.0	6.5	56.1	0.797
Russian Fed.	Mullets nei	5	5	5	5	4	5	4.8	4.9	56.1	0.797
Russian Fed.	Sea mussels nei	5	10	7	5	7	8	7.0	6.5	56.1	0.797
Russian Fed.	Sea mussels nei (Pac)	5	10	7	5	7	8	7.0	6.4	56.1	0.797
Russian Fed.	Sea trout	10	3	3	6	3	5	5.0	5.2	56.1	0.797
Russian Fed.	Sea trout (med)	10	3	3	6	3	5	5.0	5.3	56.1	0.797
Russian Fed.	Sea urchins nei	5	5	7	5	7	5	5.7	5.7	56.1	0.797
Russian Fed.	Silver carp	10	5	3	6	4	5	5.5	5.5	56.1	0.797
Russian Fed.	Sturgeons nei	5	5	6	6	4	5	5.2	5.2	56.1	0.797
Russian Fed.	Yesso scallop	10	10	7	7	7	7	8.0	6.9	56.1	0.797
Saudi Arabia	Barramundi	5	1	1	3	3	1	2.3	3.5	37.8	0.777
Saudi Arabia	Flathead grey mullet	10	3	5	5	5	5	5.5	5.7	37.8	0.777
Saudi Arabia	Giant tiger prawn	10	1	1	3	5	1	3.5	4.2	37.8	0.777
Saudi Arabia	Groupers nei	9	1	5	5	5	4	4.8	5.2	37.8	0.777
Senegal	Blackchin tilapia	10	5	3	7	5	5	5.8	5.9	51.1	0.460
Senegal	Cupped oysters nei	5	10	7	4	7	8	6.0	5.7	51.1	0.460
Senegal	Gasar cupped oyster	10	10	7	4	7	8	7.7	6.5	51.1	0.460
Senegal	Giant river prawn	1	3	3	4	4	4	3.2	4.0	51.1	0.460
Senegal	Nile tilapia	1	5	6	4	5	6	4.5	4.8	51.1	0.460
Senegal	Pacific cupped oyster	1	10	7	4	7	8	6.2	5.8	51.1	0.460

Appendix 2. Continued

Country	Sp.	Native Introduced	Fish meal usage	Intensity level	Hatchery vs wild	Habitat alteration	Waste water Treatement	Ecological	MSI	ESI	HDI
South Africa	Aquatic plants nei	7	10	7	6	8	10	8.0	6.9	46.2	0.653
South Africa	Carpet shells nei	7	10	7	6	7	8	7.5	6.5	46.2	0.653
South Africa	European flat oyster	1	10	7	7	7	8	6.7	6.1	46.2	0.653
South Africa	Giant tiger prawn	1	3	3	7	5	5	4.0	4.7	46.2	0.653
South Africa	Gracilaria seaweeds	10	10	7	6	8	10	8.5	7.3	46.2	0.653
South Africa	Indian white prawn	1	3	3	7	5	5	4.0	4.6	46.2	0.653
South Africa	Kuruma prawn	1	3	3	7	5	5	4.0	4.7	46.2	0.653
South Africa	Mediterranean mussel	1	10	7	7	7	9	6.8	6.2	46.2	0.653
South Africa	Mullets nei	5	5	4	6	5	6	5.2	5.4	46.2	0.653
South Africa	Pacific cupped oyster	1	10	7	7	7	9	6.8	6.1	46.2	0.653
South Africa	Perlemoen abalone	10	5	7	6	7	8	7.2	6.7	46.2	0.653
South Africa	Red bait	1	5	4	7	5	6	4.7	5.0	46.2	0.653
South Africa	Sea mussels nei	5	10	7	7	7	8	7.3	6.5	46.2	0.653
South Africa	Smooth mactra	10	10	7	6	7	7	7.8	6.7	46.2	0.653
Spain	Atlantic salmon	10	1	2	3	3	1	3.3	3.5	48.8	0.938
Spain	Blue mussel	10	10	9	8	7	10	9.0	8.1	48.8	0.938
Spain	Cupped oysters nei	5	10	10	7	8	10	8.3	7.2	48.8	0.938
Spain	European eel	10	3	3	3	6	7	5.3	5.9	48.8	0.938
Spain	European flat oyster	10	10	7	5	7	10	8.2	7.3	48.8	0.938
Spain	European seabass	10	3	5	5	5	5	5.5	5.7	48.8	0.938
Spain	Flathead grey mullet	10	3	5	5	5	5	5.5	5.8	48.8	0.938
Spain	Gilthead seabream	10	1	1	3	3	1	3.2	4.2	48.8	0.938
Spain	Kuruma prawn	1	3	5	5	5	7	4.3	4.8	48.8	0.938
Spain	Pacific cupped oyster	1	10	7	5	7	10	6.7	6.4	48.8	0.938
Spain	Tuna-like fishes nei	10	1	3	1	5	1	3.5	4.5	48.8	0.938
Sri Lanka	Giant tiger prawn	10	1	1	1	1	1	2.5	3.8	48.5	0.938
Sweden	Atlantic salmon	10	3	3	8	5	5	5.7	6.0	71.7	0.951
Sweden	Blue mussel	7	10	7	7	7	6	7.3	6.7	71.7	0.951
Sweden	European flat oyster	10	10	7	8	7	8	6.7	6.3	71.7	0.951
Sweden	Rainbow trout	1	3	3	8	5	5	4.2	5.2	71.7	0.951
Taiwan	Abalones nei (br)	5	5	1	5	5	3	4.0	3.9	32.7	0.925
Taiwan	Abalones nei	5	5	1	5	5	3	4.0	3.9	32.7	0.925
Taiwan	Barramundi (br)	10	1	1	3	3	1	3.2	3.6	32.7	0.925
Taiwan	Barramundi	10	1	1	3	3	3	3.5	3.9	32.7	0.925
Taiwan	Blood cockle	10	10	7	3	5	7	7.0	7.0	32.7	0.925
Taiwan	Flathead grey mullet (br)	10	3	5	5	5	3	5.2	5.5	32.7	0.925
Taiwan	Flathead grey mullet	10	3	5	5	5	3	5.2	5.5	32.7	0.925
Taiwan	Giant tiger prawn	10	1	1	1	1	1	2.5	3.5	32.7	0.925
Taiwan	Groupers nei (Pac) (br)	9	1	5	5	3	4	4.5	5.0	32.7	0.925
Taiwan	Groupers nei (br)	9	1	5	5	3	4	4.5	5.0	32.7	0.925
Taiwan	Groupers nei	9	1	5	5	3	4	4.5	5.0	32.7	0.925
Taiwan	Kuruma prawn (br)	10	3	1	5	1	3	3.8	4.6	32.7	0.925
Taiwan	Kuruma prawn	10	3	1	5	1	3	3.8	4.6	32.7	0.925
Taiwan	Laver (Nori)	10	10	7	5	7	5	7.3	7.0	32.7	0.925
Taiwan	Milkfish (br)	10	7	7	5	3	3	5.8	5.9	32.7	0.925
Taiwan	Milkfish	10	7	7	5	3	3	5.8	5.9	32.7	0.925
Taiwan	Pacific cupped oyster (br)	1	1	7	5	7	10	5.2	5.7	32.7	0.925
Taiwan	Pacific cupped oyster	1	1	7	5	7	10	5.2	5.7	32.7	0.925
Taiwan	Whiteleg shrimp	1	3	1	5	1	3	2.3	3.6	32.7	0.925
Thailand	Banana prawn	10	4	4	1	3	1	3.8	4.1	50.3	0.784
Thailand	Barramundi (Ind)	10	1	1	3	3	1	3.2	3.7	50.3	0.784
Thailand	Barramundi	10	1	1	3	3	1	3.2	3.7	50.3	0.784
Thailand	Blood cockle (Ind)	10	10	7	3	5	7	7.0	7.0	50.3	0.784
Thailand	Blood cockle	10	10	7	3	5	7	7.0	7.0	50.3	0.784
Thailand	Cupped oysters nei (Ind)	5	10	7	5	6	10	7.2	6.7	50.3	0.784
Thailand	Cupped oysters nei	5	10	7	5	6	10	7.2	6.7	50.3	0.784
Thailand	Giant tiger prawn (Ind)	10	1	1	1	1	1	2.5	3.5	50.3	0.784
Thailand	Giant tiger prawn	10	1	1	1	1	1	2.5	3.5	50.3	0.784
Thailand	Groupers nei (Ind)	9	1	5	5	3	4	4.5	5.0	50.3	0.784
Thailand	Groupers nei	9	1	5	5	3	4	4.5	5.0	50.3	0.784
Thailand	Penaeus shrimps nei	5	3	1	3	1	2	2.5	3.5	50.3	0.784
Thailand	Whiteleg shrimp	1	3	1	3	1	1	1.7	3.0	50.3	0.784
Tonga	Milkfish	10	7	10	1	5	3	6.0	6.4	-	0.815
Turkey	Atlantic salmon	1	3	3	8	5	5	4.2	4.7	46.6	0.757
Turkey	Com.2-banded seabream	10	3	3	7	5	6	5.7	5.3	46.6	0.757
Turkey	Gilthead seabream	8	3	3	7	5	6	5.3	5.1	46.6	0.757
Turkey	Mediterranean mussel	10	10	7	6	7	8	8.0	6.6	46.6	0.757

