# Responsible Aquaculture in 2050: Valuing Local Conditions and Human Innovations Will Be Key to Success

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*As aquaculture production expands, we must avoid mistakes made during increasing intensification of agriculture. Understanding environmental impacts and measures to mitigate them is important for designing responsible aquaculture production systems. There are four realistic goals that can make future aquaculture operations more sustainable and productive: (1) improvement of management practices to create more efficient and diverse systems at every production level; (2) emphasis on local decisionmaking, human capacity development, and collective action to generate productive aquaculture systems that fit into societal constraints and demands; (3) development of risk management efforts for all systems that reduce disease problems, eliminate antibiotic and drug abuse, and prevent exotic organism introduction into local waters; and (4) creation of systems to better identify more sustainably grown aquaculture products in the market and promote them to individual consumers. By 2050, seafood will be predominantly sourced through aquaculture, including not only finfish and invertebrates but also seaweeds.*

*Keywords: human capacity development, integrated multitrophic aquaculture, best management practices, recirculating aquaculture systems, responsible aquaculture*

**Aquaculture is an ancient method of food production;** early examples are in murals depicted on tombs in Egypt 4000 years ago, books written 2300 years ago in China, and coastal aquaculture from the Roman Empire (Costa-Pierce 2010). However, most of its growth and intensification has occurred within the last 30 years, so the aquaculture of today is quite different from historic systems. Aquaculture has grown three times faster than agriculture has, at an amazing rate of 8.3% per year since 1970 (Diana 2009). Aquaculture provided for 48.4% of the world's seafood consumption in 2009 (FAO 2009).

Given current trends, the world will be vastly different in 2050. Not only will the global population likely increase to nine billion, but that population will be increasingly urban and denser in developing countries (Cohen 2003). Climate change is likely to increase temperatures by 1–2 degrees Celsius by 2055, to increase sea levels by about 0.88 meters by 2100, and to dramatically change precipitation patterns (Carter et al. 2007). Water will be an even more precious resource, whereas new lands for agriculture expansion will be limited. About 50% more food (3 billion tons [all *tons* referenced are metric] of cereal crops and 200 million tons of meat) will be needed to sustain the quality of human life (FAO 2009). Given the limits on agriculture (Foley et al. 2011), novel production systems that have limited demands of land, freshwater, and nutrients; that require less energy; and that entail reduced impacts on the quality of receiving waters will become even more critical (FAO 2009). Fitting aquaculture development into this matrix will be important to meet increasing seafood consumption, because wild fisheries will remain stable at best (Duarte et al. 2009), whereas seafood will predominantly come from aquaculture (Diana 2009, Hallam 2012).

As aquaculture production expands, it is paramount that we avoid some of the mistakes made during the increased intensification of agriculture in the Green Revolution. Although agriculture intensification drove the higher production of food for human use, it also produced significant environmental damages, including the pollution of inland and coastal waterways, a high energy-and-water input to production ratio, and the widespread application of chemicals and antibiotics (Tilman et al. 2001). Therefore, understanding both environmental impacts and mitigation measures (Lotze et al. 2006) is important for designing responsible aquaculture production systems for tomorrow. Both intensive, single-species aquaculture and

*BioScience* 63: 255–262. ISSN 0006-3568, electronic ISSN 1525-3244.  doi:10.1525/bio.2013.63.4.5

more traditional, lower-intensity aquaculture are evolving, and both will be necessary to meet the future needs for seafood. In some cases, the two systems are merging, whereas in others, different methods are being used to achieve similar goals, such as the improved treatment of effluents.

The intensity of inputs passing through aquaculture systems varies. Extensive systems, which stock young organisms and allow them to grow naturally, are at one extreme, whereas very intensive systems with high stocking rates and complete feeding are at the other. Most of the concerns expressed about aquaculture have been focused on shrimp and finfish cultured at the higher end of this continuum. However, less than 40% of aquaculture production today is of an intensive nature (Verdegem and Bosma 2009, Costa-Pierce 2010). As crops increase in value, lower-intensity systems have been continually updated until they reached high production intensity. Therefore, aquaculture is in a continual state of change today, focused on new methods and technologies, such as genetic selection, feed formulation, and water quality management in order to drive higher rates of production per unit area. This continuum is important to recognize, because intensification will continue in the decades ahead.

