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Review

Aquaculture environment interactions: Past, present and likely future trends

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ABSTRACT

The two-way interactions of aquaculture and the environment are diverse and complex. Three major questions are addressed: what happened in the past, what are today's trends, and what may the future hold? Traditional aquaculture is mostly environmentally compatible as it mainly uses on-farm and locally available wastes and by-products such as crop residues and animal or human manures for nutritional inputs or natural food in open water culture-based fisheries and mollusk and seaweed farming systems. Wastes, by-products and natural food were the only sources of nutritional inputs for most farmed aquatic organisms in the past before the relatively recent and increasing use of pelleted feed in modern aquaculture, leading to major environmental concerns. Environmental aspects of intensification of aquaculture and their relation to ecosystems and agro-ecosystems in inland terrestrial and aquatic, and coastal/offshore, land- and water-scapes are reviewed. Aquaculture is increasingly being adversely impacted by pollution from agricultural, domestic and industrial pollution. Environmental issues are illustrated by case studies of traditional and modern aquaculture farming practice in temperate and tropical inland and coastal areas. Promising technologies that employ the principles of traditional aquaculture to contribute to the sustainability of modern aquaculture are outlined. There does not appear to be a panacea for environmentally sustainable aquaculture on the horizon to meet the increasing demand for aquatic food. This is more likely to be met through improvements in existing technology, including combining aspects of traditional with modern practice; better management practices (BMPs); better site selection so that aquaculture remains within the carrying capacity of inland and coastal water bodies; and the most efficient use of land and water, which is more likely to be aquaculture than farming terrestrial crops in relatively poor agro-ecosystems. Inland aquaculture, especially in ponds, is likely to continue to dominate global aquatic food production.

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1. Introduction

Three major questions are addressed regarding the development of environmentally sustainable aquaculture: what happened in the past, what are today's trends, and what may the future hold? Traditional aquaculture is mostly environmentally compatible as it uses on-farm and locally available wastes and by-products such as crop residues, animal or human manures or natural food in open water bodies as nutritional inputs for farmed aquatic organisms. Wastes, by-products and natural food were the only sources of nutritional inputs for farmed aquatic organisms in the past before the relatively recent and increasing use of pelleted feed in modern aquaculture which has led to major environmental concern. Traditional integrated fisheries aquaculture systems fed low-value/trash fish fed may have adverse environmental impact but open water culture-based fisheries and mollusk and seaweed farming systems based on naturally occurring food are environmentally compatible.

The past and present are contrasted in terms of traditional and modern aquaculture production systems, in natural ecosystems and human-made agro-ecosystems, with emphasis on type of nutrient inputs. Aquaculture is discussed in relation to natural ecosystems and human-built agro-ecosystems in inland terrestrial and aquatic, and coastal/offshore, land- and water-scapes. A major change has been the decline of traditional integrated aquaculture with increasing concerns about environmental sustainability. The two-way impacts of aquaculture on the environment, and the environment on aquaculture, are outlined, with environmental issues illustrated by selected case studies of actual traditional and modern aquaculture practice of inland and coastal aquaculture in temperate and tropical regions. The adverse impact on aquaculture of agricultural, domestic and industrial pollution is discussed. The treatment of pond effluents and examples of how promising technologies employing the principles of traditional aquaculture may contribute to the sustainability of modern aquaculture effluents are presented.

Widely held views on perceived differences in philosophy and action of the Orient and the West towards the environment are discussed. A call is made for more efficient use of nutrients, land and freshwater through aquaculture and the likely future contributions of freshwater and marine aquaculture practice, including open ocean aquaculture, are discussed.

2. Changes over time

2.1. From traditional to modern aquaculture

Aquaculture was entirely 'traditional' up to less than 30 years ago in Asia as locally available resources were the only sources of nutritional inputs available to the farmer before the relatively recent agro-industrial manufacture of pelleted feed (Edwards, 2009a). Traditional aquaculture is mainly integrated with other human activity systems. Major types of traditional aquaculture are integrated agriculture–aquaculture systems (IAAS) with on-farm or local agricultural by-products, manures and/or vegetation; integrated peri-urban-aquaculture systems (IPAS) using domestic sewage and wastes/by-products from local agro-industry; and integrated fisheries–aquaculture systems (IFAS) with carnivorous fish fed with trash and low-value fish. The farming of mollusks and seaweeds, so-called 'extractive species' because they depend for nutrition on usually naturally occurring organic detritus and plankton, and dissolved nutrients in the water column, respectively, may also be considered as traditional aquaculture systems.

There has been a relatively recent rapid increase in aquaculture production based on the development of 'modern' aquaculture through the application of science and technology, with the de-linking of aquaculture from agriculture (IAAS) and sanitation (IPAS). For the purpose of this article modern aquaculture is considered as fed with agro-industrially manufactured feed although it also includes relatively recently developed technologies such as hormonally-induced breeding, genetic improvement and use of diverse chemicals for various purposes. A major issue is the greater adverse environmental impact of modern aquaculture causing eutrophication because of intensification through increasing use of pelleted feed as well as expansion of the aquaculture area. Although there are considerable environmental impacts related to the production of feed ingredients as shown by several recent life cycle analyses (LCA) studies, this paper considers only the direct impacts of the fish farm with the immediate surrounding external environment. Most feed nutrients consumed by fish are released into the immediate environment in which they are farmed as only about 1/3 of the nutrients in the feed are removed in the harvest of the fish with 2/3 voided by fish during growth (Edwards, 1993). The potential adverse environmental impacts of aquaculture effluents increase from rice/fish culture, through pond, and to raceway and cage culture, essentially in direct proportion to the degree of intensification through use of pelleted feed and the exchange of water between the internal environment of the culture system and the external environment.

The main driving force behind the major trend to intensify production is increased farmer profitability through increasing the yield per unit area (Hepher, 1985), made possible by increasing demand for fish through expanding domestic and international markets, and availability of new technologies. The total production of pelleted feed increased more than three times from 7.6 million tonnes in 1995 to 27.1 million tonnes in 2007, with pelleted feed production growing at an average annual rate of 11.1% and expected to continue at a similar rate to 70.9 million metric tonnes by 2020 (Tacon et al., 2011). Even herbivorous and omnivorous species that are traditionally considered to be relatively low-input species such as most carps, catfish and tilapia are increasingly being fed pellets rather than being raised in semi-intensive integrated farming systems (Edwards, 2009a).

An increase in traditional aquaculture has also been constrained by the limited supply of locally available nutritional inputs, especially those from on-farm, as well as by the lower extent of intensification possible and therefore profit per unit farmed area compared to modern pellet-fed aquaculture. Low-intensity aquaculture is likely only to be feasible in relatively rare instances where ponds are sufficiently large to provide a large harvest of fish such as in milkfish ponds owned by large-scale land owners in the Philippines; and in remote areas of developing countries with limited infrastructure and few alternative livelihood options for small-scale farming households that also cannot afford to take risk. Household-level ponds in rural Bangladesh mainly provide fish at low levels of production for family subsistence while small-scale households farming shrimp in coastal areas of both Bangladesh and Vietnam cannot afford to take the risk of intensifying production because of frequent outbreaks of disease (Belton and Little, 2011). Thus farmers may chose to maintain a low intensity of production or reduce the intensity of production of their aquaculture system (extensification rather than intensification) if these contribute to a more sustainable overall livelihood portfolio.

