Part III – Expert Panel Reviews

Responsible use of resources for sustainable aquaculture

Expert Panel Review 1.1

B.A. Costa-Pierce[1] (*), D.M. Bartley[2], M. Hasan[2], F. Yusoff[3], S.J. Kaushik[4], K. Rana[5], D. Lemos[6], P. Bueno[7] and A. Yakupitiyage[8]

[1] Department of Fisheries, Animal & Veterinary Science, Rhode Island Sea Grant College Program, University of Rhode Island Graduate School of Oceanography, Narragansett, RI 02882-1197 USA. E-mail: bcp@gso.uri.edu

[2] Fisheries and Aquaculture Department, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. E-mail: devin.bartley@fao.org, mohammad.hasan@fao.org

[3] Department of Aquaculture, Faculty of Agriculture, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia. E-mail: fatimah@ibs.upm.edu.my

[4] S.J. Kaushik, Pole d'Hydrobiologie, INRA, 147 Rue de l'Université, 75 Paris, France. E-mail: kaushik@st-pee.inra.fr

[5] Dept of Animal Sciences, Faculty of AgriScience, University of Stellenbosch, stellenbosch, South Africa. E-mail: kjr3@sun.ac.za

[6] LAM – Laboratório de Aquicultura, Instituto Oceanográfico, Universidade de São Paulo, Praça do Oceanográfico, 191 – Cidade Universitária, 05508-900, São Paulo, Brasil. E-mail: dellemos@usp.br

[7] 2/387 Supalai Park at Kaset, Prasert Manukitch Road, Sena Nikhom, Jatujak, Bangkok 10900, Thailand. E-mail: pete.bueno@gmail.com

[8] Aquaculture and Aquatic Resources management Program, School of Environment, Resources and Development, Asian Institute of Technology, PO Box 4, Klong Luamg, Pathumthani, 12120, Thailand. E-mail: amara@ait.ac.th

Costa-Pierce, B.A., Bartley, D.M., Hasan, M., Yusoff, F., Kaushik, S.J., Rana, K., Lemos, D., Bueno, P. & Yakupitiyage, A. 2012. Responsible use of resources for sustainable aquaculture. *In* R.P. Subasinghe, J.R. Arthur, D.M. Bartley, S.S. De Silva, M. Halwart, N. Hishamunda, C.V. Mohan & P. Sorgeloos, eds. *Farming the Waters for People and Food.* Proceedings of the Global Conference on Aquaculture 2010, Phuket, Thailand. 22–25 September 2010. pp. 113–147. FAO, Rome and NACA, Bangkok.

Abstract

Comparisons of production, water and energy efficiencies of aquaculture versus an array of fisheries and terrestrial agriculture systems show that non-fed aquaculture (e.g. shellfish, seaweeds) is among the world's most efficient mass producer of plant and animal proteins. Various fed aquaculture systems also match the most efficient forms of terrestrial animal husbandry, and trends suggest that carnivores in the wild have been transformed in aquaculture to omnivores, with impacts on resource use comparable to conventional, terrestrial agriculture systems, but are more efficient. Production efficiencies of edible mass for a variety of aquaculture systems are 2.5–4.5 kg dry feed/kg edible mass, compared with 3.0–17.4 for a range of conventional terrestrial animal production systems. Beef cattle require over 10 kg of feed to add 1 kg of edible

---

[*] Corresponding author: bcp@gso.uri.edu

weight, whereas tilapia and catfish use less than 3 kg to add a kg of edible weight. Energy use in unfed and low-trophic-level aquaculture systems (e.g. seaweeds, mussels, carps, tilapias) is comparable to energy use in vegetable, sheep and rangeland beef agriculture. Highest energy use is in fish cage and shrimp aquaculture, comparable to intensive animal agriculture feedlots, and extreme energy use has been reported for some of these aquaculture systems in Thailand. Capture fisheries are energy intensive in comparison with pond aquaculture of low-trophic-level species. For example, to produce 1 kg of catfish protein about 34 kcal of fossil fuel energy is required; lobster and shrimp capture fisheries use more than five times this amount of energy. Energy use in intensive salmon cage aquaculture is less than in lobster and shrimp fishing, but is comparable to use in intensive beef production in feedlots. Life Cycle Assessment of alternative grow-out technologies for salmon aquaculture in Canada has shown that for salmon cage aquaculture, feeds comprised 87 percent of total energy use, and fuel/electricity, 13 percent. Energy use in land-based recirculating systems was completely opposite: 10 percent of the total energy use was in feed and 90 percent in fossil fuel/electricity. Freshwater use remains a critical issue in aquaculture. Freshwater reuse systems have low consumptive use comparable to vegetable crops. Freshwater pond aquaculture systems have consumptive water use comparable to pig/chicken farming and the terrestrial farming of oil seed crops. Extreme water use has been documented in shrimp, trout, and striped catfish operations. Water use in striped catfish is of concern to Mekong policy-makers, as it is projected that these catfish aquaculture systems will expand and even surpass their present growth rate to reach an industry of approximately 1.5 million tonnes by 2020.

Water, energy and land usage in aquaculture are all interactive. Reuse and cage aquaculture systems use less land and freshwater but have higher energy and feed requirements, with the exception of “no feed” cage and seawater (e.g. shellfish, seaweeds) systems. Currently, reuse and cage aquaculture systems perform poorly in overall life cycle or other sustainability assessments in comparison to pond systems. Use of alternative renewable energy systems and the mobilization of alternative (non-marine) feed sources could improve the sustainability of reuse and cage systems considerably in the next decade.

Resource use constraints on the expansion of global aquaculture are different for fed and non-fed aquaculture. Over the past decade for non-fed shellfish aquaculture, there has been a remarkable global convergence around the notion that solutions to user (space) conflicts can be solved not only through technological advances, but also by a growing global consensus that shellfish aquaculture can “fit in”, not only environmentally but also in a socially responsible manner, to many coastal environments worldwide, the vast majority of which are already overcrowded with existing uses.

For fed aquaculture, new indicators of resource use have been developed and promulgated. Before this resource use in fed aquaculture was being measured in terms of feed conversion ratios (FCRs) followed by FIFO ("fish in fish out") ratios. First publications a decade ago measured values of FIFO in marine fish and shrimp aquaculture. More comprehensive indicator assessments of fish feed equivalencies, protein efficiency ratios and fish feed equivalences will allow more informed decision-making on resource use and efficiencies. Over the past decade, aquafeed companies have accelerated research to reduce the use of marine proteins and oils in feed formulations, and have adopted indicators for the production efficiencies in terms of "marine protein and oil dependency ratios" for fed aquaculture species. Current projections are that over the next decade, fed aquaculture will use less marine fishmeals/oils while overall aquaculture production will continue its rapid growth.

Over the past decade, new, environmentally sound technologies and resource-efficient farming systems have been developed, and new examples of the integration of aquaculture into coastal area and inland watershed management plans have been achieved; however, most are still at the pilot scale commercially or are part of regional governance systems, and are not widespread. These pilot-scale models of commercial aquaculture ecosystems are highly productive, water and land efficient, and are net energy and protein producers which follow design principles similar to those used in the fields of agroecology and agro-ecosystems. Good examples exist for both temperate zone and tropical nations with severe land, water and energy constraints.

Increasing technological efficiencies in the use of land, water, food, seed and energy through sustainable intensification such as the widespread adoption of integrated multi-trophic aquaculture (IMTA) and integrated agriculture-aquaculture farming ecosystems approaches will not be enough, since these will improve only the efficiency of resource use and increase yields per unit of inputs and do not address social constraints and user conflicts. In most developing countries, an exponentially growing population to 2050 will require aquaculture to expand rapidly into land and water areas that are currently held in common. Aquaculture expansion into open-water freshwater and marine waters raises the complex issues of access to and management of common pool resources, and conflicts with exiting users that could cause acute social, political and economic problems. The seminal works of 2009 Nobel Laureate Elinor Ostrom could provide important insights for the orderly expansion of aquaculture into a more crowded, resource-efficient world striving to be sustainable, and rife with user conflicts.

KEY WORDS: *Aquaculture, Production efficiency, Responsible resource use, Sustainability.*

Introduction

Today, about 1.3 billion people live on less than a dollar a day, and half of the world's population lives on less than two dollars a day (World Bank, 2008). A billion people are undernourished and in poverty, with an estimated 97 percent of them residing in Africa and Asia. By 2050, the world's population will rise from its current level of 6.8 billion and plateau at approximately 9 billion, with nearly all population growth occurring in economically developing countries (Godfray *et al*., 2010). The World Bank (2008) has estimated that the world will need 70–100 percent more food by 2050, and will need to feed 2.3 billion poor, requiring food production to increase by approximately 70 percent from its current levels (FAO, 2009). Today, in ten African countries where aquatic proteins are a vital dietary component, having an estimated 316 million persons, 216 million live on USD2 per day, 88 million are undernourished and 16 million children under age five are malnourished (Allison, Beveridge and van Brakel, 2009).

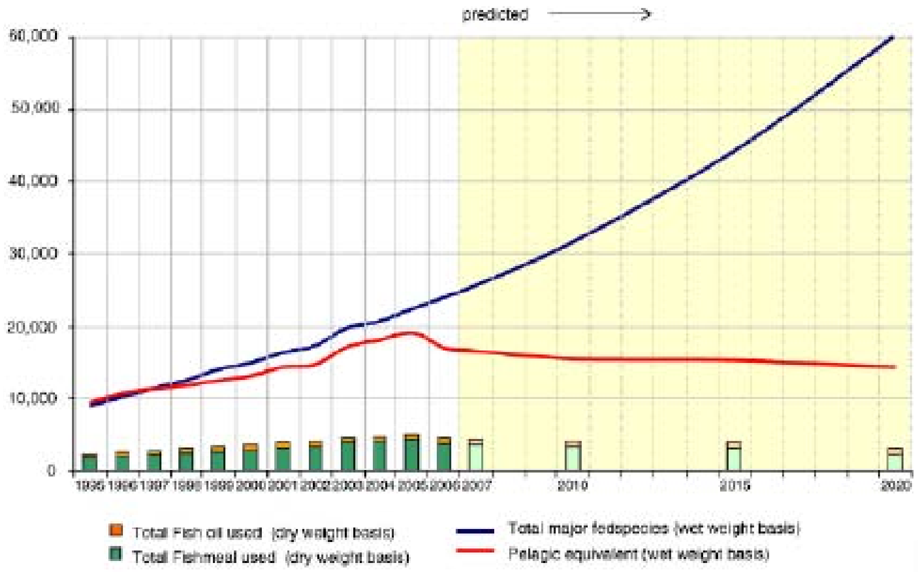
On top of this population poverty crisis are scientific predictions of alarming environmental problems for both Asia and Africa. The United Nations Framework Convention on Climate Change (2007) predicts that a 2 °C temperature increase could lead to a 20–40 percent decrease in cereal yields in Asia and Africa. Lele (2010) believes that unless the global architecture of agricultural investments, research and development is changed over the next several years that the Millennium Development Goal of reducing hunger by 2015 will not be met. Aquaculture can play a major role in delivering high-quality, energy and protein-rich foods to the world's poor, in economic development and in overall poverty alleviation. However, as pointed out by Edwards (2002), "There is a need for a paradigm shift in philosophy away from food for the poor, which addresses the symptoms of poverty, not causes, to creation of wealth." Massive decreases in poverty due to wealth creation by aquaculture have occurred in China, Bangladesh, India and Viet Nam in the past ten years (Edwards 2002; Phan *et al.,* 2009). In Chile, the employment that is generated by the salmon aquaculture industry has a positive and direct impact on the poverty indicators of communities where this industry is developed (Bórquez and Hernández, 2009). However, in order to provide additional high-energy aquatic foods for people to 2050, important flows of natural resources will need to be understood, measured, used and allocated more efficiently globally, regionally and locally, which could result in the reallocation of resources more consciously into the most efficient animal and plant production systems for food production. Food production will also need to be conducted in a way that reduces poverty, takes into account natural resource limitations, moves towards full cost accounting, resolves conflicts and generates wealth.