No ideal level of intensity is uniformly acceptable for reducing environmental impacts when all impact parameters are considered, because there are trade-offs in energy and water use, effluent burdens, and production intensity. This has created a rising interest in employing life cycle assessments (LCAs) in order to more fully understand the environmental performance of each production system (Ayer and Tyedmers 2009). An LCA can compare very different aquaculture systems for their overall impacts in energy use, water use, greenhouse gas emissions, and other environmental performance measures. It can also compare different stages of the overall production system and can provide recommendations on the stage on which to focus for significant reductions in these burdens (Cao et al. 2011). However, an LCA does not include evaluations of social aspects of sustainability, nor does it evaluate risk, such as species escapement or disease risk due to aquaculture systems, so it is not complete in the analysis of system performance. An objective analysis of the gains and impacts caused by any management action in the production chain is important for understanding aquaculture's sustainability. Intensification has not been the sole target of aquaculture's evolution, because zero water discharge or integrated multitrophic aquaculture (IMTA) systems have also been developed to reduce environmental impacts (figure 1; Tal et al. 2009, Chopin et al. 2010). Several organizations, including the World Wildlife Fund (*worldwildlife.org/industries/farmed-seafood*) and the Global Aquaculture Alliance (*www.gaalliance.org/bap/standards.php*), have been involved in defining the best management practices (BMPs) for a range of aquatic species cultivated under different levels of intensity. Using realistic information from farmers, as well as from the research and policy communities, these organizations coordinate discussions on BMPs to produce standards that can be used by certification boards, government regulators, and consumer groups.

We, as a collective group of authors, have studied aquaculture production for diverse culture species under a range of conditions and in a variety of countries. We believe that there are four realistic goals that can be implemented to make future aquaculture operations more sustainable and productive systems for growing food. The goals are (1) the improvement of management practices to create more efficient and diverse systems at every level of production intensity; (2) an emphasis on local decisionmaking, human capacity development, and collective action to generate productive aquaculture systems that fit into societal constraints and demands; (3) the development of risk management efforts for all systems that reduce disease problems, eliminate antibiotic and drug abuse, and stop exotic organism introduction into local waters; and (4) the creation of systems to better differentiate and promote more sustainably grown aquaculture products in the market and to individual consumers.

Some of these goals mirror the key steps that Foley and colleagues (2011) proposed for changes necessary in land-based agriculture for humans to meet the overall food production needs for 2050, whereas others are quite different from those in their terrestrial model.

## Goal 1: Improvement of management practices

There is no single method of growing a particular species that works best in all countries; instead, there are a wide variety of techniques. Current production systems are not always well managed, and much more food could be produced by simply improving management practices, regardless of the scale of aquaculture operations (Read and Fernandes 2003, Verdegem and Bosma 2009). This is not a dramatic revelation to aquaculture extension professionals in most countries, because they are already involved in outreach to producers in an attempt to improve the management of aquaculture systems. The same yield gap is recognized as a major problem in agriculture (Foley et al. 2011). Major improvements could be made by farmers if they simply adopted new production practices without increasing the intensity of the aquaculture grow-out operation.

An example of such improvement in management involves feeding methods. Feed is generally the most costly input to aquaculture operations, even as overfeeding and egestion are the main sources of waste materials that can deteriorate local water quality (Boyd and Tucker 1998). Diana (2012) analyzed intensive tilapia production systems in Thailand over the time period in which the industry moved from semi-intensive production using fertilizers to intensive production using feeds. Because of this change in intensity, there was not a well-developed management system for the use of feed in tilapia production. Instead of full feeding for the entire grow-out period, feeding could be delayed until the fish reached an advanced size (100 grams) and could then be limited to half satiation ration, and a similar production level to that with