Appendix 2. Continued

Country	Sp.	Native Introduced	Fish meal usage	Intensity level	Hatchery vs wild	Habitat alteration	Waste water Treatement	Ecological	MSI	ESI	HDI
Turkey	Natantian decapods nei	5	5	5	6	5	5	5.2	5.1	46.6	0.757
Turkey	Seabasses nei	5	3	3	6	5	6	4.7	4.8	46.6	0.757
Turkey	Trouts nei	5	3	3	5	5	5	4.3	4.8	46.6	0.757
Ukraine	Baltic prawn	10	3	3	6	5	5	5.3	5.2	44.7	0.774
Ukraine	Flatfishes nei	5	3	3	6	5	6	3.8	4.4	44.7	0.774
Ukraine	Gobies nei	5	5	3	5	5	6	4.0	4.5	44.7	0.774
Ukraine	Mediterranean mussel	10	10	7	6	7	8	8.0	6.9	44.7	0.774
Ukraine	Mullets nei (br)	5	10	5	5	5	5	5.8	5.6	44.7	0.774
Ukraine	Mullets nei	5	10	5	5	5	5	5.8	5.6	44.7	0.774
Ukraine	Silversides nei	10	5	5	6	5	6	6.2	6.0	44.7	0.774
Ukraine	So-iuy mullet	1	5	5	8	5	6	5.0	5.3	44.7	0.774
Ukraine	Sturgeons nei	5	5	5	6	5	7	5.5	5.6	44.7	0.774
United Kingdom	Atlantic cod	10	1	3	3	3	1	3.5	4.6	50.2	0.940
United Kingdom	Atlantic salmon	10	1	2	3	3	5	4.0	4.3	50.2	0.940
United Kingdom	Blue mussel	10	10	9	8	8	10	9.2	8.2	50.2	0.940
United Kingdom	Cupped oysters nei	5	10	7	6	8	10	7.7	6.9	50.2	0.940
United Kingdom	European flat oyster	10	10	7	5	7	10	8.2	7.3	50.2	0.940
United Kingdom	European seabass	10	3	5	7	5	5	5.8	6.0	50.2	0.940
United Kingdom	Pacific cupped oyster	1	10	7	5	7	10	6.7	6.7	50.2	0.940
U.S. of America	Abalones nei	10	5	1	5	5	5	5.2	5.6	52.9	0.948
U.S. of America	Atlantic salmon	10	1	1	5	3	5	4.2	4.5	52.9	0.948
U.S. of America	Blue mussel	10	10	8	8	7	10	8.8	7.9	52.9	0.948
U.S. of America	Coho(=Silver)salmon	10	1	1	5	3	5	4.2	4.4	52.9	0.948
U.S. of America	Cupped oysters nei	5	10	7	10	8	10	8.3	7.2	52.9	0.948
U.S. of America	European flat oyster	1	10	7	5	7	10	6.7	6.5	52.9	0.948
U.S. of America	Flat oysters nei	5	10	7	7	7	9	7.5	7.4	52.9	0.948
U.S. of America	Pacific cupped oyster	1	10	7	7	7	10	7.0	7.0	52.9	0.948
U.S. of America	Whiteleg shrimp	1	3	1	5	5	5	3.3	4.7	52.9	0.948
Venezuela	Whiteleg shrimp	1	3	3	7	3	5	3.7	4.7	48.1	0.784
Viet Nam	Banana prawn	10	4	3	3	3	3	4.3	4.5	42.3	0.709
Viet Nam	Giant tiger prawn	10	1	1	1	1	1	2.5	3.5	42.3	0.709
Viet Nam	Gracilaria seaweeds	10	10	10	5	7	10	8.7	7.9	42.3	0.709
Viet Nam	Whiteleg shrimp	1	1	7	3	1	3	2.7	3.8	42.3	0.709

Appendix 2. Continued (socio-economic scores).