There have been concerns that aquaculture has been moving away from its global responsibility to be more "sustainable" and to realize its altruistic goals of providing net benefits (additional foods) for a protein-hungry planet. Wurts

(2000) stated that "Whether the word sustainability has become overused or not, it has catalyzed a forum for oversight of the growth and development of aquaculture on a global scale." Fed aquaculture has been criticized for its resource subsidies which have fueled the expansion of aquaculture systems that can be net resource losers and, as a result, some workers have called for full accounting of resource flows and for better planning for aquaculture as part of the global effort to provide additional foods but to also maintain essential ecosystems, goods and services (Folke, Kautsky and Troell, 1994; Goldburg and Naylor, 2005; Alder *et al.,* 2008; Naylor *et al.,* 2009). Greater than 75 percent of global fisheries are traded, while only 7 percent of meat, 17 percent of wheat and 5 percent of rice is traded. In 2000, more than 60 percent of fishmeal was traded. Current projections are that over the next decade to 2020, fed aquaculture will use less marine fishmeals/oils while overall aquaculture production will continue its rapid growth (Figure 1).Concerns about the trajectories of resource use and subsidies in aquaculture have intensified as international trade in fisheries and aquaculture products and the essential resources to sustain them have increased dramatically.

Scientists and policy-makers agree that ecologically sound farming systems that include aquaculture as part of more resource-efficient, integrated farming systems are part of the answer to the world's impending protein food crisis for both inland and coastal areas (FAO, 2001; Federoff *et al.,* 2010). In 2006, the

FIGURE 1
Pelagic fish harvested and fed to aquaculture systems is predicted to decline while aquaculture production grows rapidly from 2006 to 2020



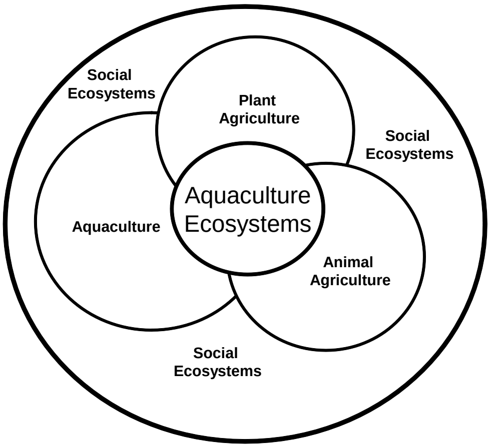
Source: Tacon and Metian (2008).

Fisheries and Aquaculture Department of the Food and Agriculture Organization of the United Nations (FAO) recognized this need and developed guidelines for an ecosystem-based management approach to aquaculture similar to the *Code of Conduct for Responsible Fisheries* (Soto *et al.*, 2008). This ecological approach to aquaculture (EAA) has the objectives of ecological and human well-being and would achieve these ideals via the more effective governance of aquaculture within a hierarchical framework that is scalable from the farm to regional and global levels. Ecological aquaculture is a holistic view of aquaculture development that brings not only the technical aspects of ecosystems design, ecological principles and systems ecology (an integrated framework for planning and design, monitoring, modeling and evaluation) to aquaculture, but also incorporates planning for community development and concerns for the wider social, economic and environmental contexts of aquaculture (Costa-Pierce, 2002, 2008; Yusoff, 2003; Culver and Castle, 2008). Ecological aquaculture farms are "aquaculture ecosystems" (Figure 2). By using an EAA, more sophisticated, environmentally sound designed and integrated aquaculture systems could become more widespread because they better fit the social-ecological context of both rich and poor countries. Ecological aquaculture provides the basis for developing a new social contract for aquaculture because it is inclusive of all producer-stakeholders and decision-makers in a modern, market economy – fisheries, agriculture, ecosystems conservation and restoration (Figure 3).

Aquaculture depends upon resource inputs connected to various food, processing, transportation and other sectors of society. Outputs from aquaculture

FIGURE 2

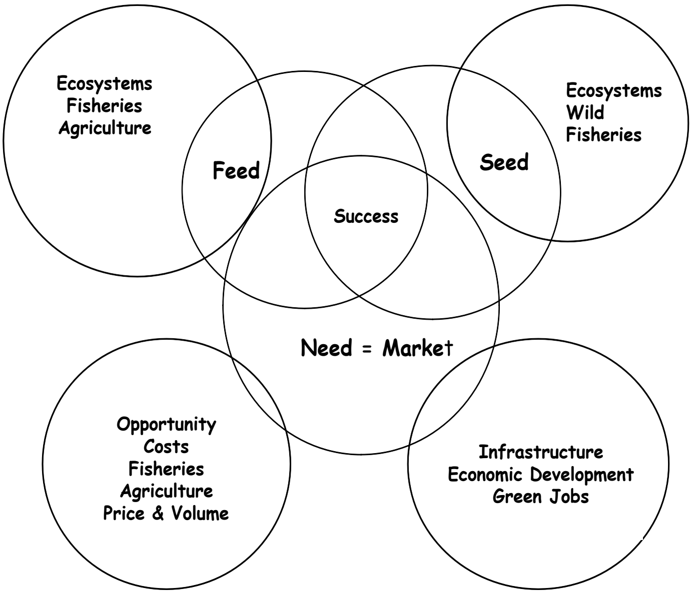
Aquaculture ecosystems mimic the form and functions of natural ecosystems. They are knowledge-based designed farming ecosystems planned as combinations of land and water-based plant, agronomic, algal and animal subunits which are embedded into the larger context of human social systems



Source: Costa-Pierce, 2010.

FIGURE 3

Success of aquaculture developments is not only the alignment of the "seed, feed and need". Each of these vital aquaculture resources has important interactions with natural ecosystems and the larger society in which they are located and therefore must be planned for in a comprehensive manner, not downgraded, misplaced or as an afterthought in the planning for more sustainable food systems. Comprehensive planning for aquaculture's economic, employment, ecological and social interactions with opportunity costs in fisheries and agriculture, and goods and services provided by natural ecosystems can ensure not only aquaculture's success, but also society's success



Source: Costa-Pierce, 2010.

ecosystems can be valuable, uncontaminated waste waters and fish wastes, which can be important inputs to ecologically designed aquatic and terrestrial ecological farming systems and habitats. In this review, we attempt to summarize data on resource use in aquaculture systems and make comparisons to other terrestrial food production systems, plus examine trends over the past decade since the FAO *Bangkok Declaration and Strategy for Aquaculture Development beyond 2000* and project the trajectories of these to 2050.

Systems ecology of comparable food systems

All modern, large-scale food systems have discernible environmental and social impacts. Even the sustainability of modern, large-scale, organic agriculture has been questioned (Allen *et al.,* 1991; Shreck, Getz and Feenstra, 2006). Fish products are the most widely traded products globally. As such, some important global resources and resource flows have, since the Bangkok Declaration

(NACA/FAO, 2000), been diverted to support its increased growth. A decade ago, Naylor *et al.* (2000) raised the issue of some fed aquaculture systems being a net loss of protein to humanity. Concerns were also raised as to the relative benefits of aquaculture in terms of resource use in comparison to capture fisheries; however, few comprehensive reviews have been conducted to analyze and compare resource use, trends in use, production and energy efficiencies of aquaculture versus other large-scale capture fisheries and terrestrial animal protein production alternatives. Only by comparing efficiencies of terrestrial and aquatic protein production systems can scientists, policy-makers and the public address in a more rigorous manner the available choices for resource use and production systems given the plethora of human needs and user conflicts, and the growing scarcities in water, land, energy and feeds.

No other food animal converts feed to body tissue as efficiently as fish (Smil, 2000). Farmed (fed) fish are inherently more efficient than any other farmed animals, since they are poikilotherms and thus divert less of their ingested food energy to maintain body temperatures. In addition, fish are neutrally buoyant in their environment and thus do not devote as much of ingested food energy to maintain bones/posture against gravity as do land animals. Principally for these reasons fish devote more of their digested food energy to flesh, and thus have much higher meat to bone ratios (and meat "dress out" percentages) in comparison to terrestrial animals. There are also inherent differences in the manner in which stored energy is processed through terrestrial and aquatic ecosystems. Land plants (primary producers) convert more of captured sunlight into plant structures in comparison to aquatic plants, and thus have lower edible percentages. Land plants store most of their energy as starches. Aquatic plants (algae) store oils (lipids) as their primary energy sources. Fish convert lipids much more efficiently than land animals convert starches and other carbohydrates (Cowey, Mackie and Bell, 1985). As a result, fish are the most valuable of any foods for human nutrition, disease prevention and brain development, since they have the highest nutrient density (highest protein and oil contents in their flesh) of all food animals (Smil, 2002).

Mass balances

Comparisons of production efficiencies of aquaculture versus an array of fisheries and terrestrial agriculture systems show that fed aquaculture is an efficient mass producer of animal protein (Table 1). Production efficiencies of edible mass for a variety of aquaculture systems are 2.5–4.5 kg dry feed/kg edible mass, compared with 3.0–17.4 for conventional terrestrial animal production systems. Beef cattle require over 10 kg of feed to add 1 kg of edible weight, whereas catfish use less than 3 kg to add a kg of edible weight. In the worldwide effort to increase food production, aquaculture merits more attention than raising grain-fed cattle (Goodland and Pimental, 2000). Since food conversions to edible mass in aquaculture are lower, aquatic animals inherently produce relatively less pollution than do terrestrial animals, as they

TABLE 1
Production efficiencies of edible proteins from some aquaculture systems compared with some animal agriculture systems

Food system	Feed conversion ratios (kg dry feed/kg wet weight gain +/- standard deviation)	% Edible	Production efficiencies (kg dry feed/kg of edible wet mass)
Tilapia	1.5 (0.2)	60	2.5
Catfish	1.5 (0.2)	60	2.5
Marine shrimp	1.5 (0.5)	56	2.7
Freshwater prawns	2.0 (0.2)	45	4.4
Milk	3.0 (0.0)	100	3.0
Eggs	2.8 (0.2)	90	3.1
Broiler chickens*	2.0 (0.2)	59	3.1
Swine	2.5 (0.5)	45	5.6
Rabbits	3.0 (0.5)	47	6.4
Beef	5.9 (0.5)	49	10.2
Lamb	4.0 (0.5)	23	17.4

* From Verdegem, Bosma and Verreth (2006).

Source: modified from Costa-Pierce (2002) except where indicated.

use nitrogen much more efficiently. Nitrogen use efficiency is 5 percent for beef and 15 percent for pork, while shrimp retain 20 percent and fish 30 percent of ingested nitrogen (Smil, 2002). As a result, aquatic animals release two to three times less nitrogen to the environment in comparison to terrestrial animal food production systems.