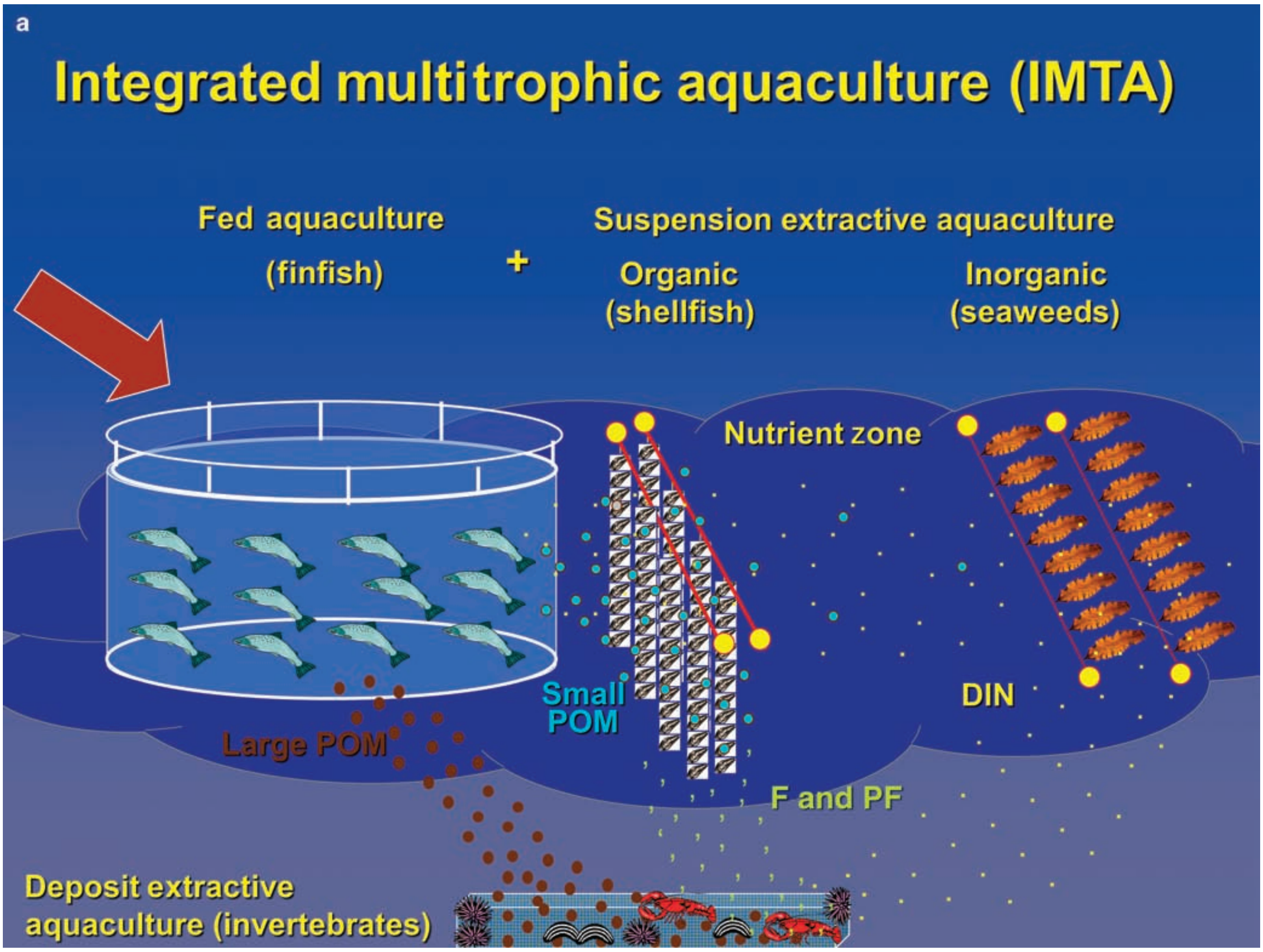


*Figure 1. Two modern and responsible aquaculture systems: (a) integrated multitrophic aquaculture systems and (b) recirculating aquaculture systems (see the next page). Abbreviations: DIN, dissolved inorganic nitrogen; F and PF, feces and pseudofeces; POM, particulate organic matter.*