Country	Sp.	Export domestic	Nutrition Protein	Antibiotic Drug use	Mol-Biol GMO	Code-practice CoC	Traceability	Employment	Socio-eco	MSI
Argentina	Blue mussel	5	5	10	7	3	5	7	6.0	7.1
Argentina	Pacific cupped oyster	5	4	7	7	5	5	7	5.7	6.4
Argentina	River Plata mussel	5	5	10	7	5	5	7	6.3	7.0
Australia	Atlantic salmon	7	9	1	5	5	3	5	5.0	3.7
Australia	Barramundi	1	10	1	5	5	6	5	4.7	4.0
Australia	Cupped oysters nei	5	4	10	3	7	7	7	6.1	7.1
Australia	Flat oysters nei	10	4	10	6	7	8	6	7.3	7.4
Australia	Giant tiger prawn (br)	5	10	1	7	7	7	5	6.0	4.9
Australia	Giant tiger prawn	5	10	1	7	7	7	5	6.0	4.9
Australia	Kuruma prawn	5	9	3	5	5	5	3	5.0	5.0
Australia	Pacific cupped oyster (br)	5	4	10	7	6	7	6	6.4	7.0
Australia	Pacific cupped oyster	5	4	10	7	6	7	6	6.4	7.2
Australia	Southern bluefin tuna	5	10	3	10	7	3	3	5.9	4.1
Bangladesh	Penaeus shrimps nei	5	10	1	6	4	1	5	4.6	3.5
Belize	Whiteleg shrimp	5	10	1	5	7	3	5	5.1	3.7
Brazil	Cupped oysters nei	5	4	10	3	7	7	7	6.1	7.1
Brazil	Groupers nei	5	9	3	7	5	5	5	5.6	5.2
Brazil	Whiteleg shrimp	5	10	1	6	7	5	5	5.6	4.0
Cambodia	Penaeus shrimps nei	5	10	1	6	4	1	5	4.6	3.5
Canada	Atlantic bluefin tuna	5	10	10	7	3	5	3	6.1	5.0
Canada	Atlantic cod	7	9	1	10	5	4	3	5.6	4.7
Canada	Atlantic salmon (Atl)	7	9	1	5	5	3	3	4.7	4.1
Canada	Atlantic salmon (Pac)	3	9	1	5	5	3	5	4.4	3.4
Canada	Blue mussel	7	5	10	10	5	7	6	7.1	8.2
Canada	Coho(=Silver)salmon	5	9	1	3	3	5	3	4.1	4.1
Canada	Pacific cupped oyster	5	4	10	7	7	7	6	6.6	6.1
Chile	Abalones nei	3	7	3	3	5	5	5	4.4	3.9
Chile	Atlantic salmon	1	9	1	5	3	3	5	3.9	2.5
Chile	Coho(=Silver)salmon	3	9	1	3	3	3	4	3.7	2.8
Chile	Gracilaria seaweeds	7	2	10	8	8	10	6	7.3	8.4
Chile	Pacific cupped oyster	3	4	10	7	6	6	6	6.0	5.6
China	Blood cockle	5	9	10	10	5	5	5	7.0	7.0
China	Groupers nei	5	9	3	7	5	5	6	5.7	5.3
China	Laver (Nori)	5	3	10	7	7	5	7	6.3	6.8
China	Pacific cupped oyster	3	4	10	7	6	6	6	6.0	5.4
China	Red drum	5	10	4	5	6	5	6	5.9	4.4
China	Whiteleg shrimp	5	10	1	5	3	5	7	5.1	3.9
Colombia	Cupped oysters nei	5	4	10	3	7	7	7	6.1	6.9
Colombia	Whiteleg shrimp (Atl)	5	10	1	5	3	5	5	4.9	4.7
Colombia	Whiteleg shrimp (Pac)	5	10	1	5	3	5	5	4.9	4.7
Costa Rica	Whiteleg shrimp (Pac) (br)	5	10	5	5	5	5	3	5.4	5.0
Denmark	Atlantic salmon	3	9	5	6	7	6	5	5.9	5.5
Denmark	Blue mussel	7	5	10	10	5	7	6	7.1	8.1
Denmark	European eel	7	9	5	7	5	5	7	6.4	5.9
Ecuador	Red drum	5	10	5	6	4	5	5	5.7	4.5
Ecuador	Whiteleg shrimp	5	10	1	5	3	5	5	4.9	4.7
Egypt	European seabass (br)	5	9	5	3	7	7	7	6.1	5.8
Egypt	European seabass	5	9	5	3	7	7	7	6.1	5.8
Egypt	Flathead grey mullet (Med)	5	9	4	7	5	5	7	6.0	5.8
Egypt	Flathead grey mullet	5	9	4	7	5	5	7	6.0	5.8
Egypt	Gilthead seabream (br)	1	9	1	5	5	6	8	5.0	3.5
Egypt	Gilthead seabream	1	9	1	5	5	6	8	5.0	3.5
Egypt	Penaeus shrimps nei	5	10	3	5	3	2	3	4.4	4.0
Faeroe Ils.	Atlantic salmon	1	9	1	7	6	5	5	4.9	4.7
Finland	Atlantic salmon	1	9	1	6	7	5	5	4.9	4.9
France	Atlantic salmon	1	9	4	5	5	5	5	4.9	4.8
France	Blue mussel	7	5	10	10	5	7	6	7.1	8.1
France	Coho(=Silver)salmon	3	9	4	3	5	5	5	4.9	3.9
France	European eel	7	9	5	7	5	5	7	6.4	5.9
France	European flat oyster	5	4	10	7	7	5	7	6.4	7.3
France	European seabass (br)	5	9	3	5	5	7	5	5.6	5.7
France	European seabass	5	9	3	5	5	7	5	5.6	5.7
France	Gilthead seabream	1	9	1	5	5	7	7	5.0	4.3
France	Kuruma prawn	7	9	4	5	5	7	3	5.7	4.9
France	Pacific cupped oyster	5	4	10	7	8	8	7	7.0	6.2
France	Pacific cupped oyster (Med)	5	4	10	7	8	8	7	7.0	6.2