2.2. Future importance of rice/fish culture

The prevalence and importance of rice/fish culture, the most basic IAAS and probably the earliest form of aquaculture, have been grossly overestimated both in the past and today, with only about 1% of the world's rice fields currently stocked with fish (Halwart and Gupta, 2004). It is a myth that rice/fish farming has ever been common or widespread, even in Asia. It has been practiced traditionally in a few areas of some countries e.g. the thousand year old rice/fish system in which a high-value red-colored common carp (*Cyprinus carpio*) is integrated with terraced rice fields in the mountains in Zhejiang Province, China (Edwards, 2006; Lu and Li, 2006); Java in Indonesia and mountainous areas in South East China, Northern Lao People's Democratic Republic (PDR) and Northern Vietnam (Edwards, 2009a). Although rice/fish farming has been promoted widely, the degree of sustainable adoption has been rather limited (Nandeesha, 2004), mostly because the culture of aquatic animals in rice fields is mostly not attractive to farmers in terms of return to labor. It requires considerable time and labor to modify rice fields for fish culture by digging trenches and raising the height of the surrounding dikes; and to maintain adequate water for the fish in the dry season as well as prevent loss of the fish through flooding in the rainy season. Furthermore, rice/fish integration is likely to become even less prevalent with new rice technology promoting less water use in view of the diminishing availability of water (Uphoff, 2007).

However, there are exceptions to the above overall view of limited potential. There has been fairly recent development of rice/fish farming in some areas of some Asian countries in low-lying rice fields with seasonally available water or in remote areas with limited alternative livelihood options and with a high incidence of poverty, especially where there has been project support. Thousands of hectares subject to flooding and able to produce only one rice crop annually have been converted to fish ponds with elevated dikes planted with trees and vegetables in the Red River Delta, Vietnam (Le Thanh Luu, personal communication); areas of 20–100 ha with 50–150 households have been converted to fish ponds with a minimum return three to five times higher than rice and with a reduced risk of flooding. Other exceptions are farming high-value river prawn (*Macrobrachium rosenbergii*) in rice fields in Bangladesh (Ahmed et al., 2013) and Vietnam (Nguyen et al., 2012); and also mitten crab (*Eriocheir sinensis*), river prawns (*M. rosenbergii* and *Macrobrachium nipponense*) and swamp crayfish (*Procambarus clarkii*) in China (Fang, 2003; Miao, 2010; Edwards, 2014). The feasibility of nursing common carp and Nile tilapia (*Oreochromis niloticus*) fry in irrigated rice fields in Northwest Bangladesh has been demonstrated and the practice has spread without further project support (Barman and Little, 2006; Haque et al., 2010) although traditional nursing of fish seed in rice fields in Indonesia has declined significantly as it is more efficient for farmers to nurse in ponds converted from rice fields than in an integrated rice/fish system (Edwards, 2009b).

2.3. Demise of integrated agriculture aquaculture systems

There is a long tradition of IAAS in Asia, with those of Chinese communes in the last few decades of the 20th century reaching the highest level of development although they have largely disappeared following privatization and the development of pellet-fed aquaculture (Edwards, 2009a). Although they probably no longer provide a majority of fish produced in Asia today, small-scale IAAS are still widespread and of considerable importance for relatively poor rural farming households in some Asian countries e.g. Bangladesh, Indonesia and Vietnam.

The most productive IAAS remaining today are systems of indirect rather than direct integration using off-farm feedlot livestock manure as pond fertilizer and brans and oil cakes as supplementary feed rather than the usually limited on-farm inputs (Edwards, 2009a). Most pond cultured tilapia in Thailand (Belton and Little, 2008) and carps in Andhra Pradesh, India, often called the 'fish bowl' of the country (Edwards, 2008a; Ramakrishna et al., 2013), both use off-farm poultry manure as fertilizer, and brans and oilcakes as supplementary feeds, respectively. Carp ponds in Central Europe are similarly indirectly integrated with cattle manure, brans and spoiled grain provided as nutritional inputs (Edwards, 2007; Adamek et al., 2012).

2.4. Demise of wastewater-fed aquaculture

The most common integrated peri-urban aquaculture system (IPAS) was nightsoil and wastewater-fed aquaculture. Nightsoil use was traditional in China and the country also had the largest area of engineered wastewater-fed ponds in the past although both types of IPAS have largely disappeared from the country (Edwards, 2009a). A major system of wastewater-fed aquaculture used to occur in the East Lake in Wuhan, China but the ponds have been removed following the development of modern sewage treatment plants and today the lake is a major tourist attraction with lakeside gardens and boating (Edwards, 2012). The world's first engineered and largest single wastewater-fed aquaculture system still exists today in Kolkata, India, where almost 4000 ha of ponds in the East Kolkata Wetlands provide the only sewage treatment system for the central part of the city (Bunting et al., 2011). Although the area has been declared a wetland of international importance under the auspices of the Ramsar Convention, the system is continually threatened by urban development. Wastewater-fed aquaculture is also used to farm water spinach (*Ipomoea aquatica*) in Phnom Penh, Cambodia and provides the city's largest supply of fresh vegetables (Edwards, 2009a) although recent reports from the local press and colleagues have indicated a major decline in area due to land fill for urban development.

3. Selected case studies from inland and coastal aquaculture

3.1. Inland aquaculture

3.1.1. Pond culture in China and Vietnam

Case studies are outlined from two major aquaculture producing countries in the world, China and Vietnam. Large-scale integrated farms became less integrated in China following privatization and most fish farms are not integrated today (Edwards, 2009a). Crops were eliminated from pond dikes on major farms by the 1990s and livestock by the 2000s. Most pond aquaculture is intensive pellet-fed mainly monoculture e.g. higher value common carp, crucian carp (*Carassius carassius*) and grass carp (*Ctenopharyngodon idella*) with production up to 30–40 tonnes/ha compared to 12–15 tonnes/ha for traditional carp polyculture (Miao and Yuan, 2007). Dike crops have mostly been eliminated except for grass to feed relatively high-value grass carp, especially broodstock, with pelleted feed as the major input; and limited vegetable production on dikes for consumption by farming households and workers, and local sale. Livestock is mostly not integrated with fish due partly to ponds having excess nutrients from residual fertilizer effects of pelleted feed with filter feeding species such as bighead carp (*Hypophthalmichthys nobilis*) and silver carp (*Hypophthalmichthys molitrix*), and tilapia (*Oreochromis* spp.) usually stocked as minor species to help to maintain water quality by consuming phytoplankton.

Large-scale integrated livestock/fish farms in China in the 1980s and 1990s were not always environmentally friendly because of their mostly total reliance on off-farm feed for feedlot livestock and their large scale of operation. While livestock wastes were treated to a certain degree in the fish pond, heavy growth of phytoplankton in pond water caused considerable eutrophication of Taihu (Lake Tai) along the shores of which many farms were located and into which it was drained, eventually leading to a ban by the local government and the elimination of integrated fish farming (Zhou En Hua, personal communication).