full feeding would be achieved (Diana 1997). This is so because the ponds used for culture are ecosystems that also produce food organisms for tilapia from feed waste and fertilizer, and the fish could receive about half of their consumption from this natural production if the pond were managed well. Such a change in management would not only reduce feed costs but would improve water quality, because the loading of feed waste would be reduced, and the tilapia would also reduce plankton abundance in pond and discharge waters. The end result would be a win–win situation, with 37% less feed, 300% higher profits, and improved environmental impacts relative to complete feeding. Such manipulations have been adopted in Thailand and tested in other regions with comparable results (Borski et al. 2011). Of course, there are numerous components of the culture system for which management can be improved, by not only influencing the feeding rate but also changing the feed type, water quality management, and many other input parameters (Diana 2012). Experiments by culturists to assess production under local differences in the species cultured, climate, soils, feed, and water are extremely important in the evolution of better management practices.

Many of the environmental impacts of aquaculture are being effectively addressed by improvements in management. For example, the reliance on fish meal in feeds has been reduced to 15% for many carnivorous species by replacement with plant-based proteins or other feed sources (Naylor et al. 2009)—a change made in response to environmental and economic concerns. Biomitigative approaches, such as IMTA, have been developed to deal with the environmental burden of intensive cage culture. IMTA is based on cocultivating in proximity organisms selected purposely at different trophic levels for their complementary ecosystem functions and services (Chopin et al. 2008). The cocultured organisms produce additional valuable crops and remove nutrients and materials wasted from aquaculture using intensive feeding.

LCAs provide a quantitative means of comparing energy and material efficiency and of determining the environmental impacts of food production systems. LCAs on