Appendix 2. Continued

Country	Sp.	Export domestic	Nutrition Protein	Antibiotic Drug use	Mol-Biol GMO	Code-practice CoC	Traceability	Employment	Socio-eco	MSI
Germany	Blue mussel	7	5	10	10	5	7	6	7.1	8.1
Germany	European seabass	5	9	5	5	7	7	5	6.1	6.2
Germany	Pacific cupped oyster	5	4	10	7	9	9	6	7.1	6.4
Greece	European eel (br)	7	9	5	7	5	5	7	6.4	5.9
Greece	European eel	7	9	5	7	5	5	7	6.4	5.9
Greece	European flat oyster	5	4	10	7	7	5	7	6.4	7.3
Greece	European seabass (br)	5	9	3	3	5	5	6	5.1	5.0
Greece	European seabass	5	9	3	3	5	5	6	5.1	5.0
Greece	Flathead grey mullet (br)	5	9	4	7	5	7	7	6.3	5.7
Greece	Flathead grey mullet	5	9	4	7	5	7	7	6.3	5.7
Greece	Gilthead seabream (br)	3	9	1	5	5	5	7	5.0	4.1
Greece	Gilthead seabream	3	9	1	5	5	5	7	5.0	4.1
Greece	Kuruma prawn	6	9	1	5	5	7	3	5.1	4.6
Guatemala	Penaeus shrimps nei	5	10	1	5	1	1	3	3.7	3.0
Honduras	Penaeus shrimps nei	5	10	1	5	2	2	3	4.0	3.6
Iceland	Abalones nei	1	8	7	9	7	10	5	6.7	6.4
Iceland	Arctic char	5	9	9	9	7	10	5	7.7	6.9
Iceland	Atlantic cod	5	9	8	9	7	10	5	7.6	7.0
Iceland	Atlantic halibut	5	9	8	9	8	10	5	7.7	7.0
Iceland	Atlantic salmon (br)	5	9	8	7	7	10	5	7.3	6.1
Iceland	Atlantic salmon	5	9	8	7	7	10	5	7.3	6.1
Iceland	Atlantic wolffish	1	7	10	9	7	10	5	7.0	6.7
Iceland	Blue mussel	10	5	8	7	8	10	5	7.6	8.0
Iceland	European seabass	5	9	8	8	7	10	5	7.4	6.2
Iceland	Haddock	5	8	8	9	7	10	5	7.4	6.9
Iceland	Rainbow trout	5	10	8	7	7	10	5	7.4	7.0
Iceland	Spotted wolffish	5	7	8	9	7	10	5	7.3	6.9
Iceland	Turbot	5	8	8	8	7	10	5	7.3	6.9
India	Giant tiger prawn (East)	1	10	1	7	4	5	7	5.0	3.9
India	Giant tiger prawn	1	10	1	7	4	5	7	5.0	3.9
Indonesia	Banana prawn (India)	5	9	2	6	3	2	5	4.6	4.5
Indonesia	Banana prawn	5	9	2	6	3	2	5	4.6	4.4
Indonesia	Barramundi (br)	1	10	1	5	3	3	5	4.0	3.6
Indonesia	Barramundi	1	10	1	5	3	3	5	4.0	3.6
Indonesia	Giant tiger prawn (India)	1	10	1	7	4	3	7	4.7	3.8
Indonesia	Giant tiger prawn	1	10	1	7	4	3	7	4.7	3.8
Indonesia	Groupers nei	5	9	3	7	5	3	6	5.4	5.0
Indonesia	Milkfish	3	10	5	8	5	3	7	5.9	5.9
Iran	Indian white prawn	1	9	5	5	5	6	7	5.4	4.5
Ireland	Atlantic salmon	1	9	5	7	7	5	5	5.6	5.4
Ireland	Blue mussel	7	5	10	10	5	7	6	7.1	8.2
Ireland	European flat oyster	5	4	10	7	7	5	7	6.4	7.3
Ireland	Pacific cupped oyster	5	4	10	7	8	8	6	6.9	6.8
Italy	Cupped oysters nei (br)	5	4	10	3	7	7	7	6.1	7.6
Italy	Cupped oysters nei	5	4	10	3	7	7	7	6.1	7.6
Italy	European eel (br)	7	9	5	7	5	5	7	6.4	5.9
Italy	European eel	7	9	5	7	5	5	7	6.4	5.9
Italy	European flat oyster	5	4	10	7	7	5	7	6.4	7.3
Italy	European seabass (br)	5	9	3	3	7	5	7	5.6	5.5
Italy	European seabass	5	9	3	3	7	5	7	5.6	5.5
Italy	Flathead grey mullet (br)	5	9	4	7	5	7	6	6.1	5.8
Italy	Flathead grey mullet	5	9	4	7	5	7	6	6.1	5.8
Italy	Giant tiger prawn	10	10	1	7	5	5	5	6.1	4.6
Italy	Gilthead seabream (br)	5	9	1	5	5	7	7	5.6	4.9
Italy	Gilthead seabream	5	9	1	5	5	7	7	5.6	4.7
Italy	Gracilaria seaweeds	10	2	10	8	7	10	5	7.4	8.2
Italy	Kuruma prawn (br)	7	9	1	5	5	7	3	5.3	4.8
Italy	Kuruma prawn	7	9	1	5	5	7	3	5.3	4.8
Japan	Coho(=Silver)salmon	7	9	1	3	5	4	3	4.6	4.4
Japan	Flathead grey mullet	5	9	4	7	5	7	5	6.0	5.8
Japan	Kuruma prawn	7	9	1	5	5	7	3	5.3	5.5
Japan	Laver (Nori)	5	3	10	7	7	8	5	6.4	7.0
Japan	Pacific cupped oyster	5	4	10	7	7	9	5	6.7	7.1
Kiribati	Milkfish	5	10	5	8	5	3	7	6.1	5.5
Korea, Dem.	Gracilaria seaweeds	5	2	10	8	7	10	7	7.0	7.4
Korea, Dem.	Laver (Nori)	5	3	10	7	7	5	7	6.3	6.8