The rapid expansion and intensification of pond aquaculture in China over the last two decades has led to major concerns in the country although there have been few studies relating water quality to farm activity, on the impact of pond effluents on receiving waters or on the quality of water used in aquaculture (Cao et al., 2007; Li et al., 2011).

Most fish ponds in China were built in the 1980s and have become degraded. The Ministry of Agriculture of China has launched a nationwide initiative since 2006, the Action Plan for Promoting Healthy Aquaculture Development to improve the efficiency and decrease the adverse environmental impact of pond aquaculture through improved land use and pond water recirculation with less pollution from effluents (Li et al., 2011; Wang, 2012). Ponds with an area at least 15 ha are being redesigned, large individual farms as well as clusters of small-scale farms. The program also involves land consolidation with transfers of land-use rights from small-scale farmers who no longer wish to remain on the farm to larger and more efficient aquaculture farms.

One of the most remarkable aquaculture success stories is that of striped catfish (*Pangasianodon hypophthalmus*) in the Mekong Delta, Vietnam which has developed in just over a decade following the development of hatchery-based mass-scale seed production from a household small-scale waste-fed pond system to one that produced more than 1 million tonnes of fish and generated an export income of over US$ 1 billion in 2010 with produce exported to over 80 countries to satisfy an increasing international market demand for 'white fish' (De Silva and Nguyen, 2011). It has the highest average production of a farmed crop ever recorded, ranging from 200 to 400 tonnes/ha/6–8 month crop. Wild sourced seed of the airbreathing fish was initially stocked in wooden cages and fed trash fish and rice bran but today's highly intensive production is attained mostly in 4–5 m deep pellet-fed ponds mostly converted from rice fields, with considerable water exchange with the Mekong River. Little to no adverse environmental impact on the main river has been reported as waste emissions from striped catfish production and processing reportedly were less than 1% of the total suspended solids and nitrogen and phosphorus loads in the Mekong River (Ahn et al., 2010; Bosma et al., 2011; De Silva et al., 2010) although localized impacts on water quality in small lateral canals have occurred (Nguyen, T.P., personal communication). Most of the solids and nutrients in the river come from agriculture, industry and human settlements and not from aquaculture. These nutrients discharged into the river, including those from aquaculture, probably lead to increased coastal fish production. However, eutrophication in Mexico has been reported to lead to a decline in water quality through the production of blooms of algae (both plankton and seaweeds), and some of the plankton may be toxic (Paez-Osuna et al., 2013). Although striped catfish farming appears to be within the carrying capacity of the Mekong River and the South China Sea, better management practices (BMPs) are being introduced to the striped catfish sector in Vietnam (NACA et al., 2011), including attempts to manage sludge that accumulates on the pond bottom during the culture cycle and must be periodically removed (Boyd et al., 2011).

3.1.2. Cage culture

Most traditional cage culture is intensive as wild low-value or trash fish are fed to farmed fish in wooden and bamboo cages in inland and coastal waters. It was probably first developed by fishers in Cambodia (Chevey and Le Poulain, 1940) and still occurs in several countries in Southeast Asia e.g. Cambodia, Indonesia, Lao PDR, Thailand and Vietnam (Edwards, 2009a). Cage culture expanded rapidly throughout the world following the invention of modern cages with metal frames and metal and plastic flotation devices in Japan in the 1950s and it is almost entirely intensive with the total feed provided by the farmer, either low-value or trash fish or increasingly formulated pelleted feed.

Extensive and semi-intensive cage culture in which all or part of the feed for fish is provided from the environment, respectively, are rare as most water bodies in which cages are installed have insufficient natural food in the water column to support sufficient fish production. Exceptions are an extensive cage culture system in lakes in Nepal in which filter feeding bighead and silver carp are raised in cages in eutrophic lakes (Husen et al., 2012); and extensive pen culture of milkfish (*Chanos chanos*) in eutrophic Laguna de Bay, Philippines (Delmendo and Gedney, 1976). The filter feeding bighead carp has been stocked in the pens in recent years as it is better able to tolerate declining water quality in the lake than milkfish and it has become the second major species after milkfish raised in fish pens in Laguna de Bay (Saguin, 2014).

A major environmental problem with cage culture is eutrophication of the water body in which the cages are installed as fish wastes are flushed by water passing through the cage into the external environment. Eutrophication of the water body from auto-pollution readily occurs if there is no planning or control of cage density in confined water bodies such as lakes and reservoirs, often leading to frequent mass fish kills. Fish kills occur regularly on almost an annual basis in Cirata Reservoir, Indonesia (Beveridge et al., 1997; Abery et al., 2005) and in Lake Taal, Philippines (ADB, 2005) due to upwelling of deep deoxygenated and hydrogen sulfide containing water from the anaerobic degradation of fish cage wastes built up from years of intensive cage culture. In contrast, cage density is controlled in a tilapia floating net cage farm owned by AquaFarm in Gadjah Mungkur Reservoir, Indonesia (Edwards, 2010). Large-scale commercial cage culture of tilapias has been developed in several large lakes in Africa and remains at low density (e.g. *Oreochromis shiranus*) in Lake Malawi, Malawi, with little to no apparent adverse environmental impact.

3.1.3. Recirculating aquaculture systems and aquaponics

Large quantities of fish are raised at high density in a relatively small volume of water in a tank in a recirculating aquaculture system (RAS), with the water treated to remove toxic fish metabolic wastes and the water then reused in the system, although sludge does accumulate and needs to be removed periodically. RAS offer the potential for relatively minimal environmental discharge but systems are complex with high capital and operating costs and as a consequence numerous examples of failures (Bostock, 2010; Zohar et al., 2005).

Aquaponics, the integration of RAS with hydroponics, the cultivation of vegetables in a soil-less nutrient solution with the plants fertilized with waste nutrients from the fish tank effluent (Rakocy, 2007; Rakocy et al., 2006), has been generating increasing interest from scientists and mostly still potential commercial operators as few successful commercial farms exist to date (Hambrey Consulting, 2013; Hambrey, J., personal communication). The best known system has been run at the University of the Virgin Islands (UVI) on a pilot scale since the mid 1970s; and systems based on the UVI design have been constructed and perform well at temperate and tropical sites in many countries (Rakocy, J.E., personal communication).

Vegetable raising predominates in aquaponic systems which may be an advantage if there is a good market for the vegetable crop but it makes little sense to use high quality fish feed as the primary nutrient source for the plant crops according to a recently commissioned study of aquaponics (Hambrey Consulting, 2013; Hambrey, J., personal communication). Aquaponic systems have high capital and operating costs, high energy inputs with higher greenhouse gas emissions per unit of production than pond and cage culture. There are other ways to produce fish and vegetables efficiently and more economically; it may be more cost effective and with need for less management skill to produce hydroponic vegetables in lower cost plant crop systems fertilized with inorganic fertilizers rather than through integration with a fish recirculating system (Pantanella, E., personal communication). To date aquaponics are mainly practiced at hobby and backyard levels with very few established commercial operations although there may be potential for aquaponics in arid climatic and/or niche markets where water is especially scarce, and consumers are willing to pay a higher price for high-quality fish and vegetables, respectively.