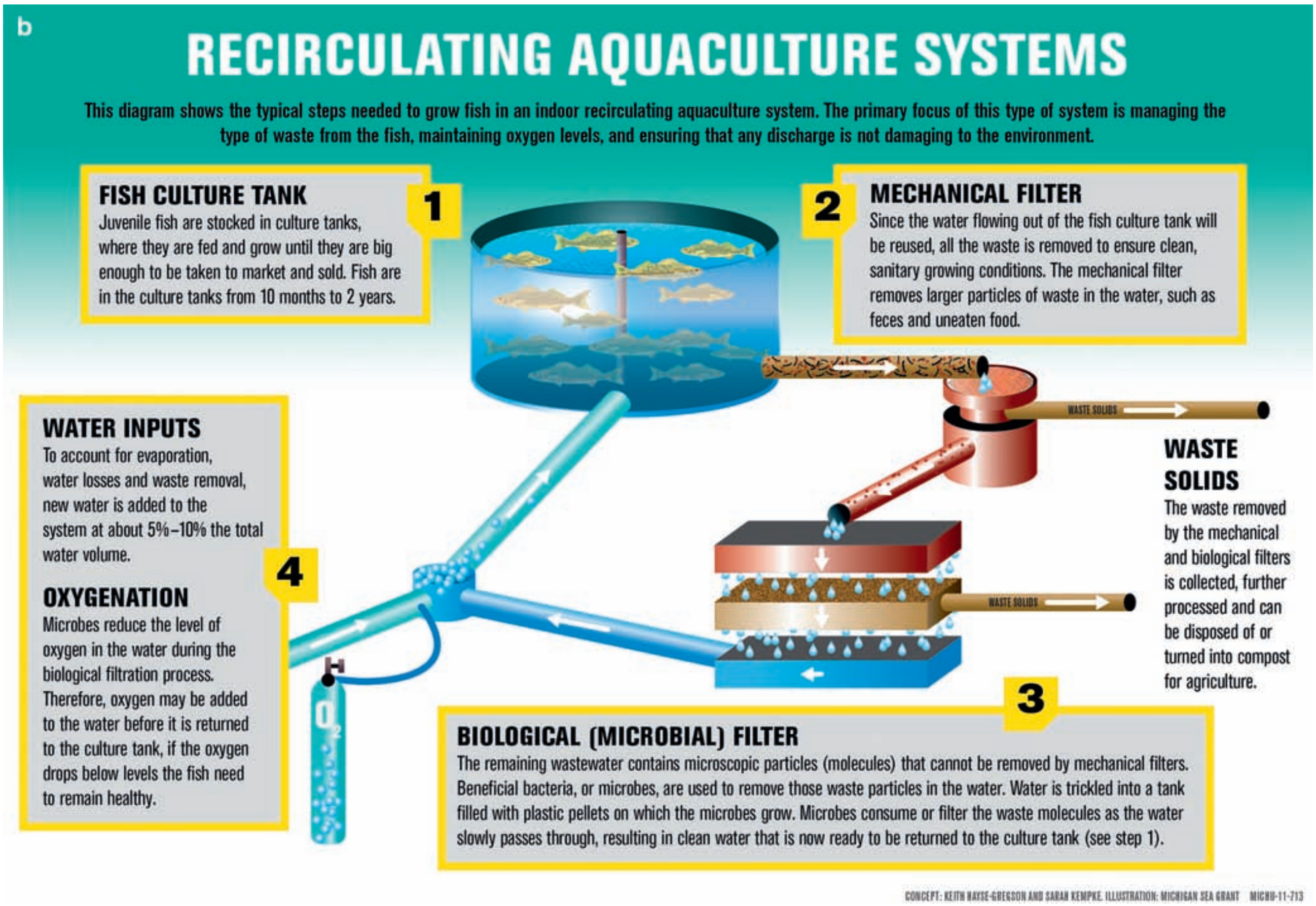


*Figure 1. (Continued)*

aquaculture systems have shown that the farming phase is more important than the hatchery, processing, or transportation phases in terms of energy use and most pollution burdens (Cao et al. 2013). For marine shrimp, semi-intensive production in China reduces acidification, eutrophication potential, greenhouse gas emissions, energy use, and biotic resource use by 50% relative to intensive systems for each ton of production (Cao et al. 2011).

In a review of 12 aquaculture LCAs, comparisons showed that closed (recirculation or zero-discharge) systems outperformed flow-through systems in eutrophication emissions and biodiversity conservation but not in energy use and greenhouse gas emissions (Cao et al. 2013). No one system outperformed all others in all emission categories. Generally, farming systems with relatively lower intensity that use more natural systems might be environmentally preferable (Cao et al. 2013). In their LCA of alternative aquaculture technologies, Ayer and Tyedmers (2009) warned that we could be shifting—not alleviating—environmental impacts by reducing local impacts but increasing material and energy demands. This shift may result in significantly increased contributions to several environmental impacts of global concern, including global warming, nonrenewable resource depletion, and acidification. Of course, the species, systems, and locations dramatically affect these outcomes. LCAs of aquaculture systems are an emerging area, and research is needed to assess the global performance of the diverse systems and settings for aquaculture.

Besides improvements on existing practices, there are some important changes that should occur in aquaculture in order for it to truly contribute to our future food needs. Terrestrial food production (6.3 billion tons in 2010) is mostly plant material (82%), in contrast to the 19 million tons of seaweeds produced, which is only 24% of aquaculture production. About 60% of agriculture products is used for human food, 35% for animal feed, and 5% for biofuels (Foley et al. 2011, Hallam 2012). Global aquaculture production to date has been mostly animals, with about 60 million tons produced in 2010 (FAO 2012). Of course, comparing the mass produced across various agriculture sectors is fraught with difficulty, because some products, such as milk, are accounted for in liquid weight, whereas others, such as meat and seaweed, are counted in wet mass. Placing these comparison issues aside, increased production of seaweeds and freshwater aquatic plants, along with the development of uses for these organisms—including human food, animal feeds, biopolymers, chemicals, agrochemicals, cosmetics, pharmaceuticals, nutraceuticals, and bioenergy compounds—is an important direction for aquaculture (Chopin and Sawhney 2009). The use of seaweeds in biomitigation is practiced on a large scale in China (Xiao et al. 2007), and seaweed production in open seas can reduce nutrient concentrations by between 20% and 94% (He et al. 2008). Even with the very positive effects of reducing elevated nutrient concentrations in coastal areas, seaweed and aquatic plants account for only a small portion of aquaculture production, and far more production and use of these organisms must occur if aquaculture is to make a major contribution to the future food deficit (Forster 2008).