Trophic efficiencies

Coastal and oceanic ecosystems have energy transfer efficiencies of 10–15 percent and mean trophic levels of 3.0 to 5.0 (Ryther, 1969). Marine capture fisheries have a mean trophic level of 3.2 (Pauly *et al.*, 1998). Mean trophic levels in aquaculture systems range from 2.3 to 3.3, with highest trophic levels in North America and Europe (Pullin, Froese and Pauly, 2007). Kaushik and Troell (2010) noted an even wider range of fish trophic levels for the species listed in FishBase. Pullin, Froese and Pauly (2007) found most ocean fish consumed by humans have trophic levels ranging from 3.0 to 4.5, which Pauly *et al.* (1998) state are “0 to 1.5 levels above that of lions”. In the wild, however, salmon are not top-level carnivores, as they are consumed by whales, sea lions and other marine predators, and thus cannot be compared to lions. In cage aquaculture systems, salmon eat agricultural and fish meals and oils, so cannot be classified at the same trophic level as wild “carnivores”; rather, such animals in culture are feeding as “farmed omnivores”. Overall, Duarte *et al.* (2009) estimated a mean trophic level of 1.9 for mariculture and 1.0 for agriculture and livestock.

Most recent debates over the efficiencies of fed aquaculture have focused on “fish in/fish out” (FIFO) ratios, but use of single ratios to measure resource efficiencies have been superseded by the more sophisticated development and use of multiple indicators to compare resource use in aquaculture (Boyd *et al.*, 2007). Since measurement of resource use in aquaculture systems is such an important determinant, it is important to review the evolutionary development of these metrics. Naylor *et al.* (2000) began the FIFO discussion when they reported that for the ten aquaculture species they examined, approximately 1.9 kg of wild fish were required for each 1 kg of farmed production. For flounder, sole, cod, seabass, and tuna, Naylor *et al*. (2000) reported greater than 5 kg of wild fish were required and that "many salmon and shrimp operations use approximately 3 kg of fish for each one produced". Farmed catfish, milkfish and carp were all found to be "net producers", since they used less wild fish than was produced by aquaculture. At the time, these data were widely criticized for not accounting for the latest advances in aquaculture feeds, feed management technologies and nutrition science, as the authors chose to calculate FIFO ratios using FCRs for farmed marine fish and farmed salmon of 5:1 and 3:1 (Naylor, *et al.*, 2000) while rapid advances had decreased FCRs to approximately 1.5:1 for farmed marine fish and approximately 1.2:1 for farmed salmon.

Jackson (2009) presented FIFO data for the world's most commonly farmed species. Jackson (2009) calculated a FIFO ratio for global aquaculture of 0.52, demonstrating that for each tonne of wild fish caught, aquaculture produced 1.92 tonnes of aquaculture products, showing global aquaculture, as currently practiced, is a net benefit to humanity. However, Jackson (2009) calculated a FIFO for salmon of 1.68, the highest for all farmed species, meaning that for every tonne of wild fish used in salmon aquaculture, just 600 kg of farmed salmon were produced, confirming the Naylor *et al.* (2000) concern that such aquaculture systems remain a net loss of protein to society from "FIFO perspective". Trends in FIFO since 1995, however, all indicate a massive increase in efficiencies of feed use and incorporation of alternative protein meals and oils in fed aquaculture (Table 2). Kaushik and Troell (2010) criticized the

TABLE 2
Trends in "fish in fish" out ratios (FIFO) from 1995 to 2008

	FIFO (1995)	FIFO (2008)
Subsidized aquaculture		
Salmon	7.5	4.9
Trout	6.0	3.4
Eels	5.2	3.5
Miscellaneous marine fish	3.0	2.2
Shrimp	1.9	1.4
Net production aquaculture		
Chinese and Indian major carps		0.2
Milkfish		0.2
Tilapia		0.4
American catfish		0.5
Freshwater prawns		0.6

Source: Tacon and Metian (2008).

calculations of Jackson (2009), recalculating a global FIFO of 0.7 for feed-based aquaculture; but more importantly, they emphasized the need to consider the environmental performances of aquaculture systems more comprehensively and recommended that life cycle and equity approaches (see Ayer *et al.,* 2007) were more appropriate measures of resource use and stewardship in aquaculture. As a complement to life cycle approaches, Boyd *et al.* (2007) gave a more comprehensive set of numerical indicators of resource use in aquaculture.

Efficiencies of resource use in aquaculture

A literature review of resource uses in aquaculture for land, water, energy and seed was conducted, with materials summarized in subsequent Tables. A compilation of trends in each resource that have occurred over the last decade since the Bangkok Declaration with a projection of trends for each to 2050 was accomplished, taken both from literature sources and with inputs from Expert Panel members.

Land use

In the major aquaculture production centers of Asia, serious land constraints for the expansion of aquaculture have occurred over the past decade, especially in China, Indonesia, Bangladesh, Thailand and India (Liao and Chao, 2009). In a few of these areas where capital is available (especially China), intensive aquaculture systems that use less land (and water) have developed using imported feedstuffs for the formulation of pellet feeds for aquaculture. Land use efficiencies for semi-intensive and intensive aquaculture systems are the highest for land-based aquaculture production systems, which produce a tonne of products for as little as 100 m^2 of land (Table 3). However, these simple calculations do not recognize the concept of the “ecological footprint” of aquaculture or the appropriation of ecosystems goods and services acquired by aquaculture systems in their production (Kautsky *et al.,* 1997; Folke *et al.,* 1998). For example, Tyedmers (2000) measured the area of ecosystem support services for a range of farmed and commercially fished salmon species,

TABLE 3
Efficiencies of land use for aquaculture systems

System type	Description	Production (kg/ha/year)	Efficiency of land use (m^2/tonne)
Extensive	On-farm resources	100–500	20 000–100 000
Extensive	On-farm resources, fertilizers	100–1 000	10 000–100 000
Semi-intensive	Supplemental feeds, static	2 000–8 000	1 250–5 000
Semi-intensive	Supplemental feeds, water exchanges	4 000–20 000	500–2 500
Semi-intensive	Supplemental feeds, water exchanges, night aeration	15 000–35 000	300–700
Intensive	Complete feeds, water exchanges, night aeration	20 000–50 000	200–500
Intensive	Complete feeds, water exchanges, constant aeration	20 000–100 000	100–500

Source: Production figures taken from Verdegem, Bosma and Verreth (2006).

TABLE 4
Area of ecosystem support services needed by salmon fishing and farming systems

Salmon species, systems	Area use (ha/tonne)
Farmed chinook	16.0
Farmed Atlantic	12.7
Fished chinook	11.0
Fished coho	10.2
Fished sockeye	5.7
Fished chum	5.2
Fished pink	5.0

Source: Tyedmers (2000).

finding that farmed species needed ecosystem support services equivalent to 12.7–16.0 ha/tonne of farmed product, higher than salmon fisheries, which appropriated 5.0–11.0 (Table 4).

Trends in land use are:

Trends in the last decade:

- Ponds have high land use in comparison to terrestrial agricultural protein production systems.
- Rice fields are increasingly being converted into fish ponds in many countries (Hambrey, Edwards and Belton, 2008).
- Application of the use of "footprints" to quantify areas of ecosystem support services required per tonne of aquaculture production.

Projected Trends to 2050:

- Ponds taken over by urbanization.
- Cage systems proliferating with user conflicts driving the development and use of submerged systems.
- More widespread use of cages in small waterbodies, reservoirs and coastal open waters, but submerged systems more common in marine areas.
- Intensive recirculating systems are more efficient uses of land (ha/tonne aquaculture production) than terrestrial animal production systems but remain uneconomic in most areas of Asia in comparison to other production systems.
- More widespread use of integrated aquaculture into landscape-scale systems of mixed aquaculture/land uses.
- Greater use of land/water use planning to address growing land/water user conflicts.

Water use

A compilation of various studies on water use in aquaculture and animal production systems is shown in Table 5. Intensive, recirculating aquaculture systems are the most efficient water use systems. Extensive aquaculture pond systems and intensive, terrestrial animal production systems are the least

TABLE 5
Estimated consumptive water usages in aquaculture and terrestrial agriculture protein food

Systems	Estimated freshwater use (liters/kg product)	References	Comments
LOW USE: Ave. use less than 3 000 liters/kg product			
Seawater farming (halophytes, marine fish, shellfish, seaweeds, euryhaline fish such as tilapia)	0–100	Hodges *et al.* (1993), Federoff, *et al.* (2010), www.seawaterfoundation.org	Freshwater use is for makeup waters to replace evaporation in land-based farming systems
Small farm pig production	0–100	Zimmer and Renault (undated)	In China, about 80 % of pig meat production (estimated 454 million heads) is of this type
Vegetables (cabbages, eggplants, onions)	100–200	Smil (2008)	
Lemons, limes, oranges, grapefruit, bananas, apples, pineapples, grapes	286–499	Barthélemy, Renault and Wallender (1993)	In California, USA
Recirculating aquaculture systems	500–1 400	Verdegem, Bosma and Verreth (2006)	Intensive African catfish, eel and turbot fed complete feeds
Wheat, millet, rye	1 159	Barthélemy, Renault and Wallender (1993)	In California, USA
Wheat	1 300	Smil (2008)	
Sugar	1 929	Barthélemy, Renault and Wallender (1993)	In California, USA
Soybeans	2 000	USDA (1998)	
Legumes (peas, beans)	2 000–4 000	Smil (2008)	
Rice	2 300	Smil (2008)	
Egg production	2 700	Verdegem, Bosma and Verreth (2006)	
Milk production	2 700	Verdegem, Bosma and Verreth (2006)	Temperate dairy farm
Freshwater fish production	2 700	Verdegem, Bosma and Verreth (2006)	Intensively mixed pond with production of 100 tonnes/ha/year
Tilapia	2 800	Brummett (1997)	

Production systems [1]

HIGH USE: Ave. use 3 000–10 000 liters/kg product			
Some legumes	>3 000	Smil (2008)	
Sunflowers	3 283	Barthélemy, Renault and Wallender (1993)	In Egypt
Catfish	3 350 (with reuse for irrigation)	Brummett (1997)	
Catfish	4 000–16 000 (lowest for undrained embankment ponds, highest for drained watershed ponds)	Boyd (2005)	Eliminating well water as consumptive use would decrease water use in embankment ponds to 2 600–3 2001
Broiler chickens	3 500	Pimentel and Pimentel (2003)	

TABLE 5 (Continued)

HIGH USE: Ave. use 3 000–10 000 liters/kg product			
Rapeseed and mustard seed oils	3 500	Barthélemy, Renault and Wallender (1993)	In California, USA
Chicken	4 000	Smil (2008)	
Pigs (farrow-finish operation)	4 700	Verdegem, Bosma and Verreth (2006)	
Fish in freshwater ponds	5 200	Verdegem and Bosma (2009)	If infiltration, drainage and recharge are considered green water
Soybean oil	5 405	Barthélemy, Renault and Wallender (1993)	In Egypt
Coconut oil, cottonseed oil, palm oil, palm kernel oil, sesame seed oil	5 500	Zimmer and Renault (undated)	In Malaysia, Indonesia
Pork	6 000	Pimentel and Pimentel (2003)	
Channel catfish	6 300 industry wide	Brummett (1997)	
Pangasiid catfish	6 400 ave. industry wide	Phan *et al.* (2009)	In Viet Nam
Fish in freshwater ponds	4 700–7 800	Verdegem, Bosma and Verreth (2006)	Production of 10–20 tonnes/ha/year with nighttime aeration
Sunflower seed oil	7 550	Barthélemy, Renault and Wallender (1993)	In California, USA
Groundnut oil	8 713	Barthélemy, Renault and Wallender (1993)	In California, USA
Pork	10 000	Smil (2008)	