It was pointed out that the concentrations of nutrients and the ratios between them are significantly different in a stable aquaponic system than in a hydroponic system which may reduce vegetable growth (Hambrey Consulting, 2013). A recent study by a commercial hydroponic greenhouse in Belgium reported that the RAS water could only supply about 25% of the nitrogen, phosphorus and potassium needed by the plants (Beyers, 2014). Furthermore, reusing RAS wastewater to save on fertilizer costs in hydroponics was hardly an issue as the cost of artificial fertilizers only comprised 2% of the total production cost in hydroponics.

3.2. Coastal aquaculture

3.2.1. Tropical cage culture

Crowded cages in coastal China and Vietnam have led to fish kills due to eutrophication but where inshore cage culture is still at a relatively low density such as in Indonesia, adverse environmental impact tends to be minor (Rimmer et al., 2013). In fact, most caged fish wastes are consumed by wild fish around the cages in Indonesia. Clearly there is a need to limit the number of cages in a particular area so that the ecological carrying capacity of the water body in which the cages are installed is not exceeded, with undesirable changes in biota and water quality.

3.2.2. Temperate salmon cage culture

The high pollution from caged salmon farming was recognized over two decades ago with Norwegian production in 1989 of 150,000 tonnes then comparable to a pollution load from a human population of 2.7 million people, 64% of the population of the country of 4.2 million people (Seymour and Bergheim, 1991). Salmon production in Norway has increased considerably since then, exceeding 1 million tonnes two decades later in 2009, with concerns of the environmental sustainability of a rapidly growing industry (Bannister et al., 2013). The size of individual cages also continues to increase with cages up to 60,000 m^3 in volume and holding 1000 tonnes of fish, equivalent to 2000 cows weighing 0.5 tonnes each (Svennevig, 2013).

The development of new cage technology in Norway has allowed sites to be moved to more exposed locations off-shore with deeper water, stronger currents and more suitable seabed topography with more dynamic water exchange between cages and the environment. Thus, there are increased dispersal and natural treatment of waste products with less adverse environmental impact (Tveteras, 2002; Bannister et al., 2013). A good environment to provide well-flushed cages is essential to reduce the risk of disease and especially so in large-scale cage farming with a US$ 3 million production cost for 1000 tonnes of salmon held in the largest cage (Svennevig, 2013).

3.2.3. Seaweed farming

Seaweed farming is environmentally friendly as it is mostly extensive, depending on naturally occurring nutrients in the water column. While it has a long tradition in East Asia, especially in Japan, it has been developed more recently in tropical Asia, initially in the Philippines which has recently been overtaken by Indonesia as the largest producer of the red seaweeds in the genera *Kappaphycus* and *Eucheuma*. These species are farmed for carrageenan, a polysaccharide widely used in processed foods and cosmetics (Rimmer et al., 2013). It is mainly carried out by small-scale fisher families with considerable benefits for household income and has considerable potential for sustainable expansion. Carrageenan containing seaweeds have been introduced from Asia into Tanzania, Africa, although rising temperature of seawater has reduced production, adversely affecting the livelihoods of poor seaweed farmers (Msuya, 2011).

4. Towards environmentally sustainable aquaculture

Aquaculture in common with the other major food producing sectors, agriculture and animal husbandry, should operate within ecological limits to minimize environmental degradation as the environment provides 'ecosystem services' vital to human welfare and ultimate survival (Millennium Ecosystem Assessment, 2003) as well as to that of farmed fish. The 'Blue Revolution' is a term often applied to the rapid growth of global aquaculture and according to Costa-Pierce (2002), the 'Blue Revolution must go green' with the 'alternative aquaculture development model…ecological aquaculture' incorporating ecological principles. The concept of ecological aquaculture is not new as traditional integrated aquaculture closely resembles a natural ecosystem (Costa-Pierce, 2002) but with the exceptions of so-called extractive culture systems such as seaweeds and mollusks, and culture-based fisheries, aquaculture systems that closely resemble natural ecosystems have too low productivity to be attractive to the vast majority of farmers as they have limited input of nutrients from the external environment. Boyd and Chainark (2009) outlined the recent evolution of aquaculture technology to intensify pond production: initially manures and chemical fertilizers to increase natural food, followed by pelleted feed to provide more nutrition for the fish, and then mechanical aeration to increase the supply of dissolved oxygen and thereby allow greater input of feed.

Aquaculture itself may be adversely impacted by sources of pollution from the external environment, from agricultural, industrial and domestic effluents, especially cages installed in public water bodies (Beveridge et al., 1997). Mass mortalities of fish raised in cages in rivers in Thailand are of common occurrence from clandestine and illegal release of untreated factory effluents as reported in the local press. There was a loss of 8000 tonnes of red tilapia in the Chao Phraya River in 2007 (Pongpao and Wipatayotin, 2007). There was a mass fish kill in another incident in Thailand in 2011 when a sugar barge sank in the Chao Phraya River, causing a section of the river to becoming anaerobic. Asian sea bass (*Lates calcarifer*) used to be mainly raised in cages in the brackish water Bang Pakong River in Thailand but production has mostly been moved to freshwater ponds because of declining quality of the river water (Merican, 2013). Cage-based fish production in open or flowing water bodies such as rivers may ultimately be unsustainable due to increasing pollution which leads to disease and occasionally causes mass fish kills.

Major and mostly adverse external environmental impacts on aquaculture are likely from climate change (De Silva, 2012). General impacts are likely to be increased temperature leading to changes in weather patterns with less rain in some areas, more in others; more frequent occurrence of extreme weather with increased storms, drought and/or flooding; and sea level rise. Examples of more specific nutrient-related and potentially adverse impacts on aquaculture are increased upwelling of deoxygenated water in reservoirs which would impact inland cage culture as well as damage relatively fragile infrastructure such as cages and pond dikes from increased frequency and severity of storms; and sea level rise impacting aquaculture in coastal areas and salinity intrusion into deltas which are major areas of freshwater aquaculture.

4.1. Pond effluents

While 'all modern large-scale food systems have discernible environmental…impacts' (Costa-Pierce et al., 2012), the polluting potential of aquaculture depends on the type of culture system used and the intensity of culture (Bergheim and Asgard, 1996). Fish wastes pass directly into the external environment with flow-through raceways and cages but the release of nutrients to the external environment from ponds is inversely proportional to the rate of water exchange with static water ponds treating a considerable amount of wastes in situ in the pond.