Another consideration for aquaculture is the domestication of plant and animal species for traits such as growth, disease resistance, and induced sterility. The terrestrial agriculture model has been focused on fewer species targeted for production, with very intense genetic selection to increase the efficiency of production under farm conditions. The aquaculture industry uses a large number of species, many from stocks of nearly wild genotypes (Hulata 2001). With increased production of seaweeds and invertebrates, even more species will become important in the aquaculture industry, and their production will start with wild genotypes. Selective breeding can produce rapid increases in growth (10%–20% per generation; Eknath et al. 2007) and disease resistance (50% reduction in mortality after several generations; Wetten et al. 2007) and has resulted in improved yields for several culture species, including Atlantic salmon (*Salmo salar*) and Nile tilapia (*Oreochromis niloticus*). The rate of selective breeding can be made even more rapid with modern genetic techniques such as marker-assisted selection to identify families (Sonesson 2007), so we might expect even more dramatic improvements in yield from the domestication of culture animals in the future.

Concerns abound regarding the genetic effects of escaped culture organisms on wild populations (Fleming et al. 2000), and these concerns may become even more intense as domestication causes greater differentiation between wild and domesticated genotypes. Induced sterility through polyploidy (a genetic manipulation) is widely practiced, and the polyploidy of some species produces 100% sterile animals, whereas there have been less-certain results for other species (Piferrer et al. 2009). Another promising sterilization technique is to ablate the production of gonadotropin-releasing hormones through genetic methods (Weber 2009), but this is quite far from being a routine application in the field. The development of genetic technology to cause sterility is a promising technique to stem most problems caused by organisms escaping from culture systems and should be pursued as a first step in domestication for aquaculture purposes.

### Goal 2: Emphasis on local human capital

One challenge in disseminating information about better management methods involves local decisionmaking and the amount of human capital available. Within a country, much information on aquaculture technology is transferred by communication among people who are in the process of growing the same crop. This farmer-to-farmer exchange extends the effort of government outreach organizations or academic institutions (Brummett and Williams 2000). The local dissemination of knowledge on production systems may be well integrated into new management technology or dominated by old technology (Costa-Pierce 2002). Because production methods rely on local environmental conditions, such as climate and water, it is impractical to have one common technology or practice extended to all locations, even within one country. Human capital, including the level of education, training, and innovation, combined with availability of local resources is what makes aquaculture succeed (Brummett and Williams 2000, Lebel et al. 2010). These characteristics are also important determinants of the ecological efficiency of aquaculture. A well-educated and -trained workforce would be capable of evaluating alternative methods of aquaculture production and of developing a system that fits well with local conditions. For example, local feed sources for a particular organism may vary considerably because of the differing costs and availability of products from local agriculture. Because the success of aquaculture operations is dependent on local conditions, this also presents a complication for management organizations and policymakers as they consider applying large-scale standards to the industry.

The key for producing aquaculture crops more sustainably is the flexibility to allow for the best mix of local resources and human capital while reducing or eliminating negative environmental impacts, all on the basis of a few guiding principles most often rooted in common sense. This flexibility is also important in responding to future challenges to aquaculture production. For example, about 40% of aquaculture currently occurs in coastal marine and brackish water. These areas are also locations in which there is great uncertainty related to climate change, water levels, storm frequencies, and human population growth. Flexibility will be very important for aquaculture to adapt to future climate scenarios, not only in production systems and species but also in capital investments in facilities, because many of these could be damaged or destroyed by the predicted rise in sea level, as well as by increased storm size and frequency.