Appendix 2. Continued

Country	Sp.	Export domestic	Nutrition Protein	Antibiotic Drug use	Mol-Biol GMO	Code-practice CoC	Traceability	Employment	Socio-eco	MSI
Korea	Abalones nei	5	8	5	2	4	5		4.1	5.0
Korea	Blood cockle	5	9	10	10	5	5	5	7.0	7.0
Korea	Flathead grey mullet	5	9	4	7	5	7	5	6.0	5.8
Korea	Groupers nei	5	9	3	7	5	5	5	5.6	5.2
Korea	Kuruma prawn	7	9	1	5	5	7	3	5.3	5.5
Korea	Laver (Nori)	5	3	10	7	7	8	5	6.4	7.0
Korea	Pacific cupped oyster	5	4	10	7	7	7	5	6.4	6.5
Madagascar	Giant tiger prawn	1	10	1	7	3	3	6	4.4	4.0
Malaysia	Banana prawn	5	9	2	5	3	3	5	4.6	4.4
Malaysia	Banana prawn	5	9	2	5	3	3	5	4.6	4.4
Malaysia	Barramundi (India)	1	10	1	5	3	3	5	4.0	3.6
Malaysia	Barramundi	1	10	1	5	3	3	5	4.0	3.6
Malaysia	Blood cockle (India)	5	9	10	10	5	5	5	7.0	7.0
Malaysia	Blood cockle	5	9	10	10	5	5	5	7.0	7.0
Malaysia	Cupped oysters nei (India)	5	4	10	3	7	7	7	6.1	6.7
Malaysia	Cupped oysters nei	5	4	10	3	7	7	7	6.1	6.7
Malaysia	Giant tiger prawn (India)	1	10	1	7	3	3	6	4.4	3.6
Malaysia	Giant tiger prawn	1	10	1	7	3	3	6	4.4	3.6
Mexico	Abalones nei	3	7	5	3	5	5	5	4.7	4.6
Mexico	Atlantic bluefin tuna	5	10	10	7	1	5	3	5.9	4.6
Mexico	Flathead grey mullet	5	9	4	7	5	5	7	6.0	5.8
Mexico	Pacific cupped oyster (Atl)	5	4	10	7	6	6	6	6.3	6.6
Mexico	Pacific cupped oyster	5	4	10	7	6	6	6	6.3	6.6
Mexico	Whiteleg shrimp (br)	5	10	3	5	5	5	3	5.1	5.0
Mexico	Whiteleg shrimp	5	10	3	5	5	5	3	5.1	5.0
Mexico	Yellowfin tuna	5	10	3	10	1	3	5	5.3	4.1
Morocco	Clams, etc nei	3	3	8	9	5	6	7	5.9	6.5
Morocco	European eel	3	9	4	7	5	6	7	5.9	5.7
Morocco	European flat oyster	3	4	8	8	5	7	7	6.0	6.9
Morocco	European seabass	3	9	4	5	5	6	8	5.7	5.4
Morocco	Gilthead seabream	3	9	5	5	5	6	8	5.9	5.5
Morocco	Marine fishes nei	3	8	5	7	5	6	7	5.9	5.3
Morocco	Mediterranean mussel	3	5	8	9	5	7	8	6.4	6.4
Morocco	Pacific cupped oyster	3	4	8	8	5	6	7	5.9	6.3
Morocco	Pacific cupped oyster (Med)	3	4	8	8	5	6	7	5.9	6.3
Morocco	Penaeus shrimps nei	3	10	4	5	5	6	7	5.7	4.9
Morocco	Yesso scallop	3	7	8	9	5	7	6	6.4	6.5
Myanmar	Giant tiger prawn	1	10	1	7	4	3	6	4.6	3.7
Namibia	Blue mussel	1	5	8	8	3	5	6	5.1	5.8
Namibia	Gracilaria seaweeds	1	2	10	8	3	5	6	5.0	6.7
Namibia	Pacific cupped oyster	1	4	8	8	3	5	3	4.6	5.5
Netherlands	Blue mussel	7	5	10	10	5	7	6	7.1	8.1
Netherlands	Cupped oysters nei	5	4	10	3	7	7	7	6.1	7.1
Netherlands	European flat oyster	5	4	10	7	7	5	7	6.4	7.3
New Zealand	Abalones nei	3	8	5	3	4	6	5	4.9	4.2
New Zealand	Pacific cupped oyster	3	4	10	7	8	7	7	6.6	6.7
Nicaragua	Whiteleg shrimp	5	10	5	5	3	5	5	5.4	4.8
Nigeria	Bagrid catfish	8	9	4	8	3	5	3	5.7	5.5
Nigeria	Freshwater fishes nei	7	8	4	8	4	5	3	5.6	5.0
Nigeria	Mullets nei	6	9	4	8	3	5	3	5.4	4.8
Nigeria	Snappers nei	6	9	4	8	4	5	3	5.6	4.9
Nigeria	Tilapias nei	8	8	4	8	4	5	3	5.7	4.8
Nigeria	Torpedo catfishes nei	6	8	4	8	4	5	3	5.4	4.6
Norway	Atlantic cod	7	9	1	8	5	7	3	5.7	4.6
Norway	Atlantic salmon	1	9	1	5	5	5	5	4.4	4.0
Norway	Blue mussel	7	5	10	10	5	7	6	7.1	8.1
Norway	European flat oyster	5	4	10	7	7	5	7	6.4	7.3
Norway	Pacific cupped oyster	5	4	10	7	8	8	7	7.0	6.6
Pakistan	Marine crustaceans nei	3	8	4	5	5	5	3	4.7	4.3
Panama	Whiteleg shrimp	5	10	5	5	5	5	5	5.7	5.3
Peru	False abalone	5	8	7	7	7	8	5	6.7	7.2
Peru	Gracilaria seaweeds	5	2	10	10	7	10	6	7.1	8.2
Peru	Pacific cupped oyster	3	4	10	7	5	5	7	5.9	6.5
Peru	Whiteleg shrimp	5	10	3	3	3	5	5	4.9	4.5