There is minimal effluent discharge in low-intensity pond culture with little to no adverse environmental impact as significant amounts of wastes are treated by the pond ecosystem during the culture cycle (Bergheim and Asgard, 1996; Boyd et al., 2007). However, an increasing amount of waste is discharged directly to the external environment with the major trend of intensification of production and in most cases the farmer does not bear the cost of its treatment (Boyd et al., 2007; Costa-Pierce, 1996). Unfortunately it is not cost-effective to treat relatively dilute pond effluents by conventional sewage treatment technology (Boyd et al., 2007; Cripps and Kelly, 1996). Pond effluent treatment options are to use effluents to irrigate crops, to treat effluents in constructed wetlands or settling basins, or to reduce or eliminate water exchange (Tucker et al., 2008). It is land-intensive to treat effluents using constructed wetlands, settling basins or sedimentation ponds, as well as to fertilize semi-intensive fish ponds. Reuse of intensive fish pond effluents to fertilize adjacent terrestrial crops has been reported but is not widespread, in part because of limited opportunities for fish ponds to be located adjacent to terrestrial crops which could be fertilized. Research has been carried out for a number of years in Hungary on the treatment of effluents from intensive pond culture of walking catfish (*Clarias gariepinus*) and Nile tilapia in adjacent fish ponds with significant treatment of the intensive pond effluent although the area of the latter was four times greater than that of the former (Gal et al., 2003). Research on these systems has recently been carried out in China (Varadi, L., personal communication).

4.2. Linking traditional and modern practice

There are promising technologies that link traditional and modern aquaculture practice to reduce the adverse environmental impact of modern pellet-fed aquaculture and/or to lower the cost of production (Edwards, 2009a).

4.2.1. Modern polyculture

Traditional Chinese polyculture involves stocking the pond with up to 6–8 carp species (Edwards, 2009a). Soon after the introduction of pellet-fed monoculture of high-value species such as common carp, crucian carp, grass carp and tilapia spp., Chinese farmers returned in part to traditional polyculture practice by stocking filter feeding species such as bighead and silver carp in an attempt to reduce excessive growth of phytoplankton induced by residual fertilization of fish feces and uneaten feed in the intensive pond culture. Such a modern polyculture system, the '80:20 system' is being promoted in China by the American Soybean Association (ASA) (Manomaitis and Cremer, 2007; Ye, 2002). About 80% of the harvest weight is high-value 'target species' and the other 20% comprises low-value 'service species', mainly filter-feeding silver carp to reduce the biomass of phytoplankton. High physical quality extruded and nutritionally complete feed is promoted in the aerated, closed water ponds and their use is reported to lead to faster growth, higher production and better feed conversion with higher profits than traditional polyculture technology and less adverse environmental impact.

4.2.2. Cage-in-pond culture system

Considerable experimentation has developed an integrated cage-in-pond system with fish grow-out in cages installed in a pond in which nursing takes place simultaneously. Intensive pellet-fed cage grow-out is integrated with semi-intensive pond nursing with fingerlings nursed in the same pond on spilled feed and 'green water' from fish feces from the caged fish. Another major environmental benefit of the system, besides the in-pond treatment of pellet-fed fish wastes, is protection from external agricultural, industrial and urban water pollution which increasingly threatens aquaculture in public water bodies, with numerous reports of mass fish kills on commercial farms.

The initial experiments were carried out with hybrid walking catfish (*Clarias macrocephalus* x *C. gariepinus*) stocked in the cages and Nile tilapia in the pond (Lin, 1990) but subsequent research developed coordinated and integrated nursing and grow-out cycles for tilapia (Yi, 1999; Yi et al., 1996): pellet-fed 100 g nursed fingerlings were stocked in a cage at $50/m^3$ and grew to 500 g in 3 months; 20 g fingerlings were stocked at $1.4/m^2$ in the surrounding pond and grew to 120 g in 3 months only on 'green water' from cage waste.

A small number of farmers has been reported to use a cage-in-pond system for the culture of tilapia in Thailand, nursing at high density in an aerated green water pond to 200–300 g before fattening in cages in the pond on pelleted feed (Belton et al., 2009).

Experiments on intensive production of African catfish in a pellet-fed cage installed in a large pond stocked with common carp that fed only on natural food derived from caged fish waste have been reported from Hungary (Gal et al., 2012).

4.2.3. Raceway-in-pond culture

Two promising technologies that minimize or even eliminate the adverse impact of pond effluents on the environment are a partitioned aquaculture system (PAS) and a raceways-in-pond system, both closed aerated systems with zero water discharge.

A PAS incorporated high-rate micro-algal culture with fish culture (Brune et al., 2003; Hargreaves, 2006). Pellet-fed channel catfish (*Ictalurus punctatus*) were stocked at high density in a rearing tank with the water circulated through a shallow high-rate phytoplankton pond by a low-energy paddle to treat the fish wastes. Low-speed paddle wheels moved large volumes of water at low velocities uniformly throughout the pond with filter-feeding tilapia reducing phytoplankton biomass in water produced by residual fertilization from the pellet-fed catfish raised in adjacent raceways. The PAS was reported to also have the potential to reduce total water usage per unit of fish produced by 90%.

A new intensive pond aquaculture technology with zero-discharge developed in the USA, has been demonstrated in China (Cremer et al., 2014). An in-pond concrete raceway system comprising three cells stocked with pellet-fed grass carp within an earthen fish pond yielded 42 tonnes from the 2.1 ha combined system, an extrapolated yield of 20 tonnes/ha, almost three times the average Chinese pond yield of 7.2 tonnes/ha. A high volume air blower supplied air to diffuser mats to promote circulation of water through the raceways, with solid wastes collected two or three times daily by vacuuming from the quiescent zone located in each concrete cell.

4.2.4. Integrated multi-trophic aquaculture

Integrated multi-trophic aquaculture (IMTA) is a recent aquaculture approach that integrates pellet-fed finfish culture with inorganic extractive seaweeds and organic extractive mollusks and benthic detritivores such as sea cucumber (Folke and Kautsky, 1989, 1992; Reid et al., 2010; Chopin et al., 2012). There are ongoing research projects on IMTA in many countries with IMTA systems either experimental, at pilot stage, or near or at commercial-level scale in Canada, Chile, China, Israel and South Africa (Chopin et al., 2010). According to these authors, sufficient data have now been accumulated to 'support proof of concept at the biological level so the next step is the scaling up of more experimental systems to commercial scale'.

However, open water IMTA systems face constraints to the efficient removal of nutrients from caged fish wastes. While there are reports of increased growth of shellfish and seaweeds in the vicinity of fish cages, the effectiveness of bivalve mollusks to reduce the environmental impact of marine fish farming has been questioned (Navarrete-Mier et al., 2010). The capture of particulate organic particles by mussels has been shown to be highly inefficient as they remove only a small fraction from the water flowing past them (Cranford et al., 2013). Increasing the density of mussels for the highest degree of waste extraction would require such a high stocking density that it would exceed the shellfish production carrying capacity leading to relatively low mussel production. Mussels also consume natural as well as fish cage organic particles with a fraction of digested matter released as fecal solids (Reid et al., 2013a) so deposit feeders need to be installed beneath mussel infrastructure to increase the efficiency of IMTA (Reid et al., 2013a). It is also not feasible to sequester all the soluble inorganic nutrients from the fish cage waste plume by seaweeds as the number of rafts required would exceed the space available (Reid et al., 2013b).