Since local stakeholders are crucial in developing practices that lead to aquaculture success, they must be involved in policy and regulatory decisions. The collective action of farmer organizations can be an effective assistance mechanism, especially for small-scale producers, in overcoming the challenges and facing the opportunities offered through aquaculture (Kassam et al. 2011). Well-defined individual or collective rights (property, access, human, labor) would act as incentives for the private and public promoters of aquaculture development to make decisions with a more secure and informed basis. Many small-scale actions taken individually (e.g., choosing a location to build ponds) can also aggregate into cumulative impacts with greater environmental effects (Peterson and Lowe 2009).

A good example of the value of collective action is cluster management, which is being used in aquaculture farms to deal with certification and marketing (Kassam et al. 2011). The certification of aquaculture farms is seen as one way to promote better environmental performance. However, most farms in Asia and in other regions are small scale, with an individual farmer owning just one to a few ponds and producing a limited overall crop. Although this dispersed system of production has strong economic and social benefits, it makes certification difficult, because the systems used to date rely on the farmers' paying some organization to certify their farm performance (Kassam et al. 2011). Cluster farms link groups of 20–75 local farmers into voluntary alliances with group farms using agreed-on management practices and accessing certification as an entity rather than as an individual farm. Similarly, cluster farms can use their collective strength to market their crops to either local or export markets cooperatively, and the strength of the larger group is important in making these marketing efforts successful.

### Goal 3: Development of risk management systems

Many authors believe one key impact of aquaculture that needs addressing is the introduction of invasive species associated with bringing new species for aquaculture into a region (Naylor et al. 2001). There are reasonably biosecure systems for animal production, such as indoor recirculating systems, particularly for locations in which the target species tend not to survive in the wild, such as indoor tilapia culture in northern climates. However, most culture systems include a risk of escape, and given the large number of transfers of organisms made during aquaculture production, as well as potential escape during natural disasters such as floods and storms (Schofield et al. 2007), there is a large risk of escape for most cultured species. Much of aquaculture already depends on nonnative species (Molnar et al. 2008, De Silva et al. 2009), and in many areas, these exotic species have already escaped and may have naturalized populations. Aquaculture for exotic species in a watershed can also extend and increase that species' rate of expansion in a region (Peterson et al. 2005), so government agencies need to develop regulations on the introduction of new species both in a country and within the regions of a country. In this regard, permits should not allow the importation of a new species unless there is strong evidence that it will not become invasive.

Infectious bacteria, such as *Vibrio*; viruses, such as the Koi herpes virus; and parasites, including sea lice, may concentrate in culture systems and cause disease and mortality. The initial source of these pathogens is often wild organisms (Krkošek 2010), and the concentration of animals under culture conditions may accelerate pathogen outbreaks and subsequent transfer to additional cultured and wild populations. A number of risk-management measures are currently being developed to enhance two lines of defense against pathogens: prevention and protection (Bondad-Reantaso et al. 2005, 2009). Improved responsibility in the movement of aquatic animals and their products can be achieved by effective national strategies and regulatory frameworks in compliance with international standards of aquatic animal health. Timely risk analysis is important for the assessment of the threat from newly introduced species or those with a newly expanded range for culture. Good surveillance programs and diagnostic services can lead to early detection and identification of the emergence and spread of diseases. Emergency preparedness through rapid and timely responses should reduce the potential catastrophic consequences of disease incursions. Building partnerships and enhancing regional and international cooperation is crucial in addressing transboundary disease issues. Many of these changes have already occurred, largely as a result of farmers' adapting to challenges from the environmental community and to their own production regimes, and have often preceded government regulations.