EXTREME USE: Ave. use >10 000 liters/kg product			
Shrimp farming in ponds	11 000–43 000	Beveridge, Phillips and Clarke (1991)	
Olive oil	11 350	Barthélemy, Renault and Wallender (1993)	In Tunisia
Fish culture	11 500	Verdegem, Bosma and Verreth (2006)	Fed freshwater species
Beef	15 000–43 000	Smil (2008); Pimentel and Pimentel (2003)	
Butter	18 000	Barthélemy, Renault and Wallender (1993)	In California, USA
Trout (90% recycling)	25 000 (252 000 withdrawal)	Brummett (1997)	
Boneless beef	30 000	Smil (2008)	
Fish in freshwater ponds	30 100	Verdegem, Bosma and Verreth (2006)	Production of 30 tonnes/ha/year with 20% water exchange
Extensive fish culture	45 000	Verdegem, Bosma and Verreth (2006)	No feed
Sheep	51 000	Pimentel and Pimentel (2003)	
Pangasiid catfish	up to 59 700 (700 to 59 700	Phan *et al.* (2009)	In Viet Nam
Trout (75% recycling)	63 000 (252 000 withdrawal)	Brummett (1997)	

[1] Consumptive water use in aquaculture remains a controversial measure. J.A. Hargreaves (personal communication, 2011) noted that Boyd (2005) defined, then measured water use in aquaculture, but that his definition included groundwater use as consumptive use, which contradicts the definitions used by hydrologists and agricultural scientists (Gleick, 2003; Falkenmark and Lannerstad, 2005; Lamm, 2008).

efficient. Water use in aquaculture can be extreme – as high as 45 m^3/kg of fish production. The potential for increased water use efficiencies in aquaculture is higher than in terrestrial systems. Globally, about 1.2 m^3 (or 1 200 liters) of water is needed to produce 1 kg of grain used in animal feed (Verdegem, Bosma and Verreth, 2006). A kg of tilapia can be produced with no consumptive freshwater use (e.g. in cages, seawater farming systems) or using as little as 50 liters of freshwater (Rothbard and Peretz, 2002). Seawater aquaculture systems (mariculture) can use brackishwaters unsuitable for agriculture; plus, integrated, land-based saltwater faming is possible (Fedoroff *et al.,* 2010).

Water use is connected to changing land use, and conflicts between these have reached a crisis point in some of the major aquaculture farming regions of the world, such as Bangladesh. Fish and fisheries are very important in Bangladesh, where millions of people are directly and indirectly involved. Aquaculture, which developed only recently (1980s) in Bangladesh, now contributes around 40 percent of total fish production of the country (FAO, 2009). Bangladesh is a nation of rivers that originate in the Himalayas. It is home to a huge hydrological system that connects the world's highest mountains to the Bay of Bengal. Upstream dams in India across South Asia's major rivers (e.g. the Ganga, Tista) have caused serious water problems in southern Bangladesh, which is a major aquaculture production zone. As a result, important tributaries are drying, reducing both capture fisheries and aquaculture production. Fish breeding, nursery and feeding areas have been degraded due to heavy siltation and less water in the rivers.

Coastal Bangladesh has rapidly become saline due to the decreased flows of freshwaters and intrusions of saline waters from the Bay of Bengal, which has disrupted both rice and shrimp farming in the region.

Trends in water use are:

Trends in the last decade:

- High water use in ponds in comparison to terrestrial agricultural protein production systems.
- Severe water competition growing with alternative users.
- Massive damming and urbanization in Asia diverting water to coastal cities and agriculture.

Projected Trends to 2050:

- Upstream dams cut off downstream users.
- Freshwater use conflicts and droughts increase in aquaculture production zones, closing many pond areas.
- More rapid development of cage systems in open waters.
- Rapid decrease in the costs and increased efficiencies of intensive, recirculating systems that use water more efficiently than ponds and terrestrial animal production systems.

- Multiple uses of water in landscape-scale systems of mixed reservoir production with downstream aquaculture/agriculture.
- Changes to traditional rice/fish systems in Asia, with large-scale land modification, addition and replacement of rice with high-value species (prawns) in Bangladesh, Viet Nam and China.
- Development of seawater farming systems in arid areas.
- Development of low-energy membranes with wind turbines breaking the 2 kW/h/m^3 barrier which accelerates use of seawater for freshwater aquaculture.

Energy use

A compilation of various studies on energy use in aquaculture and animal production systems is shown in Table 6. Seaweed and extensive pond aquaculture of omnivores are comparable to vegetable farming, while mussel aquaculture is comparable to sheep and rangeland beef farming. Catfish farming is similar to poultry and swine production. Cage aquaculture of salmonids and marine fish is comparable to intensive capture fisheries.

Energy comparisons between systems have become part of more detailed analyses of life cycles (Papatryphon *et al.,* 2004; Ayer and Tyedmers, 2008). Comparisons of these with terrestrial farming show clearly the huge production benefits of intensive aquaculture, albeit at a much higher energy cost, contained mostly in feed (Ayer and Tyedmers, 2008, Table 7). Over the coming decades, increasing global energy, processing, shipping/transportation costs of both products and feeds are predicted (FAO, 2008a; Tacon and Metian, 2008).

Trends in energy use are:

Trends in the last decade:

- Globalization and intensification of food production increases energy density and use in fed aquaculture in comparison to fishing and terrestrial agricultural protein production systems.

Projected Trends to 2050:

- Recirculating systems are energy intensive compared to other systems and have large carbon footprint.
- Life Cycle Assessments show advantages/disadvantages of aquaculture.
- Large-scale development and use of cost-effective renewable energy systems make intensive recirculating systems more widespread and accessible.

Feed use

Aquaculture uses most of the world's fishmeal (68 percent) and fish oil (88 percent) with the balance used by intensive livestock agriculture and for pet foods (Tacon, 2005; Tacon, Hasan and Subasinghe, 2006; Tacon and Metian, 2008). Salmon, trout and shrimp aquaculture, which account for less than 10 percent of world aquaculture production use an estimated 26 percent of the world's

TABLE 6
Ranking of fossil fuel protein production efficiencies for various aquatic and terrestrial food production systems

Food production system	Fossil fuel energy input/protein output (kcal/kcal)
LOW ENERGY USE (ave. use less than 20 kcal)	
North Atlantic herring fisheries	2–3
Seaweed aquaculture, West Indies and elsewhere	1 (range 5–7)
Carp aquaculture, Asian ponds	1–9
Vegetable row crops	2–4
North Pacific salmon fisheries	7–14
Atlantic salmon ranching	7–33
Tilapia aquaculture, Indonesian ponds	8
Trout cage aquaculture, Finland & Ireland	8–24
Rangeland beef	10
Sheep agriculture	10
North Atlantic cod fisheries	10–12
Mussel aquaculture, European longlines	10–12
USA Dairy	14
Tilapia aquaculture, Africa semi-intensive	18
HIGH ENERGY USE (ave. use 20–50 kcal)	
Cod capture fisheries	20
Rainbow trout raised in cages	24
USA eggs	26
Atlantic salmon capture fisheries	29
Pacific salmon fisheries	up to 30 (range 18–30)
Broiler chickens	up to 34 (range 22–34)
American catfish raised in ponds	up to 34 (range 25–34)
Swine	35
Shrimp aquaculture, Ecuador ponds	40
Atlantic salmon cage aquaculture, Canada & Sweden	up to 50 (range 40–50)
EXTREME USE (ave. use greater than 50 kcal)	
North Atlantic flatfish fisheries	53
Seabass cage aquaculture, Thailand	67
Shrimp aquaculture, Thailand ponds	70
Feedlot beef	up to 78 (range 20–78)
Oyster aquaculture, intensive tanks, USA	136
North Atlantic lobster capture fisheries	up to 192 (range 38–59)
Shrimp capture fisheries	up to 198 (range 17–53)

Source: summarized from Costa-Pierce (2002) and Troell *et al.* (2004); where multiple studies exist, they are both listed.

fishmeal, but 74 percent of the fish oil (Tacon and Metian, 2008). However, Tacon and Metian (2008) predict that fishmeal and oil use in aquaculture will decrease while aquaculture production grows significantly (Figure 1), and that fishmeal/oil will increasingly be diverted from uses as bulk products to high-priced, specialty feed ingredients.

TABLE 7
Total energy use efficiencies of agriculture versus salmon farming systems. To obtain salmon production, data in Table 1 in Ayer and Tyedmers (2008) was used and a cage depth of 5 m

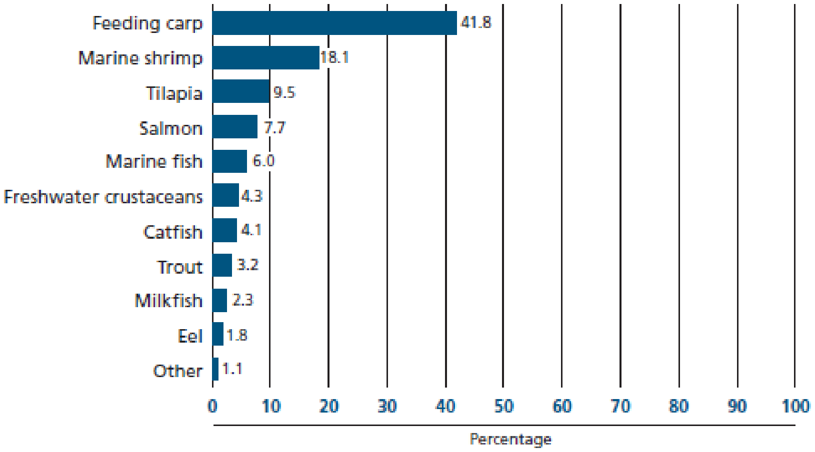
Food system	Production (tonnes/ha)	MJ/tonne	References
Sugar beets	57.9	550	Elferink, Nonhebel and Moll (2008)
Potatoes	47.0	940	Elferink, Nonhebel and Moll (2008)
Soybeans	2.5	2 950	Elferink, Nonhebel and Moll (2008)
Wheat	8.2	3 100	Elferink, Nonhebel and Moll (2008)
Canada salmon net-pen, water-based	1 000	26 900	Ayer and Tyedmers (2008)
Canada salmon bag system, water-based	1 733	37 300	Ayer and Tyedmers (2008)
Canada salmon flow-through, land based	2 138	132 000	Ayer and Tyedmers (2008)
Canada salmon recirculating, land-based	2 406	233 000	Ayer and Tyedmers (2008)

The major development in feed use in aquaculture over the past decade has been the rapid increase in the global trade of feedstuffs and feeds for fed aquaculture systems in Asia which has allowed the widespread use of formulated feeds. Tacon and Metian (2008) estimated that in 2005 about 45 percent of world aquaculture production (about 63 million tonnes, including aquatic plants) was estimated to be dependent on the direct use of feed, either as a single feed ingredient, farm-made aquafeed or as industrially manufactured compound aquafeeds. A striking increase in the use of formulated feeds for the intensification of herbivorous and omnivorous fish culture in Asia, especially for carps in China, India and Bangladesh and for catfish in Viet Nam has occurred since the Bangkok Declaration. An estimated 23 million tonnes of aquafeed was produced in 2005, and about 42 percent was consumed by carps (Figure 4). However, it has to be noted that the use of fishmeal for carp feed is only about 13–14 percent of total fishmeal use for aquaculture, while the amount of fishmeal used for salmonids, marine fish and marine shrimp is 18, 18 and 22 percent, respectively.

Research on the use of agricultural meals and oils to replace use of ocean resources (especially the functional components of fishmeals/oils needed for fish nutrition) are a major subject of aquaculture research and development (Watanabe, 2002; Opstvedt *et al.,* 2003). Turchini, Torstensen and Ng (2009) reported that for all of the major aquaculture fish species, 60–75 percent of dietary fish oil can be substituted with alternative lipid sources without significantly affecting growth performance, feed efficiency and feed intake. Oo *et al.* (2007) found that palm oil could replace fish oil in rainbow trout diets and reduce the dioxin contents in fish.