Research is underway to characterize the benefits of IMTA in China where coastal aquaculture in the study area is dominated in terms of production by seaweeds and shellfish, with relatively limited production of caged finfish. Chinese farmers introduced various aquaculture commodities at different trophic levels as the technologies became available to take advantage of available space in the bay rather than to purposely benefit from nutrient recycling. IMTA developed incidentally in China as first seaweeds in the 1950s and 1960s, then scallops in the 1990s and more recently finfish cage culture have been sequentially developed on a commercial scale in coastal bays (Fang and Lui, 2013; Fang et al., 2013) rather than being promoted purposefully as in the West. This has been referred to as incidental IMTA, 'not purposely designed cultivation of species of different trophic levels situated in close geographical proximity' (Reid et al., 2013b). However, it is undoubtedly true that seaweeds play an important role in bioremediation in China, as stated by Sorgeloos (2013), 'If the Chinese had not engaged in massive seaweed farming since the 1950s, coastal eutrophication would today have become much more critical' as almost 10 million tonnes of seaweeds harvested annually remove hundreds of thousands of tonnes of nitrogen and phosphorus from the sea.

Major questions remain to be addressed on open-water IMTA as outlined in a seminal paper entitled 'Integrated mariculture: asking the right questions' published a decade ago (Troell et al., 2003). Experimentation and financial modeling have demonstrated the feasibility of open water integration of finfish with seaweed and shellfish culture and have appeared to demonstrate attractive returns for investors but more data are required to demonstrate 'real world' viability, as Bunting (2013) wrote, 'empirical evidence to substantiate claims concerning production rates, management demands, financial returns and economic performance is limited'. Furthermore, there should be an evaluation of the full value of IMTA component species, with the economic values of the environmental and societal services provided by the extractive species both recognized and accounted for to facilitate open-water IMTA becoming a widespread commercially viable system (Chopin et al., 2012).

Land-based, closed systems of IMTA are also being developed. Perhaps the best known example is that of Commercial SeaOr Marine Enterprises, Israel, which used to farm gilthead seabream (*Sparus aurata*), the green seaweed *Ulva* and the red seaweed *Gracilaria* and Japanese abalone (*Haliotis discus*), but it has closed down reportedly because of poor management rather than an inherent weakness in system design, function and economic viability (Neori, A., personal communication).

5. Future contribution of aquaculture by species, systems and environment

5.1. Myths and misunderstandings

5.1.1. East versus West

There is a widely believed myth that there is a fundamental difference in action towards nature and the environment between the environmentally benign East with Taoism and Buddhism in China stressing harmony with nature, and the environmentally destructive West with Judaism and Christianity traditionally preaching that humans have dominance over nature (Murphey, 1967; Tuan, 1968). Although different religions and philosophies did develop in the two regions, the Chinese have altered the environment and probably on a greater scale than in the West for over 3 millennia until recently. The confusion has probably arisen because, as suggested by Elvin (2004), 'a sympathetic feeling for nature … was simply a reaction against environmental degradation' rather than a guiding principle for action. The major driving force behind the development of integrated aquaculture in China was use of on-farm and locally available by-products and wastes as nutritional inputs, the only sources then available, rather than a philosophy leading to a cultural practice of environmentally friendly aquaculture.

5.1.2. Current and future role of Chinese carp polyculture

There is also misunderstanding, as widely stated in both popular and scientific literature, regarding the current prevalence and likely future role of traditional Chinese carp polyculture as well as extensive and semi-intensive pond culture in other countries in the world. Several quotations are cited from the literature to indicate just how widespread is this misunderstanding (Box 1). Most Chinese carps today are produced in modern pellet-fed ponds and not in traditional integrated systems as widely believed as discussed in Sections 2.3 and 3.1.1 (Edwards, 2009a).

5.2. More efficient use of nutrients, land and freshwater through aquaculture

5.2.1. Future role of traditional aquaculture

The view that traditional IAAS have a major role in future fish production persists (Box 2).

Rather futile calls have been and continue to be made for more widespread dissemination of traditional integrated aquaculture (Sugunan et al., 2006) as well as Chinese carp polyculture (Chan, 1993; Korn, 1996) which has been considered to be an ecologically closed system

Box 1
Misunderstanding regarding the current prevalence of traditional Chinese carp polyculture, and extensive and semi-intensive pond culture in China and other countries in the world (the main misunderstood point/s are in bold font).

- **'Most of China's aquaculture is integrated with agriculture'** (Brown, 2001)
- **The Chinese carp polyculture system** is a 'highly efficient protein production model' **that accounted for the 'major part of China's carp harvest of 16 million tons in 2011'** (Brown, 2012)
- **'Polyculture of Chinese and Indian major carps … account for the bulk of world aquaculture production'** (World Bank, 2007)
- 'Despite the trend in intensification of production methods **the majority of aquaculture production is still derived from extensive and semi-intensive aquaculture** of omnivores and carnivores' (Hall et al., 2011)
- 'Freshwaters were the source for 60% of the world aquaculture production in 2008 …Of this, 65.0% were **carp and other cyprinids which are mostly cultured in ponds using semi-intensive methods**' (Bostock et al., 2010)
- **'Current extensive/semi-intensive aquaculture of low trophic level freshwater fish…currently represent the bulk of global finfish culture production'** (Tacon et al., 2010)
- **'Traditional integrated farming produces close to 15 million tonnes in China alone'** (Sorgeloos, 2013).

Box 2
Myth of a major future role for traditional aquaculture.

- 'China has evolved a fish polyculture … emulating natural aquatic ecosystems' (Brown, 2001)
- 'The freshwater, herbivorous carp polyculture on which the Chinese rely heavily for their vast production of farmed fish offers an ecological model for the rest of the world' (Brown, 2001)
- 'Priority is to increase production in the presently available volumes of water, not necessarily by further intensification but rather by polyculture and integration with terrestrial production' (Sorgeloos, 2001)
- 'Integrated aquaculture systems can provide efficient and environmentally sound recycling of nutrients and organic materials. For example, polyculture of Chinese and Indian major carps … is environmentally benign and can convert agricultural wastes' (World Bank, 2007).

with the 'bulk of inputs generated from within the system' (Ruddle and Zhong, 1988; Yee, 1999). It was explained two decades ago that the traditional Chinese polyculture system was mainly driven by human excreta and pig manure derived from off-farm human and pig food and not from nutrient recycling within the pond which would have been ecologically impossible with export from the farm of 7 tonnes of fish annually (Edwards, 1993, 2008b; Ruddle and Christensen, 1993).

Calls are still being made for research into traditional aquaculture with the aim of increasing fish production based on natural pond productivity by maximizing nutrient cycling within the pond e.g. improved polyculture to more effectively use pond niches; and periphyton on solid substrates placed in pond (Azim et al., 2005; Azim and Little, 2006; Bosma and Verdegem, 2011; Brody et al., 2012; Costa-Pierce et al., 2012; Diana, 2012; Milstein, 2005). While traditional integrated systems are mostly environmentally friendly as they use mainly on-farm and locally available by-products and wastes, and can treat livestock and human manures, production is unlikely to be increased sufficiently to make traditional aquaculture significantly more attractive to farmers. As stated by Bostock et al. (2010): 'a widespread return to low-intensity production is unlikely to be an acceptable option'. The major trend to use formulated pelleted feed for fish is certain to continue; and the statement by Bosma and Verdegem (2011) that 'a large fraction of the production increase must be realized through low-cost technologies' is unlikely to occur.