Appendix 2. Continued

Country	Sp.	Export domestic	Nutrition Protein	Antibiotic Drug use	Mol-Biol GMO	Code-practice CoC	Traceability	Employment	Socio-eco	MSI
Philippines	Banana prawn (br)	5	9	2	6	3	2	5	4.6	4.5
Philippines	Banana prawn	5	9	2	6	3	2	5	4.6	4.3
Philippines	Barramundi	3	10	1	5	3	3	5	4.3	3.9
Philippines	Giant tiger prawn (br)	1	10	1	7	3	3	6	4.4	3.5
Philippines	Giant tiger prawn	1	10	1	7	3	3	6	4.4	3.5
Philippines	Gracilaria seaweeds	3	2	10	10	7	10	7	7.0	7.8
Philippines	Groupers, seabasses nei (br)	5	9	3	7	5	3	6	5.4	5.2
Philippines	Groupers, seabasses nei	5	9	3	7	5	3	6	5.4	5.2
Philippines	Milkfish (br)	5	10	5	8	5	3	7	6.1	5.7
Philippines	Milkfish	5	10	5	8	5	3	7	6.1	5.7
Philippines	Penaeus shrimps nei	5	10	3	5	3	2	5	4.7	3.9
Poland	Freshwater fishes nei	8	8	4	4	5	6	4	5.6	5.4
Portugal	Atlantic salmon	5	9	4	5	6	7	4	5.7	4.5
Portugal	Brill	5	8	4	8	6	5	4	5.7	5.7
Portugal	Common cuttlefish	5	8	8	8	6	6	4	6.4	6.5
Portugal	Common edible cockle	5	8	4	8	6	6	4	5.9	6.9
Portugal	Common sole	5	9	4	8	6	6	4	6.0	5.8
Portugal	European eel	5	9	4	8	6	6	4	6.0	5.8
Portugal	European flat oyster	5	4	8	8	6	7	4	6.0	6.9
Portugal	European seabass (br)	5	9	4	5	6	5	4	5.4	5.2
Portugal	European seabass	5	9	4	5	6	5	6	5.7	5.4
Portugal	Flat and cupped oysters nei	3	4	8	8	6	7	5	5.9	7.0
Portugal	Freshwater fishes nei	5	8	4	8	6	5	4	5.7	5.4
Portugal	Gilthead seabream (br)	5	9	4	5	6	5	4	5.4	5.1
Portugal	Gilthead seabream	5	9	4	5	6	5	6	5.7	5.3
Portugal	Grooved carpet shell (br)	4	5	8	8	6	6	4	5.9	7.2
Portugal	Grooved carpet shell	4	5	8	8	6	6	6	6.1	7.3
Portugal	Kuruma prawn	3	9	4	8	6	7	4	5.9	4.6
Portugal	Marine fishes nei	5	8	4	8	6	5	4	5.7	5.4
Portugal	Marine molluscs nei	5	7	4	8	6	5	4	5.6	5.3
Portugal	Mullets nei	5	9	4	8	6	5	4	5.9	5.4
Portugal	Octopuses nei	5	8	4	8	6	5	4	5.7	5.7
Portugal	Pacific cupped oyster	3	4	8	8	6	7	4	5.7	6.3
Portugal	Pullet carpet shell	3	5	8	8	6	5	4	5.6	7.0
Portugal	Razor clams nei	3	4	8	8	6	5	4	5.4	6.5
Portugal	Sargo breams nei	5	9	4	5	6	5	4	5.4	4.8
Portugal	Sea mussels nei	5	5	8	8	6	5	4	5.9	6.5
Portugal	Turbot	5	8	4	5	6	5	5	5.4	5.3
Russian Fed.	Atlantic salmon	5	9	3	5	3	5	4	4.9	4.1
Russian Fed.	Brown seaweeds	3	2	10	8	4	6	5	5.4	7.4
Russian Fed.	Brown seaweeds (Pac)	3	2	10	8	4	6	4	5.3	7.3
Russian Fed.	Flatfishes nei	3	8	4	5	4	5	5	4.9	4.6
Russian Fed.	Marine fishes nei	5	8	4	5	4	5	5	5.1	4.7
Russian Fed.	Mediterranean mussel	5	5	4	8	4	5	4	5.0	6.5
Russian Fed.	Mullets nei	3	9	4	5	4	5	5	5.0	4.9
Russian Fed.	Sea mussels nei	5	5	10	8	4	5	5	6.0	6.5
Russian Fed.	Sea mussels nei (Pac)	5	5	10	8	4	5	4	5.9	6.4
Russian Fed.	Sea trout	5	10	4	5	4	6	4	5.4	5.2
Russian Fed.	Sea trout (med)	5	10	4	5	4	6	5	5.6	5.3
Russian Fed.	Sea urchins nei	3	7	8	8	4	5	5	5.7	5.7
Russian Fed.	Silver carp	5	8	8	5	4	5	4	5.6	5.5
Russian Fed.	Sturgeons nei	3	9	4	6	4	7	4	5.3	5.2
Russian Fed.	Yesso scallop	3	7	8	8	4	5	5	5.7	6.9
Saudi Arabia	Barramundi	1	10	1	5	5	5	5	4.6	3.5
Saudi Arabia	Flathead grey mullet	5	9	4	7	5	5	6	5.9	5.7
Saudi Arabia	Giant tiger prawn	1	10	1	7	3	5	7	4.9	4.2
Saudi Arabia	Groupers nei	5	9	3	7	5	5	5	5.6	5.2
Senegal	Blackchin tilapia	8	8	4	6	4	6	6	6.0	5.9
Senegal	Cupped oysters nei	3	4	8	8	4	6	5	5.4	5.7
Senegal	Gasar cupped oyster	3	4	8	8	4	5	6	5.4	6.5
Senegal	Giant river prawn	3	8	4	5	4	5	5	4.9	4.0
Senegal	Nile tilapia	3	8	4	6	4	5	6	5.1	4.8
Senegal	Pacific cupped oyster	3	4	8	8	4	6	5	5.4	5.8