Current projections forecast an expansion of agricultural and other terrestrial sources of feed proteins and oils in aquaculture, and these alternatives are

FIGURE 4
The major global consumers of aquafeeds are herbivorous and omnivorous fish and shrimp



Source: Tacon and Nates (2007).

developing rapidly. Terrestrial proteins and oils from soybeans, sunflowers, lupins and rendered livestock are available at volumes larger than the quantity of global fishmeal. Soybeans have high protein content of ~28 percent, peas have ~22 percent, and these have good amino acid profiles. Other abundant cereals have protein contents of only 12–15 percent. However, soybean meal processing can create protein concentrates with protein levels of >50 percent (Bell and Waagbo, 2008). Vegetable oils have very low eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) levels. However, substitution of plant oils upwards of 50 percent of added dietary oil has not resulted in growth reductions or increased mortalities in fish such as salmon and trout. Terrestrial animal by-products from the rendering industry are the largest supply of high-quality feed-grade animal protein and lipid for animal feeds (Tacon and Nates, 2007).

The massive use of plant resources in feeds for meat production in developed countries has been recently questioned, considering food deficits of some countries and regions and the global food availability balance (Agrimonde, 2009). According to this study, attending for predicted population increments in food-deficit countries in the next decades would include the access to some near food-grade raw materials currently used for animal feeds. Thus, future aquafeeds could largely depend upon lower grade raw materials (including those possibly recovered from crop wastages) that may be further improved by processing and biotechnological transformation to fit as consistent nutrient sources for farmed species. This variety of available raw materials with different qualities and costs would further require strategic diversification in feed formulation and processing strategies to allow manufacture flexibility according to availability and cost-benefit relationship.

If agricultural sources of meals and oils are the future of fed aquaculture, there will be a need for a new global dialogue on the impacts of fed aquaculture as a driver of agriculture production, especially so for soybeans. Increased aquaculture consumption of the world's grains and oils raises concern over the spread of unsustainable agriculture practices. Brazil has been targeted as one of the world's major soybean suppliers. Costa *et al.* (2007) have demonstrated that soybean farms are causing reduced rainfall in the Amazonian rainforest. About one-seventh of the Brazilian rainforest has been cut for agriculture, about 15 percent of which is soybeans. Soybeans, which are light in color, reflect more solar radiation, heating the surface of the land less and reducing the amount of warm air convected from the ground. Fewer clouds form as a result, and less precipitation falls. In soybean areas, there was 16 percent less rainfall compared to a 4 percent decrease in rainfall in land areas cleared for pasture.

Trends in feed use are:

Trends in the last decade:

- Overuse of marine meals/oils, threatening sustainability of pelagic fish stocks.
- High feed costs.
- Fish feed ingredients imported, and there is a crisis in feed qualities; meat-bone meal also imported but quality is not assured.
- Social equity/poverty concerns with use of pelagics as feeds rather than as direct human foods.
- Polychlorinated biphenyl (PCB) and mercury contamination of fishmeals/oils.

Projected Trends to 2050:

- Increased use of imported fishmeals/oils in formulated feeds for traditional carp and imported tilapia species in Asia (especially in China), decreasing FCR.
- Increased use of wet feeds (cakes, wastes from poultry processing plants) and chicken manures in South Asia fish culture with high FCR (>3.0), resulting in deterioration of water quality.
- Decreased use of marine meals/oils in intensive cage/tank systems and improvement in FCRs.
- Replacement of marine meals/oils by agricultural sources and by algal/bacterial/fungal bioreactors, but new issues arising about aquaculture leading to deforestation.
- Use of biotechnology to elongate/upgrade essential fatty acids.
- Cleansing of oils by high technology.

Seed

A major FAO review of freshwater seed sources for aquaculture which included 21 country case studies was completed recently by Bondad-Reantaso (2007). Studies indicated that seed resources were an essential and profitable phase of aquaculture production, and that efficient use of seed resources is necessary to guarantee optimum production. Studies identified challenges concerning water allocation and land use conflicts for seed culture production in all countries. The study recommended a shift from high-water-use, land-based hatchery systems to water-saving and water-productivity-enhancing technologies such as integrating seed production with agriculture and optimizing the use of irrigated agricultural land, and the use of cages and *hapas* for fry to fingerling rearing, especially where large numbers of perennial waterbodies exist. Such integrations enhance the productivity of reservoirs and irrigation dams and enable landless households to participate in aquaculture.

Seed quality is related to the quality of the broodstock used, genetic quality and good hatchery/nursery management. Broodstock management and seed quality will be a key issue in meeting projected fingerling requirements to 2020 (Bondad-Reantaso, 2007). Approaches to genetic improvement using selective breeding, use of genetic markers, sex control techniques, chromosome set manipulation, crossbreeding and transgenesis need to be integrated during the domestication and translocation of aquaculture stocks. Seed certification and accreditation of hatchery practices are needed worldwide. Certification is a quality assurance system with certain minimum predetermined quality standards and criteria (e.g. genetic purity, appropriate husbandry, high grow-out performance, pathogen-free status). Seed certification is part of a wider programme on genetics and breeding, biodiversity conservation and international trade. In many Asian countries, seed is produced in hundreds of small hatcheries where genetic erosion is a serious concern. For example, around 99 percent of freshwater seed available in Bangladesh is produced in about 900 public and private hatcheries where the quality of seed has seriously deteriorated due to genetic erosion of broodstock.

Trends in seed use are:

Trends in the last decade:

– Inadequate and unreliable supply of quality seed.
– Poor genetic quality of seed.
– Basic production from regional hatcheries – the human infrastructure, financial and business/marketing support, and policy and legal frameworks are not in place in many nations.
– Impacts of uncontrolled releases of cultured seed stocks.

Projected Trends to 2050:

– Rapid expansion of export-oriented international seed trade, especially of high-value species.
– Increasing need to introduce quality assurance measures beyond simple official zoosanitary certificates.
– Regional hatchery infrastructure taking shape in many nations.

Non-fed aquaculture

Concerns and constraints regarding the expansion of global aquaculture are much different for fed and non-fed aquaculture. Non-fed, herbivorous fish capture-based aquaculture in Asian reservoirs remains a major source of production, but has not expanded (Lovatelli and Holthus, 2008). In Africa, aquaculture of herbivorous fish in reservoirs remains a priority but is still poorly developed, largely due to inadequate hatchery capacity and training, despite including countries having some of the highest reservoir densities in the world (Sri Lanka has the highest density at 230 ha/100 km^2, while Zimbabwe has 139) (Petr, 2005). Seaweed aquaculture is one of the world's largest marine production systems, with plant production in 2004 reaching an estimated 13.9 million tonnes, of which 99.8 percent originated in the Asia-Pacific region, 10.7 million tonnes from China. Japanese kelp (*Laminaria japonica* – 4.5 million tonnes) was the most commonly produced species, followed by wakame (*Undaria pinnatifida* – 2.5 million tonnes) and nori (*Porphyra tenera* – 1.3 million tonnes) (FAO, 2008b). Production of aquatic plants has increased rapidly from the 2002 total of 11.6 million tonnes, mainly due to large production increases in China. The greatest threats to aquatic plant production in Asia are water pollution, biofouling and the urbanization of coastal ocean areas.

For non-fed, shellfish aquaculture, there has been a convergence over the past ten years or so around the notion that user conflicts in shellfish aquaculture can be solved not only through technological advances, but also by a growing global science/non-governmental organization (NGO) consensus that shellfish aquaculture can "fit in" in an environmentally and socially responsible manner, and into many coastal environments, many of which are already crowded with existing users (Costa-Pierce, 2008). Included in this "evolution" of shellfish aquaculture are:

- Development of submerged technologies for shellfish aquaculture such as longlines (Langan and Horton, 2003), modified rack and bag shellfish gear (Rheault and Rice, 1995) and upwellers for nursery stages of shellfish, some of which are placed unobtrusively under floating docks at marinas (Flimlin, 2002).
- Scientific findings and reviews demonstrating the environmental benefits of shellfish aquaculture in providing vital ecosystem and social services (National Research Council, 2010) such as nutrient removal (Haamer, 1996; Lindahl *et al.*, 2005) and habitat enhancement (DeAlteris, Kilpatrick and Rheault, 2004; National Research Council, 2010).
- Research on natural and social carrying capacities for shellfish aquaculture and on sophisticated, collaborative work group processes (McKinsey *et al.*, 2006; Byron *et al.*, 2011).
- Development and wide use by industry of best (and better) management practices (BMPs) (National Research Council, 2010).

- Diversification of traditional wild-harvest fishing/shellfishing families into shellfish aquaculture as part-time enterprises, breaking down barriers between fishing/aquaculture user communities.
- Publication of global comparisons with fed aquaculture indicating a strong movement in shellfish aquaculture globally towards an adoption of ecological approaches to aquaculture at all levels of society (Costa-Pierce, 2008).

Major constraints to shellfish culture are the growing occurrences of red tides causing paralytic shellfish poisoning and the proliferation of human bacterial and viral diseases.

Major trends potentially affecting resource allocation and uses

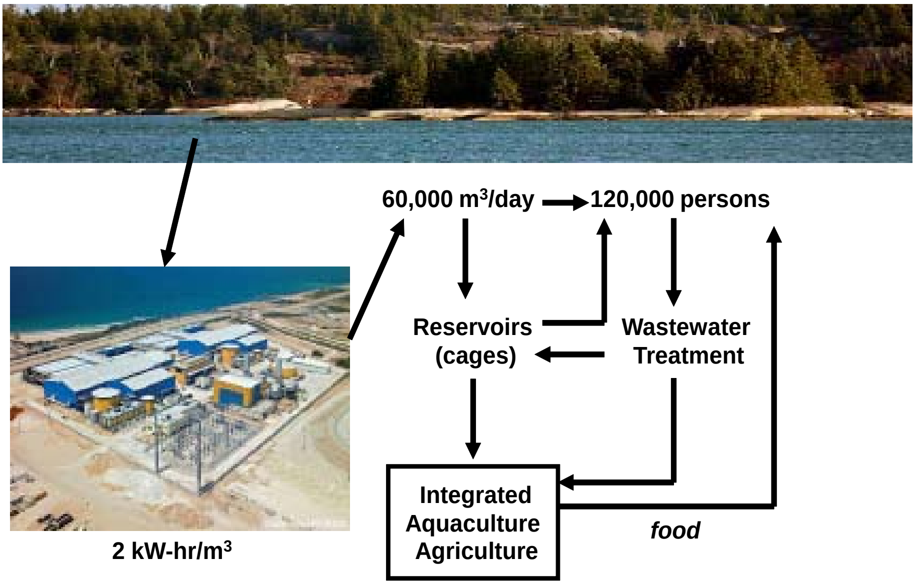
"As population growth, urbanization, and climate change have affected all industrial inputs and outputs, humanity entered, for all food producing industries, the sustainability transition at the turn of the 21st century." (Brown, 2009).

The three major trends occurring in the last decade that will affect decision-making as to resource use and allocation in aquaculture are: (i) energy use in transportation affecting the globalization/localization of aquaculture feeds and products; (ii) capital investments in alternative energy; and (iii) a global strategy for aquaculture to deliver massive amounts of aquatic proteins to the world's poor.