The sustainable intensification of areas already developed for human use, as intensively as possible, has been suggested to reduce pressure on natural ecosystems as 'the world is moving toward a wholesale transformation from a wild landscape with pockets of human population and industry, to one of a managed landscape with pockets of wild places' (Brummett et al., 2013). The same point was made decades earlier with regard to the 'Green Revolution', the development of improved varieties of wheat and rice which were introduced into irrigated areas throughout Asia and averted an impending food crisis. As Norman Borlaug, the originator of the Green Revolution wrote: 'by producing more food from less land…high yield farming will preserve…wild habitats' and therefore benefit the environment (Hesser, 2009).

5.2.2. Land use for agriculture or aquaculture?

The idea that aquaculture should not compete with agriculture, even though fertilizers and feeds for traditional inland pond aquaculture are provided by integration with agriculture derived from adjacent crop and livestock farm subsystems, goes back almost half a century. The British Government constructed the Tropical Fish Culture Research Institute near Malacca, Malaya, as it was then known, to serve as the aquaculture research station for tropical Commonwealth Territories of the UK, although it was opened only 10 days before Malaya (today's Malaysia and Singapore) became independent in 1957. Prowse (1966) wrote: 'The site selected for the construction of the ponds was really chosen because it was regarded as totally useless for agriculture'; the site was toxic to most terrestrial crops, including rice, because of the high aluminum and iron contents of the soil although fish could be grown in heavily limed and fertilized ponds.

More recent quotations indicating the continuing perception of a land use clash between agriculture and aquaculture from the popular and scientific literature are: 'Competitive uses of land precludes large-scale expansion of pond area' (Bosma and Verdegem, 2011); and 'A slowing down of aquaculture growth is anticipated due to constraints in available land and water' (OECD-FAO, 2013). Most global fish production is from ponds which are likely to remain the major grow-out system for freshwater fish production in the future (Boyd and Chainark, 2009). Furthermore, as discussed below, there is huge potential to increase fish production from expansion of fish ponds newly built from conversion of agricultural land as well as intensification of pond culture.

Most inland fish ponds have been converted from rice fields although data on the amount of land used for aquaculture are not readily available. Most fish ponds in China were converted from rice fields during the 1970s and 1980s but the practice has now been banned due to concerns about national food security. Some countries continue to convert land to fish ponds e.g. Vietnam (De Silva, 2012) although a ceiling on national rice field conversion to maintain at least 4 million ha of rice fields has been established recently (Le Thanh Luu, personal communication). Vietnam encouraged the conversion of poor rice land to fish ponds in the past to improve farmer earnings, previously low-yielding rice fields to more profitable pond-based IAAS systems with raised broad dikes for vegetables, fruit and livestock and less susceptible to monsoonal flooding than the previously low-level rice fields. The recent acceleration of development of aquaculture in Nepal has taken place mainly in ponds converted from rice fields (Edwards, 2013).

The continued conversion rice fields to fish ponds is a major and most contentious issue because of the need to produce more rice to meet future demand for food. Governments are faced with a difficult choice: continued national food security through farming of staples such as rice for human populations that continue to grow in absolute number; and agricultural diversification for farmers, many of whom are poor, out of primary staples to more profitable crops such as vegetables, fruit and livestock (Pingali, 2004); and of course fish. Rice production needs to be increased for the next two decades at least because demand for rice from human population growth is expected to be greater than the decline in per caput rice consumption from the universal trend in diversification of diets associated with economic growth and urbanization (Bouman, 2007). However, diversification of rice cultivation has been identified as the 'single most important source of poverty reduction for small farmers in South and Southeast Asia as farming rice earns a relatively low income for farming households' (Pingali, 2004).

There is still considerable potential to increase rice yields in many countries, and 'with increased rice yields part of the farm land can be taken out of rice production and converted into more profitable crops' (Bouman, 2007); these crops could include fish of course, and therefore be a potential pathway to increase farming household income while continuing to produce rice. Two cases indicate that conversion of rice fields to fish ponds may have relatively limited impact on national rice production. In Vietnam 1 million tonnes of striped catfish have been produced from 6000 ha of ponds (De Silva and Nguyen, 2011) and in Bangladesh, one of the most densely populated countries in the world, 0.3 million tonnes of striped catfish have been produced from 7400 ha of ponds (Belton et al., 2011). These represent only a miniscule 0.08% of the total national area of 7.8 million ha of rice fields (USDA, 2012) in Vietnam; and again a miniscule 0.09% of total national area of 11.0 million ha of rice fields in Bangladesh (Awal and Siddique, 2011). The conversion of rice fields to fish ponds should hardly be an issue in terms of reduction of national rice production because of huge fish production mostly from converting less than 0.1% of the total area of rice fields in both countries to ponds. While aquaculture converts land into ponds to grow aquatic organism just as agriculture uses land to grow terrestrial crops, far less land has been used by aquaculture to date and a comparison should be made of the two to compare aquaculture's impacts with those of other food producing systems (Diana, 2009). An extreme example of the more efficient use of both land and water is the conversion in China of rice fields producing a relatively low-value rice crop below a reservoir, with an abundant year round supply of available water, to an intensive fish farm raising high-value paddy field eel (*Monopterus albus*) (Edwards, 2013).

5.2.3. Alternative use of water

A critical challenge for the early 21st century is the resolution of the water crisis, increasing scarcity and quality of water in the near future, with less water available for agriculture, including aquaculture (Molden, 2007). Traditional low-input pond aquaculture is an inefficient use of water and 'ponds must become more intensive with respect to water use' (Funge-Smith and Phillips, 2001). More efficient use of water could be attained by integration of aquaculture with natural and constructed water bodies. Large fish ponds, 100 s to 1000 s ha in area, built centuries ago, are considered to be an integral part of the Czech landscape where they function for irrigation, water management, recreation and nature reserves as well as for fish culture (Adamek et al., 2012; Adamek and Kouril, 2000). The productivity of water may be increased through the integration of aquaculture in irrigation systems, or integrated irrigated aquaculture (IIA) as it has been referred to, essentially a non-consumptive activity with fish grown in the water on its way to or from agriculture (FAO, 2006). There are major reviews of the integration of aquaculture into small as well as large-scale engineered irrigation systems (Haylor, 1994; Murray et al., 2002).

Community or culture-based fisheries (CBF), usually extensive aquaculture in small water bodies, has been described as an 'underutilized opportunity in aquaculture development' (De Silva, 2003). Production of more fish from existing waters with minimal external feed inputs provides an important means to augment conventional aquaculture practices. While aquaculture-based fisheries enhancements have been successfully implemented in more than 27 countries with an estimated production of 2 million tonnes of fisheries products (Bostock et al., 2010), it has been estimated that there are 67 million ha of small water bodies, constructed mainly for irrigation, in Asia (De Silva, 2003). The promotion of CBF is likely to deliver more immediate yield increases than investment in technology as it is technically simpler than conventional aquaculture although there are usually complex technical, social and institutional issues regarding biodiversity, access to water bodies, social equity arrangements, and competition of water use to be addressed (De Silva et al., 2006).