Antimicrobial resistance is a global crisis, and antimicrobial use in aquaculture plays a role in its generation; therefore, aquaculturists should be educated on the problems that excessive antimicrobial use has on their activities, on human health, and on the environment (Heuer et al. 2008). Studies in which the environment around intensive aquaculture sites was sampled have shown elevated levels of residual antimicrobials and antimicrobial-resistant bacteria (Kümmerer 2009). Such increased levels have the potential to negatively affect the health of shellfish, fish, and human beings as a result of the horizontal gene transfer of antimicrobial-resistance determinants between environmental bacteria and shellfish, fish, and human pathogens (Barlow 2009). Transfer of antimicrobial-resistance determinants is stimulated by residual antimicrobials in water and sediments; this could potentially impair the treatment of bacterial infections in fish and human beings (Angulo et al. 2004). International organizations have advised against using antimicrobials in aquaculture if they are used in clinical medicine (e.g., quinolones) and, instead, promote ancillary healthy practices of animal husbandry (Heuer et al. 2008). At the same time, as hygiene and sanitary conditions of husbandry are improved, the routine usage of vaccines has increased, which has allowed antimicrobial use in aquaculture to be reduced (Cabello 2006). Improved knowledge of the amounts and classes of antimicrobials used in aquaculture is needed in order to assess their impact on piscine and human health and on the environment (Burridge et al. 2010).

### Goal 4: Identification of more sustainably grown crops

Certification of aquaculture products, BMPs decided on by groups of farmers and environmentalists, interdisciplinary research, and government involvement in outreach to design and implement more responsible aquaculture systems have been combined to make major improvements in environmental performance (Boyd et al. 2007). However, they can go only so far to promote more sustainable global aquaculture practices. Currently, products from more-sustainable aquaculture systems are poorly differentiated in the market, so farmers do not always receive financial benefits for their better stewardship, and consumers cannot easily make decisions about which products to buy (Jacquet and Pauly 2008). Standards that are commonly used to differentiate land-based crops, including fair trade, organic, and free range, do not currently exist for seafood. Although there are organizations that certify wild-caught and cultured seafood, it is most often done on an individual-business basis, not widely accepted by the industry. Seafood exported to the United States and to the European Union is required to be processed following certain standards of hygiene and public health and to have labels indicating the source (cultured or captured) and country of origin. However, there is no requirement to indicate capture or culture methods or any certifications achieved. Several companies, such as Naturland and Walmart, require compliance with their own certification standards in order for seafood to be sold in their stores, but such certification is not common throughout retail systems. Because many sustainable seafood evaluations rank products on the basis of their culture methods or certifications, consumers are often unable to verify the quality of their purchases. Until more detailed labeling standards are developed for seafood, this confusion is likely to continue. Not only are labeling standards important, but consistent nomenclature for product classes (i.e., organic seafood) and species must be enforced to properly allow consumers to more strongly encourage seafood sustainability.

## Conclusions

For many commodities, the potential of terrestrial food production to expand appears limited, because of the lack of land, water, or other resource inputs into agriculture (Foley et al. 2011), whereas the future looks much more promising for aquaculture. By 2050, seafood will be predominantly sourced through aquaculture. These products may not be mainly finfish, because seaweeds, invertebrates, and their derived products will become an increasing part of our diets, especially in the Western world. There are large areas of the ocean, as well as coastal and inland waters, that are suitable for aquaculture production. However, expansion to these areas must be accomplished with more sustainable practices than those currently used, in order to eliminate invasive species introductions and to provide an environment with good water quality, low incidence of diseases, and normal rates of sedimentation (Diana 2009). For the ever-growing human population to be able to secure its food, it has no alternative but to change its business models and to develop efficient food production systems that consumers will trust as being sustainable and as providing healthy products. Aquaculture can provide such products, but human consumption patterns will have to change in order to take advantage of seaweed and other seafood products.

## Acknowledgments

This article is the outcome of a workshop and symposium presentation entitled "The effects of semi-intensive aquaculture on biodiversity in nearshore and inland waters," which was held at the annual meeting of the American Fisheries Society in September 2011. Financial support for this symposium was from US Agency for International Development Cooperative Agreement Leader with Associates grant no. EPP-A-00-06-00012-00 through the Aquaculture and Fisheries Collaborative Research Support Program (AquaFish CRSP) and also by participating institutions. This is contribution no. 1399 of the AquaFish CRSP.

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