Increasing seafood imports remains a viable option for the rich countries such as Japan, the United States of America and the Member States of the European Union, but it is questionable if this level of globalization is sustainable and will continue, especially as the era of "peak oil" arrives and fuel prices continue to rise. The UK Energy Research Centre (UKERC, 2009) reports that peak oil may be reached by 2030 and that humanity may have already consumed 1 228 of the estimated 2 000 billion barrels of the "ultimate recoverable resource". Local seafood production will spread rapidly as the cost and availability of transportation fuels from oil increase. Rapid developments of alternative energy and water treatment systems (desalinization) offer new opportunities for large-scale integrated food production in the coastal zone (Figure 5).

Siting of intensive industrial aquaculture facilities, especially siting of cages in enclosed seas such as the Mediterranean Sea, is a very controversial topic, especially so when it is now estimated that cage aquaculture facilities contribute ~7 percent of total nitrogen and ~10 percent of total phosphorous discharges (Pitta *et al.,* 1999). Inappropriate siting of cages has been blamed for the destruction of nearshore and benthic aquatic ecosystems (Gowen and Bradbury, 1987). However, Mirto *et al.* (2009) found that if seabass/seabream cages were sited above seagrass (*Posidonia oceanica*) meadows, the seagrasses responded

FIGURE 5
Coastal ecological aquaculture systems of the future will merge energy, desalinization and wastewater treatment with integrated aquaculture-agriculture systems to deliver renewable sources of energy, food and water. This pictorial diagram is an ecological design which connects three coastal 3 MW electric-generating windmills to a coastal desalinization plant using low energy, reverse osmosis membranes (the Ashekon plant in Israel is pictured) to produce freshwater that can be used for: a) human direct consumption (120000 persons), and/or b) food production in integrated reservoir/agriculture-aquaculture farming systems



Source: Tacon and Nates (2007).

positively to aquaculture discharges and that there were no impacts on benthic biodiversity. These findings raise the possibility that seagrass meadows can be created and enhanced by ecological engineering of a systems approach and evolving a non-toxic, cage ecological aquaculture model for fish production and environmental improvement in this region. There are well-developed examples of aquaculture ecosystems, both land and water-based, mostly in Asia (Costa-Pierce, 2008; Hambrey, Edwards and Belton, 2008; Edwards, 2009). In the West, there are few commercial aquaculture ecosystems, with most being small-scale, research and development operations; however, there are advanced freshwater aquaculture ecosystems that combine aquaculture units (ponds/tanks), aquaponics for food and fodder with wetlands, and aquaculture ecosystems that incorporate advances in waste treatment and solar energy, and others that are landscape ecological models that have a tight integration between aquaculture and agriculture (Rakocy, 2002; Costa-Pierce and Desbonnet, 2005; Costa-Pierce, 2008). A wide array of technologies and organisms can be used to not only remediate nutrient discharges (especially nitrogenous compounds)

TABLE 8
Different organisms/technologies used in biological management of nitrogenous compounds to improve water quality in aquaculture systems

Organisms/technologies	% reduction/uptake
Bacteria – *Nitrosomonas* and *Bacillus*	96% TAN*
Fungus – *Aspergillus niger*	25 mg TAN/liter
Fungus – *Penicillium*	0.72 mg TAN/liter
Macrophyte – *Elodea densa*	0.2 mg NH_4-N/liter; 0.4 mg NO_2-N/liter
Biofilter	3.46 g TAN/m^3/d; 0.77 g NO_2/m^3/d
Trickling filter	0.24–0.55 g TAN/m^2/d 0.64 g TAN/m^2/d
Microbead filter	0.450.60 g TAN/m^2/d 0.30 g TAN/m^2/d
Fluidized bed reactor	0.24 g N/m^2/d
Seaweed – *Ulva lactuca*	49-56% mean NH_3-N
Seaweed – *Ulva pertusa*	0.45 g N/m^2/d
Periphyton – cyanobacteria	91% TAN/liter; 91% NO_2-N/liter
Periphyton – diatoms	62% TAN/liter; 82% NO_2-N/liter
Periphyton	0.56 mg TAN/liter
AquaMats®	0.22 g ammonia/m^2/d
Biofilms	0.42 µg ammonia/liter
Immobilized nitrifying bacteria	4.2–6.7 mg TAN/liter/d

* TAN = Total ammonia nitrogen.

Source: Yusoff *et al.* (2010). References to the many individual studies that are summarized here can be found in the paper.

from aquaculture but also produce additional, highly valuable aquatic crops for human consumption or for environmental and agricultural improvement (Table 8). In Israel, highly efficient, landscape-sized integrations of reservoirs with aquaculture and agriculture have been developed (Hepher, 1985; Mires, 2009), as well as highly productive, land-based aquaculture ecosystems for marine species (Neori, Shpigel and Ben-Ezra, 2000). Intensive, integrated coastal farming systems are common in many areas of China where the two main forms of marine integrated systems are seaweed aquaculture integrated with fish cages and suspended shellfish aquaculture (Troell *et al.,* 2009). In China, the polyculture of shrimp with mussels, and clams plus crabs is also popular, with shrimp yields of approximately 300–600 kg/ha/year (Nunes *et al.,* 2003), which, if properly managed, could be a model for ecological intensification worldwide (Nunes *et al.,* 2011).

A global strategy for aquaculture to assist in delivering more benefits to the world's poor could include:

1. Allocating more feed fish for poverty alleviation and human needs worldwide, thus allocating less for fed aquaculture so as to: (a) increase the ecosystem resilience of the Humboldt ecosystem, and (b) relieve the increasing overdependence of aquaculture countries such as Thailand (shrimp) and

Norway (salmon) on this southeastern Pacific Ocean marine ecosystem. Alder *et al*. (2008) estimated that about 36 percent of the world's fisheries catch (30 million tonnes) is processed into fishmeal and oil, mostly to feed farmed fish, chickens and pigs. Jacquet *et al.* (2009) report that Peru exports about half of the world's fishmeal from its catch of 5–10 million tonnes/year of anchovies while half of its population of 15 million live in poverty and 25 percent of its infants are malnourished. A campaign launched in 2006 combining scientists, chefs and politicians to demonstrate that anchovies are more valuable to the Peruvian people and its economy as direct foods has resulted in a 46 percent increase in demand for fresh anchovies and 85 percent increase in canned product. One tonne of fillets has sold for five times the price of 1 tonne of meal and requires half the fish (3 tonnes for 1 tonne of fillets vs 6 tonnes for 1 tonne of meal). Peru has decided to dedicate 30 percent of its annual food security budget (approximately USD80 million) for programmes to supply anchovies to its people. Higher prices for fish used as direct human foods for food security will limit processing of fish to meals for terrestrial animal and aquaculture feeds, thereby decreasing the supply of fishmeal and oils for global aquaculture trade and development but meeting the Millennium Development Goals of eliminating everywhere extreme hunger and starvation.

2. Accelerating research into elucidating the functional feed ingredients in fish diets that are showing the potential to eliminate the needs for fishmeal and oils in aquaculture. Skretting Aquaculture Research Centre (2009) reported on research on "functional ingredients" that are contained in fishmeals and oils which contribute to efficient feed conversions and high growth rates, fish health and welfare. Initial research focused on beta-glucans that stimulate the immune system of fish and protect against the effects of bacterial furunculosis while also allowing reductions in fishmeal contents in diets to 25 percent. Additional research in 2008 with phospholipids in meals, triglycerides in fish oil and antioxidants have resulted in excellent fish performances from feeds with almost no marine fishmeal and oil. Current research is exploring the extraction of functional ingredients from other non-marine by-products.

Developing alternative ecological aquaculture models that accelerate the movement towards the use of agricultural, algal, bacterial, yeasts meals and oils.

The globalization of seafood trade has meant less dependence on local natural and social ecosystems, and has resulted in some virulent opposition to aquaculture development, especially as industrial aquaculture has removed the local sources of production and markets, and jobs have been externalized. One major consequence of this globalization has been the increased dependence of industrial, "fed" aquaculture on the southeastern Pacific Ocean marine ecosystem for fishmeals and oils. The global implications for the Humboldt ecosystem, for local poverty, and the scoping of this unsustainable situation to the entire global protein food infrastructure are profound and are still largely unrealized.

The Bangkok Declaration expressed the need to develop resource-efficient farming systems which make efficient use of water, land, seed and feed inputs by exploring the potential for commercial use of species feeding low in the food chain. Although significant resource competition exists, significant technological advancements in aquaculture over the past decade have occurred to make production systems less consumptive of land, water and energy, to the point where aquaculture resource use, overall, is comparable to poultry production. However, there are serious questions about feed resources over the next decade. The potential is limited for direct or on-farm integration to satisfy national food security due to the limited on-farm resource bases, especially in Africa. To make a more significant contribution by increasing production, there is a need to use off-farm inputs, as has occurred most dramatically in Asia. Currently, about 40 percent of aquaculture depends on formulated feeds: 100 percent of salmon, 83 percent of shrimp, 38 percent of carp (Tacon and Metian, 2008). An estimated 72 percent of all use of global aquafeeds is by low-trophic-level herbivorous and omnivorous aquatic organisms (carps, tilapias, milkfish and shrimp) (Figure 4). Trophic-level positioning for aquaculture species that is contained in the "FishBase" database for wild species is thereby less useful as an indicator of "sustainability".

The major species being fed in Asia are "herbivores/omnivores" such as tilapia, labeo roho, grass carp, common carp, and striped catfish, each of which dominates in various countries. Where aquaculture is growing rapidly (e.g. China, Viet Nam, Bangladesh and India) many finfish aquaculture systems are increasingly being fed on lower quality "cakes", which are mixtures of local brans, oil cakes and manure from intensive terrestrial animal feedlots. Discharges from these systems are causing water quality problems. Movement of these aquaculture production centers towards the use of high-quality complete feeds could exert major pressure on global (and regional) marine and agricultural meals/oil resources. Pangasiid catfish development in ponds in the Mekong Delta of Viet Nam by 2007 was estimated at 683 000 tonnes, 97 percent fed by commercial feeds from 37 feed companies (Phan *et al*., 2009). Plans are to expand this production to 1.5 million tonnes over the next few years, causing concerns not only over feed but on water use as well.

Conclusions

The next 20 years will see an increase in the efficient use of land, water, food, seed and energy through intensification and widespread adoption of integrated agriculture-aquaculture farming ecosystems approaches. However, this will not be enough to increase aquaculture production, as these will improve only the efficiency of use, and increase aquaculture yields per unit of inputs. An exponentially growing population will require aquaculture to expand rapidly into land and water areas that are currently held as common pool resources ("commons"). This raises issues of access to and management of common pool resources, which could result in conflicts with existing users and potentially acute social, political and economic problems. Nobel Laureate Elinor Ostrom provides important insights for the future expansion of aquaculture in a more crowded world striving to be resource-efficient and sustainable. Ostrom has studied how humans interact with ecosystems in common pool resource systems, emphasizing the value of self-organization, stakeholder engagement due to the complexity of issues, the diversity of actors involved and the growing scarcity of resources that have to be shared. Her proposal is that of a local, "polycentric approach", where key management decisions should be made as close to the scene of events and the actors involved (Ostrom, 1990; Ostrom, Gardner and Walker*,* 1994). Examples of the merits of such approaches to smallholder aquafarmers now exist, especially in Asia (De Silva and Davy, 2010).

Acknowledgements

We wish to acknowledge the contributions of the international expert panelists, with special thanks to Devin Bartley and Mohammad Hasan, FAO, for their insightful reviews of first outlines and drafts. We wish to also acknowledge the assistance of two anonymous reviewers, as well as Claude Boyd, Malcolm Beveridge, Peter Edwards, John Hargreaves and Kifle Hagos, who provided data and information for this review.