Appendix 2. Continued

Country	Sp.	Export domestic	Nutrition Protein	Antibiotic Drug use	Mol-Biol GMO	Code-practice CoC	Traceability	Employment	Socio-eco	MSI
South Africa	Aquatic plants nei	5	6	10	9	6	6	5	6.7	6.9
South Africa	Carpet shells nei	3	3	8	8	6	6	5	5.6	6.5
South Africa	European flat oyster	3	4	8	8	6	5	5	5.6	6.1
South Africa	Giant tiger prawn	3	10	3	5	6	6	5	5.4	4.7
South Africa	Gracilaria seaweeds	3	2	10	9	6	7	5	6.0	7.3
South Africa	Indian white prawn	3	9	3	5	6	6	5	5.3	4.6
South Africa	Kuruma prawn	3	9	3	5	6	7	5	5.4	4.7
South Africa	Mediterranean mussel	3	5	8	7	6	5	5	5.6	6.2
South Africa	Mullets nei	5	9	4	6	6	5	5	5.7	5.4
South Africa	Pacific cupped oyster	3	4	8	7	6	5	5	5.4	6.1
South Africa	Perlemoen abalone	3	8	8	7	6	7	5	6.3	6.7
South Africa	Red bait	3	8	4	6	6	5	5	5.3	5.0
South Africa	Sea mussels nei	5	5	8	6	6	5	5	5.7	6.5
South Africa	Smooth mactra	3	5	8	7	6	5	5	5.6	6.7
Spain	Atlantic salmon	1	9	1	5	3	4	3	3.7	3.5
Spain	Blue mussel	7	5	10	10	5	7	6	7.1	8.1
Spain	Cupped oysters nei	5	4	10	3	7	7	7	6.1	7.2
Spain	European eel	7	9	5	7	5	5	7	6.4	5.9
Spain	European flat oyster	5	4	10	7	7	5	7	6.4	7.3
Spain	European seabass	5	9	3	5	5	7	7	5.9	5.7
Spain	Flathead grey mullet	5	9	4	7	5	7	5	6.0	5.8
Spain	Gilthead seabream	3	9	1	5	5	7	7	5.3	4.2
Spain	Kuruma prawn	7	9	1	5	5	7	3	5.3	4.8
Spain	Pacific cupped oyster	3	4	10	7	6	7	6	6.1	6.4
Spain	Tuna-like fishes nei	5	10	5	10	3	1	5	5.6	4.5
Sri Lanka	Giant tiger prawn	1	10	1	7	4	5	7	5.0	3.8
Sweden	Atlantic salmon	7	9	4	5	8	6	5	6.3	6.0
Sweden	Blue mussel	5	5	8	7	8	5	5	6.1	6.7
Sweden	European flat oyster	5	4	8	7	8	5	5	6.0	6.3
Sweden	Rainbow trout	6	10	4	5	8	6	5	6.3	5.2
Taiwan	Abalones nei (br)	5	8	3	3	4	4	5	4.6	3.9
Taiwan	Abalones nei	5	8	3	3	4	4	5	4.6	3.9
Taiwan	Barramundi (br)	1	10	1	5	3	3	5	4.0	3.6
Taiwan	Barramundi	3	10	1	5	3	3	5	4.3	3.9
Taiwan	Blood cockle	5	9	10	10	5	5	5	7.0	7.0
Taiwan	Flathead grey mullet (br)	5	9	4	7	5	5	6	5.9	5.5
Taiwan	Flathead grey mullet	5	9	4	7	5	5	6	5.9	5.5
Taiwan	Giant tiger prawn	1	10	1	7	3	4	6	4.6	3.5
Taiwan	Groupers nei (Pac) (br)	5	9	3	7	5	3	6	5.4	5.0
Taiwan	Groupers nei (br)	5	9	3	7	5	3	6	5.4	5.0
Taiwan	Groupers nei	5	9	3	7	5	3	6	5.4	5.0
Taiwan	Kuruma prawn (br)	5	9	1	5	3	7	7	5.3	4.6
Taiwan	Kuruma prawn	5	9	1	5	3	7	7	5.3	4.6
Taiwan	Laver (Nori)	5	3	10	7	7	8	7	6.7	7.0
Taiwan	Milkfish (br)	5	10	5	8	4	3	7	6.0	5.9
Taiwan	Milkfish	5	10	5	8	4	3	7	6.0	5.9
Taiwan	Pacific cupped oyster (br)	3	4	10	7	7	5	7	6.1	5.7
Taiwan	Pacific cupped oyster	3	4	10	7	7	5	7	6.1	5.7
Taiwan	Whiteleg shrimp	5	10	1	5	3	3	7	4.9	3.6
Thailand	Banana prawn	5	9	2	5	3	2	5	4.4	4.1
Thailand	Barramundi (Ind)	3	10	1	5	3	3	5	4.3	3.7
Thailand	Barramundi	3	10	1	5	3	3	5	4.3	3.7
Thailand	Blood cockle (Ind)	5	9	10	10	5	5	5	7.0	7.0
Thailand	Blood cockle	5	9	10	10	5	5	5	7.0	7.0
Thailand	Cupped oysters nei (Ind)	5	4	10	3	7	7	7	6.1	6.7
Thailand	Cupped oysters nei	5	4	10	3	7	7	7	6.1	6.7
Thailand	Giant tiger prawn (Ind)	1	10	1	7	3	4	6	4.6	3.5
Thailand	Giant tiger prawn	1	10	1	7	3	4	6	4.6	3.5
Thailand	Groupers nei (Ind)	5	9	3	7	5	3	6	5.4	5.0
Thailand	Groupers nei	5	9	3	7	5	3	6	5.4	5.0
Thailand	Penaeus shrimps nei	5	10	1	5	4	1	5	4.4	3.5
Thailand	Whiteleg shrimp	5	10	1	4	4	1	5	4.3	3.0
Tonga	Milkfish	10	10	5	8	5	3	7	6.9	6.4
Turkey	Atlantic salmon	3	9	3	5	5	6	5	5.1	4.7
Turkey	Com.2-banded seabream	3	9	4	5	4	5	5	5.0	5.3
Turkey	Gilthead seabream	3	9	4	5	5	3	5	4.9	5.1
Turkey	Mediterranean mussel	3	5	8	7	4	5	5	5.3	6.6
Turkey	Natantian decapods nei	3	9	4	5	5	4	5	5.0	5.1
Turkey	Seabasses nei	3	9	4	5	4	5	5	5.0	4.8
Turkey	Trouts nei	3	9	4	5	5	6	5	5.3	4.8

Appendix 2. Continued

Country	Sp.	Export domestic	Nutrition Protein	Antibiotic Drug use	Mol-Biol GMO	Code-practice CoC	Traceability	Employment	Socio-eco	MSI
Ukraine	Baltic prawn	3	9	3	5	5	6	5	5.1	5.2
Ukraine	Flatfishes nei	3	8	4	5	5	5	5	5.0	4.4
Ukraine	Gobies nei	3	8	4	5	5	5	5	5.0	4.5
Ukraine	Mediterranean mussel	5	5	8	7	5	5	5	5.7	6.9
Ukraine	Mullets nei (br)	5	9	4	5	5	4	5	5.3	5.6
Ukraine	Mullets nei	5	9	4	5	5	4	5	5.3	5.6
Ukraine	Silversides nei	5	9	4	6	5	7	5	5.9	6.0
Ukraine	So-iuy mullet	5	9	4	6	5	5	5	5.6	5.3
Ukraine	Sturgeons nei	3	9	4	7	5	7	5	5.7	5.6
United Kingdom	Atlantic cod	7	9	1	8	5	7	3	5.7	4.6
United Kingdom	Atlantic salmon	3	9	1	5	6	4	4	4.6	4.3
United Kingdom	Blue mussel	7	5	10	10	5	7	6	7.1	8.2
United Kingdom	Cupped oysters nei	5	4	10	3	7	7	7	6.1	6.9
United Kingdom	European flat oyster	5	4	10	7	7	5	7	6.4	7.3
United Kingdom	European seabass	5	9	5	5	7	7	5	6.1	6.0
United Kingdom	Pacific cupped oyster	5	4	10	7	8	8	5	6.7	6.7
U.S. of America	Abalones nei	7	8	5	2	7	7	6	6.0	5.6
U.S. of America	Atlantic salmon	7	9	1	5	5	4	3	4.9	4.5
U.S. of America	Blue mussel	7	5	10	10	5	7	5	7.0	7.9
U.S. of America	Coho(=Silver)salmon	7	9	1	3	5	4	3	4.6	4.4
U.S. of America	Cupped oysters nei	5	4	10	3	7	7	7	6.1	7.2
U.S. of America	European flat oyster	5	4	10	7	7	5	7	6.4	6.5
U.S. of America	Flat oysters nei	10	4	10	6	7	8	6	7.3	7.4
U.S. of America	Pacific cupped oyster	7	4	10	7	8	8	5	7.0	7.0
U.S. of America	Whiteleg shrimp	10	10	5	3	7	5	3	6.1	4.7
Venezuela	Whiteleg shrimp	5	10	3	5	7	5	5	5.7	4.7
Viet Nam	Banana prawn	5	9	2	5	3	2	7	4.7	4.5
Viet Nam	Giant tiger prawn	1	10	1	7	3	3	7	4.6	3.5
Viet Nam	Gracilaria seaweeds	3	2	10	10	7	10	8	7.1	7.9
Viet Nam	Whiteleg shrimp	5	10	1	5	3	3	7	4.9	3.8

Appendix 3. Primary production required (PPR) indicator

This indicator was not used in the mariculture sustainability analysis because it requires information that is specific to the diet of each species. The composition of diets used in production are generally not published for many species, especially for feed of the higher-valued species (e.g. salmon, shrimps, etc.). Such information is only available for a few species-county combinations. In the future, the use of this indicator may be possible, and therefore described below.