References

Agrimonde, 2009. *Scenarios and challenges for feeding the world in 2050. summary report.* 39 pp. (available at: www.cirad.fr/en/news/all-news-items/articles/2009/science/results-of-the-agrimonde-foresight-study)

Alder, J., Campbell, B., Karpouzi, V., Kaschner, K. & Pauly, D. 2008. Forage fish: from ecosystems to markets. *Annual Reviews in Environment and Resources*, 33: 153–166.

Allen, P., Van Dusen, D., Lundy, J. & Gliessman, S. 1991. *Integrating social, environmental, and economic issues in sustainable agriculture*. *American Journal of Alternative Agricultur*e, 6(1): 34–39.

Allison, E.H., Beveridge, M.C.M. & van Brakel, M. 2009. Climate change, small-scale fisheries and smallholder aquaculture. *In* M. Culberg, ed. *Fish, trade and development*, pp. 73–87. Stockholm, Royal Swedish Academy of Agriculture and Forestry.

Ayer, N. W., Tyedmers, P.H. Pelletier, N.L., Sonesson, U. & Scholz, A. 2007. Co-product allocation in life cycle assessments of seafood production systems: review of problems and strategies. *International Journal of Life Cycle Assessment*, 12(7): 480-487.

Ayer, N.W. & Tyedmers, P.H. 2008. Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture systems in Canada. *Journal of Cleaner Production,*17(3): 362–373.

Barthélemy, F., Renault, D. & Wallender, W. 1993. *Water for a sustainable human nutrition: inputs and resources analysis for arid areas.* Davis, University of California. (as cited in D. Zimmer, & D. Renault. *Virtual water in food production and global trade review of methodological issues and preliminary results.* available at: www.fao.org/nr/water/docs/VirtualWater_article_DZDR.pdf)

Bell, J.G. & Waagbo, R. 2002. Safe and nutritious aquaculture produce: benefits and risks of alternative sustainable aquafeeds. *In* M. Holmer, K. Black, C.M. Duarte, N. Marbà & I. Karqakasis, eds. *Aquaculture in the ecosystem*, pp. 185–226. New York, Springer.

Beveridge, M.C.M., Phillips, M.J. & Clarke, R.M. 1991. A quantitative and qualitative assessment of wastes from aquatic animal production. *In* D.E. Brune & J.R. Tomasso, eds. *Aquaculture and water quality,* pp. 506–533. Advances in World Aquaculture, Vol. 3. Baton Rouge, World Aquaculture Society.

Bondad-Reantaso, M.G. 2007. *Assessment of freshwater fish seed resources for sustainable aquaculture.* FAO Fisheries Technical Paper No. 501. Rome, FAO. 628 pp.

Bórquez, A. & Hernández, A.J. 2009. Status and trends on the use of small pelagic fish species for reduction fisheries and for human consumption in Chile. *In* M.R. Hasan & M. Halwart, eds. *Fish as feed inputs for aquaculture: practice, sustainability and implications.* FAO Fisheries and Aquaculture Technical Paper No. 518. Rome, FAO. 407 pp.

Boyd, C.E. 2005. Water use in aquaculture. *World Aquaculture*, 36(3): 12–16.

Boyd, C.E., Tucker, C., McNevin, A., Bostick, K. & Clay, J. 2007. Indicators of resource use efficiency and environmental performance in fish and crustacean aquaculture. *Reviews in Fisheries Science,* 15: 327–360.

Brown, L.R. 2009. *Plan B 4.0: mobilizing to save civilization.* New York, W.W. Norton and Co. 368 pp.

Brummett, R.E. 1997. Farming fish to save water. *Bioscience,* 47: 402.

Byron, C. D., Bengtson, D., Costa-Pierce, B.A. & Calanni, J. 2011. Integrating science into management: ecological carrying capacity of bivalve shellfish aquaculture. *Marine Policy*, 35: 363-370.

Costa, M.H., Yanagi, S.M.M.N., Souza, P.J.O.P., Ribeiro, A. & Rocha, E.J.P. 2007. Climate change in Amazonia caused by soybean cropland expansion, as compared to caused by pastureland expansion. *Geophysical Research Letters,* 34(L07706): doi:10.1029/2007GL029271.

Costa-Pierce, B.A. 2002. Ecology as the paradigm for the future of aquaculture. *In* B.A. Costa-Pierce, ed. *Ecological aquaculture: the evolution of the blue revolution*, pp. 339–372. Oxford, Blackwell Science.

Costa-Pierce, B.A. 2008. An ecosystem approach to marine aquaculture: a global review. *In* D. Soto, J. Aguilar-Manjarrez & N. Hishamunda, eds. *Building an ecosystem approach to aquaculture*, pp. 81–116. Fisheries and Aquaculture Proceedings 14. Rome, FAO.

Costa-Pierce, B.A. 2010. Sustainable ecological aquaculture systems: the need for a new social contract for aquaculture development. *Marine Technology Society Journal*, 44(3): 88–112.

Costa-Pierce, B. & Desbonnet, A. 2005. A future urban ecosystem incorporating urban aquaculture for wastewater treatment and food production. *In* B.A. Costa-Pierce, A. Desbonnet, P. Edwards & D. Baker, eds. *Urban aquaculture,* pp. 1–14. Wallingford, CABI Publishing.

Cowey, C.B., Mackie, A.M. & Bell, J.G. (eds.) 1985. *Nutrition and feeding in fish.* London, Academic Press. 489 pp.

Culver, K. & Castle, D. (eds.) 2008. *Aquaculture, innovation and social transformation*. New York, Springer. 348 pp.

DeAlteris, J.T., Kilpatrick, B.D. & Rheault, R.B. 2004. A comparative evaluation of the habitat value of shellfish aquaculture gear, submerged aquatic vegetation and a non-vegetated seabed. *Journal of Shellfish Research,* 23: 867–874.

De Silva, S.S. & Davy, F.B. (eds.) 2010. *Success stories in Asian aquaculture.* New York, Springer. 214 pp.

Duarte, C.M., Holmer, M., Olsen, Y., Soto, D., Marbà, N., Guiu, J., Black, K. & Karakassis, I. 2009. Will the oceans help feed humanity? *BioScience,* 59(11): 967–976.

Edwards, P. 2002. Aquaculture for poverty alleviation and food security. *Aquaculture Asia,* 7(2): 53–56.

Edwards, P. 2009. Traditional Asian aquaculture. *In* G. Burnell & G. Allan, eds. *New technologies in aquaculture: improving production efficiency, quality and environmental management*, pp. 1029–1063. Cambridge, Woodhead Publishing Series in Food Science, Technology and Nutrition No. 178.

Elferink, E.V., Nonhebel, S. & Moll, H.C. 2008. Feeding livestock food residue and the consequences for the environmental impact of meat. *Journal of Cleaner Production*, 16: 1227–1233.

Falkenmark, M. & Lannerstad, M. 2005. Consumptive water use to feed humanity – curing a blind spot. *Hydrology and Earth System Sciences,* 9: 15–28.

FAO. 2001. *Integrated agriculture-aquaculture. A primer.* FAO Fisheries Technical Paper No. 407. Rome, FAO. 149 pp. (available at: www.fao.org/DOCREP/005/Y1187E/y1187e00.htm)

FAO, 2008a. *Food Outlook – Global Market Analysis. June 2008*. FAO, Rome. 95 pp.

FAO. 2008b. *The state of world fisheries and aquaculture 2007.* Rome, Fisheries Department, FAO. pp.

FAO. 2009. *The state of world fisheries and aquaculture 2008.* Rome, Fisheries Department, FAO. 176 pp.

Fedoroff, N.V., Battisti, D.S. Beachy, R.N., Cooper, P.J.M., Fischhoff, D.A., Hodges, C.N., Knauf, V.C, Lobell, D., Mazur, B.J., Molden, D., Reynolds, M.P., Ronald, P.C., Rosegrant, M.W., Sanchez, P.A., Vonshak A. & Zhu, J.-K. 2010. Radically rethinking agriculture for the 21st century. *Science,* 327: 833–834.

Flimlin, G. 2002. *Nursery and growout methods for aquacultured shellfish.* Northeast Regional Aquaculture Center Publication No. 00-002. 15 pp.

Folke, C., Kautsky, N. & Troell, M. 1994. The costs of eutrophication from salmon farming: implications for policy. *Journal of Environmental Management,* 40: 173–182.

Folke, C., Kautsky, N., Berg, H., Jansson, M. & Troell, M., 1998. The ecological footprint concept for sustainable seafood production: a review. *Ecological Applications*, 8, *Supplement* 1, 63–71.

Gleick, P.H. 2003. Water use. *Annual Review of Environment and Resources,* 28: 275–314.

Godfray, H.C., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M. & Toulmin, C. 2010. Food security: the challenge of feeding 9 billion people. *Science,* 327: 812–818.

Goldburg, R. & Naylor, R. 2005. Future seascapes, fishing, and fish farming. *Frontiers in Ecology and the Environment,* 3(1):21–28.

Goodland, R. & Pimental, D. 2000. Environmental sustainability and integrity in the agriculture sector. *In* D. Pimental, L. Westra & R.F. Noss, eds. *Ecological integrity*, pp. 121–138. Washington DC, Island Press.

Gowen, R.J. & Bradbury, N.B. 1987. The ecological impact of salmonid farming in coastal waters: a review. *Oceanography and Marine Biology Annual Review*, 25: 563–575.

Haamer, J. 1996. Improving water quality in a eutrophied fjord system with mussel farming. *Ambio*, 25: 356–362.

Hambrey, J., Edwards, P. & Belton, B. 2008. An ecosystems approach to freshwater aquaculture: a global review. *In* D. Soto, ed*. Building an ecosystem approach to aquaculture,* pp. 117–221. Fisheries and Aquaculture Proceedings 14. Rome, FAO.

Hambrey, J. & Senior, B. 2007. *Taking forward environmental carrying capacity and ecosystem services. Recommendations for CCW.* CCW Policy Research Report No. 07/22.

Hepher, B. 1985. Aquaculture intensification under land and water limitations. *GeoJournal*, 10: 253–259.

Hodges, C.N., Thompson, T.L., Riley, J.J. & Glenn, E.P. 1993. Reversing the flow: water and nutrients from the sea to the land. *Ambio,* 22: 483–490.

Jackson, A. 2009. Fish in-fish out (FIFO) ratios explained. *Aquaculture Europe,* 34(3): 5–10.

Jacquet, J., Hocevar, J., Lai, S., Majluf, P., Pelletier, N., Pitcher, T., Sala, S. Sumaila, R. & Pauly, D. 2009. Conserving wild fish in a sea of market-based efforts. *Oryx, The International Journal of Conservation,* 44: 45–46. doi:10.1017/ S0030605309990470.

Kaushik, S. & Troell, M. 2010. Taking the fish-in fish-out ratio a step further. *Aquaculture Europe,* 35(1): 15–17.

Kautsky, N., Berg, H., Folke, C., Larsson, J. & Troell, M., 1997. Ecological footprint for assessment of resource use and development limitations in shrimp and tilapia aquaculture. *Aquaculture Research*, 28, 753–766.

Lamm, F.L. 2008. Consumptive water use. *In* S.W. Trimble, B.A. Stewart & T.A. Howell, eds. *Encyclopedia of water science*, pp, 113–116. 2nd Edn. Boca Raton, CRC Press.

Langan, R. & Horton, C. 2003. Design, operation and economics of submerged longline mussel culture in the open ocean. *Bulletin of the Aquaculture Association of Canada,* 103(3): 11–20.

Lele, U. 2010. Food security for a billion poor. *Science,* 326: 1554.

Liao, I. C. & Chao, N.-H. 2009. Aquaculture and food crisis: opportunities and constraints. *Asia Pacific Journal of Clinical Nutrition,* 18(4): 564–569

Lindahl, O., Hernroth, B., Kollberg, S., Loo, L.O., Rehnstam-Holm, A.S., Svensson, J., Svensson, S. & Syversen, U. 2005. Improving marine water quality by mussel farming: a profitable solution for Swedish society. *Ambio*, 34: 131–138.

Lovatelli, A. & Holthus, P.F. (eds). 2008. *Capture-based aquaculture. Global overview*. FAO Fisheries Technical Paper. No. 508. Rome, FAO. 298 pp.

McKinsey, C.W., Thetmeyer, H., Landry, T. & Silvert, W. 2006. Review of recent carrying capacity models for bivalve culture and recommendations for research and management. *Aquaculture,* 261(2): 451–462.

Mires, D. 2009. Development of inland aquaculture in arid climates: water utilization strategies applied in Israel. *Fisheries Management & Ecology,* 7: 189–195.

Mirto, S., Bianchelli, S., Gambi, C., Krzelj, M., Pusceddu, A., Scopa, M., Holmer, M. & Danovaro, R. 2009. Fish-farm impact on metazoan meiofauna in the Mediterranean Sea: analysis of regional vs. habitat effects. *Marine Environmental Research,* 69: 38–47.

NACA/FAO. 2000. *Aquaculture development beyond 2000: the Bangkok Declaration and Strategy.* Conference on Aquaculture in the Third Millennium, 20–25 February 2000, Bangkok, Thailand. NACA, Bangkok and FAO, Rome. 27 pp.

National Research Council. 2010. Ecosystem concepts for sustainable bivalve mariculture. Washington DC, National Academies Press. 190 pp.

Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubchenco, J., Mooney, H. & Troell, M. 2000. Effect of aquaculture on world fish supplies. *Nature,* 405: 1017–1024.

Naylor, R.L., Hardy, R.W., Bureau, D.P., Chiu, A., Elliott, M., Farrell, A.P., Forster, I., Gatlin, D.M., Goldburg, R.J., Hua, K. & Nichols, P.D. 2009. Feeding aquaculture in an era of finite resources. *Proceedings of the National Academy of Sciences,* 106(36): 15103–15110.

Neori, A., Shpigel, M. & Ben-Ezra, D. 2000. A sustainable integrated system for culture of fish, seaweed and abalone. *Aquaculture,* 186: 279–291.

Nunes, J.P., Ferreira, J.G., Bricker, S., O'Loan, B., Dabrowski, T., Dallaghan, B., Hawkins, A.J.S., O'Connor, B. & O'Carroll, T. 2011. Towards an ecosystem approach to aquaculture: assessment of sustainable shellfish cultivation at different scales of space, time and complexity. *Aquaculture,* 315: 369–383.

Nunes, J.P., Ferreira, J., Gazeau, F., Lencart-Silva, J., Zhang, X.L., Zhu, M.Y. & Fang, J.G. 2003. A model for sustainable management of shellfish polyculture in coastal bays. *Aquaculture,* 219: 257–277.Opstvedt, J., Aksnes, A., Hope, B. & Pike, I. 2003. Efficiency of feed utilization in Atlantic salmon (*Salmo salar* L.) fed diets with increasing substitution of fish meal with vegetable proteins. *Aquaculture,* 221: 365–379.

Oo, A.N., Satoh, S., & Tsuchida, N. 2007. Effect of replacements of fishmeal and fish oil on growth and dioxin contents of rainbow trout. *Fishery Science,* 73: 750–759.

Ostrom, E. 1990. *Governing the commons: the evolution of institutions for collective action*. Cambridge, Cambridge University Press. 280 pp.

Ostrom, E., Gardner, R. & Walker, J. 1994. *Rules, games, and common pool resources.* Ann Arbor, University of Michigan Press. 392 pp.

Papatryphon, E., Petit, J., Kaushik, S.J. & van der Werf, H.M. 2004. Environmental impact assessment of salmonid feeds using Life Cycle Assessment (LCA). *Ambio*, 33: 316–323.

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R. & Torres, Jr., F. 1998. Fishing down marine food webs. *Science,* 279: 860–869.

Petr, T. 2005. Fisheries topics: ecosystems. Reservoirs. *In FAO Fisheries and Aquaculture Department* [online]. Rome. Updated 27 May 2005. (available at: www.fao.org/fishery/topic/13471/en ; accessed 31 March 2010)

Phan, L.T., Bui, T.M., Nguyen, T.T.T., Gooley, G.J., Ingram, B.A., Nguyen, H.V., Nguyen P.T. & DeSilva, S.S. 2009. Current status of farming practices of striped catfish, *Pangasianodon hypophthalmus* in the Mekong Delta, Vietnam. *Aquaculture,* 296: 227–236.

Pimentel, D. & Pimentel, M. 2003. Sustainability of meat-based and plant-based diets and the environment. *American Journal of Clinical Nutrition,* 78(3): 660–663.

Pitta, P., Karakassis, I., Tsapakis, M. & Zivanovic, S. 1999. Natural vs. mariculture induced variability in nutrients and plankton in the eastern Mediterranean. *Hydrobiologia,* 391: 181–194.

Pullin, R.S.V., Froese, R. & Pauly, D. 2007. Indicators for the sustainability of aquaculture. *In* T.M. Bert, ed. *Ecological and genetic implications of aquaculture activities*, pp. 53–72. New York, Kluwer Academic Publishers.

Rakocy, J.E. 2002 An integrated fish and field crop system for arid areas. *In* B.A. Costa-Pierce, ed. *Ecological aquaculture: the evolution of the blue revolution,* pp. 263–285. Oxford, Blackwell Science.

Rheault, R. & Rice, M.A. 1995. Transient gear shellfish aquaculture. *World Aquaculture,* 26(1): 26–31.

Rothbard, S. & Peretz, Y. 2002. Tilapia culture in Negev, the Israeli desert. *In* R.D. Guerrero and M.R. Guerrero-del Castillo, eds. *Tilapia farming in the 21st century,* pp. 60–65. Los Banos, Philippines Fisheries Association.

Ryther, J.H. 1969. Photosynthesis and fish production in the sea. *Science,* 166: 72–76.

Shreck, A., Getz, C. & Feenstra, G. 2006. Social sustainability, farm labor, and organic agriculture: findings from an exploratory analysis. *Agriculture and Human Values*, 24(4): 439–449.

Skretting Aquaculture Research Centre. 2009. *Revealing the essential functions of vital feed ingredients.* (available at: www.skretting.com/Internet/SkrettingGlobal/webInternet.nsf/wPrId/D30B62DD93F65CFEC1257663004DA962!OpenDocument)

Smil, V. 2000. *Feeding the world: a challenge for the twenty-first century.* Cambridge MA, MIT Press. 362 pp.

Smil, V. 2002. Nitrogen and food production: proteins for human diets. *Ambio,* 31: 125–131.

Smil, V. 2008. Water news: bad, good and virtual. *American Scientist,* 96: 399–407.

Soto, D., Aguilar-Manjarrez, J., Brugère, C., Angel, D., Bailey, C., Black, K., Edwards, P., Costa-Pierce, B., Chopin, T., Deudero, S., Freeman, S., Hambrey, J., Hishamunda, N., Knowler, D., Silvert, W., Marbà, N., Mathe, S., Norambuena, R., Simard, F., Tett, P., Troell, M. & Wainberg, A. 2008. Applying an ecosystem-based approach to aquaculture: principles, scales and some management measures. *In* D. Soto, J. Aguilar-Manjarrez & N. Hishamunda, eds. *Building an ecosystem approach to aquaculture,* pp. 15–35. FAO Fisheries and Aquaculture Proceedings 14. Rome, FAO.

Tacon, A.J.G. 2005. *State of information on salmon aquaculture feed and the environment.* Washington D.C., World Wildlife Fund Salmon Aquaculture Dialogue. 80 pp.

Tacon, AJ.G., Hasan, M.R. & Subasinghe, R.P. 2006. *Use of fishery resources as feed inputs for aquaculture development: trends and policy implications.* FAO Fisheries Circular No. 1018. Rome, FAO. 99 pp.

Tacon, A.G.J. & Metian, M. 2008. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: trends and future prospects. *Aquaculture,* 285: 146–158.

Tacon, A.G.J. & Nates, S.F. 2007. Meeting the feed supply challenges. *In* R. Arthur & J. Nierentz, eds. *Global Trade Conference on Aquaculture. Qingdao, China, 29–31 May 2007.* FAO Fisheries Proceedings, 9. FAO, Rome. 271 pp.

Troell, M., Joyce, A., Chopin, T., Neori, A., Buschmann, A.H. & Fang, J.-G. 2009. Ecological engineering in aquaculture – potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. *Aquaculture,* 297: 1–9.

Troell, M., Tyedmers, P., Kautsky, N. & Ronnback, P. 2004. Aquaculture and energy use. *Encyclopedia of energy*, Volume 1, p. 97–108. Amsterdam, .Elsevier Inc.

Turchini, G.M., Torstensen, B.E. & Ng, W.-K. 2009. Fish oil replacement in finfish nutrition. *Reviews in Aquaculture,* 1(1): 10–57.

Tyedmers, P. 2000. Salmon and sustainability: the biophysical cost of producing salmon through the commercial salmon fishery and the intensive salmon culture industry. PhD. Thesis, Vancouver, University of British Columbia. 258 pp.

UKERC (UK Energy Research Centre). 2009. *Global oil depletion report 2009.* (available at: www.ukerc.ac.uk/support/))

United Nations Framework Convention on Climate Change. 2007. *Climate Change: Impacts, Vulknerabilties and Adaptation in Developing Countries*. Bonn, Climate Change Secretariat. (available at: http://unfccc.int/resource/docs/publications/impacts.pdf)

USDA. 1998. *Farm and ranch irrigation survey, census of agriculture 1997, estimated quantity of water applied and method of distribution by selected crop: 1998 and 1994.* United States Department of Agriculture, National Agricultural Statistics Service. (available at: www.agcensus.usda.gov/Publications/2007/Full_Report/index.asp))

Verdegem, M.C.J. & Bosma, R.H. 2009. Water withdrawal for brackish and inland aquaculture, and options to produce more fish in ponds with present water use. *Water Policy, 11*: 52–68.

Verdegem, M.C.J., Bosma, R.H. & Verreth, J.A.J. 2006. Reducing water use for animal production through aquaculture. *International Journal of Water Resources Development,* 22(1): 101–113.

Watanabe, T. 2002. Strategies for further development of aquatic feeds. *Fishery Science,* 68: 242–252.

World Bank. 2008. *World development report 2008: agriculture for development.* Washington DC, World Bank. 365 pp.

Wurts, W.A. 2000. Sustainable aquaculture in the twenty-first century. *Reviews in Fisheries Science,* 8: 141–150.

Yusoff, F.M 2003. *An ecological approach: a viable option for aquaculture industry in Malaysia.* Dewan Taklimat Tingkat I, Bangunan Pentadbiran. Serdang, Universiti Putra Malaysia. 43 pp.

Yusoff, F.M., Banerjee, S., Khatoon, H. & Shariff, M. 2010. Biological approaches in management of nitrogenous compounds in aquaculture systems. *In* R. Russo, ed. *Aquaculture 1. Dynamic biochemistry, process biotechnology and molecular biology* (Special Issue 2), pp. 21-31. Kagawa, Japan, Global Science Books.

Zimmer, D. & Renault D. undated. *Virtual water in food production and global trade review of methodological issues and preliminary results.* 19 pp. (available at: www.fao.org/nr/water/docs/VirtualWater_article_DZDR.pdf)