The type and proportion of dietary inputs (e.g. aquafeeds and supplements) required to sustain current levels of mariculture production was investigated. Specific diet compositions based on aquafeed formulae for farmed organisms were gathered where available and categorized by origin of feed component (e.g. plant crops, animal meals, fishmeal, fish discards and bycatch) and converted into grams of carbon per kilogram ($gC\cdot kg^{-1}$) of product. This was converted into the net primary productivity (NPP) required to produce one kilogram of plant or animal biomass (Tables A 3.1 and A 3.2), i.e., the carbon content in a kg of dietary inputs. An estimate of the NPP to sustain the farmed organisms, can ultimately contribute to estimating a country's ecological footprint.

The primary productivity required (PPR), measured in ($gC\cdot kg^{-1}$), to sustain a farmed species was estimated by back-calculating the net primary productivity (NPP) required to produce the food items that make up the diet of the farmed organisms (e.g. wheat, soybean, rapeseed, corn etc.) based on Table A 3.1. The PPR for vegetal items were calculated at ($gC\cdot kg^{-1}$) of dry weight. Similarly, the $gC\cdot kg^{-1}$ of wet weight for animal products was also back-calculated based on Table A3.2.

Table A 3.1 Net primary productivity (NPP) required to produce one kg of a plant crop in ($gC \cdot kg^{-1}$) dry weight. The NPP of plants and oil components of the feeds are derived from Canadian Agricultural Statistics (1992 – 1996) and reported in Tyedmers (2000).

Plant crop	**NPP ($gC \cdot kg^{-1}$)**
Wheat	460
Soybean	528
Rapeseed	607
Corn Grain	465
Linseed	565

Table A 3.2 Net primary productivity required to produce one kg of fishmeal and fish oil, assuming a 9:1 ratio for the conversion of wet weight to carbon ($gC \cdot kg^{-1}$), for fish (adapted from Tyedmers 2000).

Fish meal/oil source	**Fishmeal NPP ($gC \cdot kg^{-1}$)**	**Fish oil NPP ($gC \cdot kg^{-1}$)**
Norwegian	22170	37024
Peruvian	13988	23360
Danish	26654	44512
French	70106	117077
SA Fmeal	12956	21636
BC Herring	3956	6607
Mex M oil	not available	2660
BC oil	not available	20000

Estimates of PPR for mariculture are based on 2-step method used by Pauly and Christensen (1995) for the primary productivity required to sustain global fisheries. First, the grams of carbon that must be fixed by autotrophs annually was estimated by assuming an average transfer efficiency between trophic levels of 10% (Pauly and Christensen 1995) and a conservative 9:1 conversion ratio from wet weight of organism to carbon content (Strathmann 1967) (see Equation 1).

$$P = (M/9) \times 10^{(T-1)}$$ Eq.1 (from Tyedmers 2000)

Where: **P** = primary productivity required, expressed in $gC \cdot kg^{-1}$ fixed;
M = the wet weight mass, in g, of the organisms for which an ecosystem support area is being calculated, and
T = is the mean trophic level at which the organism(s) feeds using a scale in which autotrophs are assigned a trophic level of 1.0 by default.

Step two, estimated the trophic levels by averaging the respective feed items' trophic levels by using equation 2 (see also Table 3.3)

$$TL_i = 1.0 + \sum T_j (P_{ij})$$ Eq.2

Where: **TL** = the average trophic at which the organism 'i' feeds on "j";
T_j = the mean trophic level of the feed item(s) 'j' and
P_{ij} = the proportion of each type of feed for a specific organism.

Fishmeal and fish oil are assigned trophic level 3 since the average trophic level of small pelagic fish used in fishmeal is approximately 3 from (Froese and Pauly 2000); ruminant livestock are assigned level 2; and plant components are assigned level 1.

Table A 3.3 Example of the trophic level for the species-country combination based on the feed components.

Group/species	Country	Year	TL	Fish meal	Fish oil	livestock	plants	Total feed	Marine component of diet (%)
Abalone	Australia	2000	2.38	0	20	329	627	976	**2**
Anguilla australis	Australia	2001	3.15	530	44	0	427	1000	**57**
Barramundi	Australia	2000	3.46	414	118	413	65	1010	**53**
Barramundi	Australia	2003	3.50	470	150	210	134	964	**64**
Giant Tiger Prawn	Australia	1999	2.90	310	38	200	449	997	**35**
Murray Cod	Australia	2002	3.60	730	50	0	195	975	**80**

The trophic levels of the farmed species estimated in this study were significantly different than those reported for wild capture fish (Pauly and Christensen 1995, Stergiou and Karpouzi 2002, Pinnegar etal 2003). These differences are a result of different inputs consumed in farmed versus natural conditions. Upon examination of feed compositions for aquaculture it was evident that higher-valued omnivorous and carnivorous fish species are converging to a similar trophic level of 3.1, irrespective of their natural diet trophic levels (Figure A3.1).

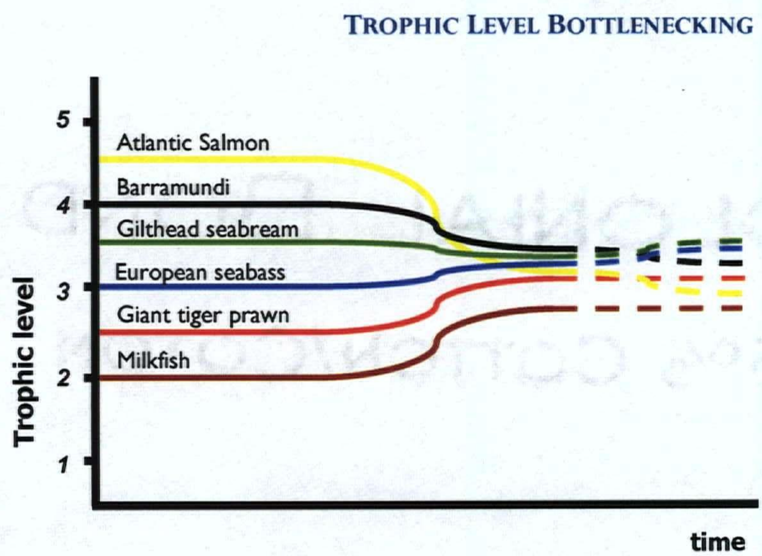

Fig. A3.1 Converging trophic levels in six farmed fish species