There is considerable potential to expand cage culture in underutilized reservoirs, lakes and rivers. However, fluctuating water levels in reservoirs used for irrigation and hydropower generation can adversely affect aquaculture due to draw downs (Finlayson et al., 2013). The culture of fish in cages in irrigation canals also requires coordination between the water authorities that manage the system and fish farmers. There was a recent mass kill of caged fish due to a water shortage in an irrigation canal in Thailand in 2012 after the irrigation authority drew down a reservoir to increase the storage capacity in the coming monsoon season to reduce the chance of floods; the authorities had been instructed by the government to lower the level of water in the reservoir before the monsoon season to avoid having to suddenly release large volumes of water when the reservoir filled up, one of the causes of the massive flooding that occurred in the country in 2011. Cage aquaculture in irrigation canals is prohibited in some countries because of concerns that it may reduce water flow and increase sedimentation in the canal (Dugan et al., 2007).

Agricultural water storage reservoirs are dual purpose water bodies as they are also stocked with fish in Israel (Hepher, 1985; Sarig, 1984) and more recently in Egypt where fish farms are prohibited from using water in irrigation canals (van der Heijden et al., 2012).

Although there is major concern about the limits of water to sustain future increases in agriculture and aquaculture, a recent study has indicated that 'renewable freshwater appears adequate for considerable expansion of aquaculture, especially outside Asia' (Boyd and Brummett, 2012). Furthermore, aquaculture would be a more efficient use of water as well as land (Section 5.2.2) in many contexts, especially in low-yielding rice fields.

5.3. Open ocean aquaculture

There is another mantra (in the more recent connotation of endlessly repeating a phrase rather than in the sacred Hindu and Buddhist religious context of repetitious chants) in the popular and scientific literature, dating back more than half a century, that the future of aquaculture is in the oceans because of perceived constraints of land and freshwater (Box 3). The open ocean does offer tremendous potential to increase global aquaculture production with almost unlimited space and diffusion of wastes in contrast to coastal aquaculture. Significant expansion of coastal aquaculture is constrained as favorable sites in many countries are often being used already for aquaculture, and there may be competition for space from multiple users as well as external pollution as coastal areas often have high population densities with discharge of domestic and industrial effluents, especially through estuaries on which major cities tend to be located. The composition of production would also have to change for open ocean aquaculture to contribute significantly to global food supplies. Mariculture is currently dominated by seaweeds (46%) and bivalve mollusks (43%) at 89% of total production, which do not provide major sources of human food, with crustaceans (2%) and finfish (9%) providing only a total of 11% of total mariculture production (FAO, 2013).

Significant research and development (R&D) is underway and the feasibility of aquaculture in the high-energy offshore environment with large and variable winds, swells and waves has been demonstrated with major advances in technology (Langan, 2009; Fredheim and Langan, 2009). Cages may need to be large and of sophisticated design requiring large capital investments to provide sufficient scale of operations to be financially viable (Bostock et al., 2010). Marine Harvest, the largest salmon farming company is taking up the challenge to develop

Box 3
The future of aquaculture lies in the oceans.

- 'It seems not outrageous to suggest that the oceans may some-day produce a greater proportion of the food consumed by humans than is grown on the land' (Brittain, 1952)
- 'We are now entering a new era — the era of mariculture …As the world's population expands, land farming will be increasingly unable to meet the ever greater demands for food' (Bente, 1970)
- 'The oceans…will constitute the next food revolution in human history' (Duarte et al., 2009)
- 'Indeed with terrestrial food production now reaching its limits, the ocean is … the final option' (Greenberg, 2010)
- 'Experts agree that most of the future aquaculture expansion will occur in the seas and oceans, certainly further offshore, perhaps even as far as the high seas' (FAO, 2010)
- 'Freshwater fish will become increasingly scarce in the coming decades…we can expect and in fact should promote a significant shift to farming the oceans and seas' (Sorgeloos, 2013)
- 'The oceans…are the secret to the creation of food and food security as our plant's population continues to grow' (Palmer, 2014).

offshore cages with the search now on for the 'tropical salmon' (Myrseth, 2013; Myrseth, B., personal communication). According to Myrseth (2013), 'Asia can feed itself and most of the world with fish', if large Norwegian type cages were to be installed in the tropics in the calm water belt between 10°N and 10°S, with Indonesia having the greatest potential in the world.

Small-scale cages have also been designed that would allow developing country fish farmers to move away from protected bays and into more exposed sites: a small-scale submersible fish cage (Chambers et al., 2011); and the low-volume high-density aquapod, a spheroid shaped cage constructed of individual triangular net panels which permits much higher fish densities, improved fish growth and potentially higher profit per unit volume of cage than more conventional larger cages as well as facilitating management (Page, 2013).

However, technological, operational, economic and political challenges remain (Langan, 2009), including the lack of institutional or regulatory frameworks. FAO has launched an Offshore Mariculture Initiative, part of which is to estimate the spatial potential of offshore mariculture development for all maritime nations (Kapetsky and Aguilar-Manjarrez, 2012). Furthermore, participants at the International Workshop on Open Ocean Aquaculture held in Germany in 2012, drafted the 'Bremerhaven Declaration on the Future of Global Open Ocean Aquaculture' with recommendations to promote and support R&D in open ocean aquaculture (Bremerhaven Declaration, 2013).

6. The way forward

Aquaculture has great potential to expand and intensify sustainably to meet the demand for fish in 2050 as the human population is predicted to continue to grow for the next 40 years before stabilizing at a minimum of 9 billion people (Godfray et al., 2010). The major trend towards intensification and use of formulated pelleted feed in aquaculture will continue because the main driver for intensification is farm profit; once there is an available market and seed and feed become readily available, farm income is greater from intensive aquaculture even though the cost of production as well as the adverse environmental impacts are both larger than in traditional semi-intensive aquaculture which characterizes most integration. While production from traditional IAAS systems has declined considerably in well-endowed aquaculture areas, especially in China where they were dominant until relatively recently, integrated systems still have a role to play in densely populated rural areas, especially those in remote areas and with limited livelihood opportunities. Aquaculture production will continue to increase through both expansion and intensification; and in Asia, as well as in Africa and Latin America with greater underdeveloped potential.

Inland aquaculture is likely to continue to be the major source of fish rather than mariculture, including open ocean aquaculture. While there is a trend towards expansion of aquaculture into open marine waters as they have high water quality for culture and virtually unlimited potential for flushing and natural treatment of wastes from aquaculture, major technological, operational, economic and political challenges remain to be resolved before the oceans become a major supplier of farmed fish. The 'growth of such developments is unlikely to be high' (FAO, 2006).

Inland ponds will almost certainly remain the major producer of farmed fish for the foreseeable future as the culture of currently farmed major species groups such as carps, catfish and tilapias has great potential for expansion in ponds. Rice/fish culture has limited overall potential, although rice/freshwater prawn culture has expanded considerably in low-lying rice lands in Bangladesh and Vietnam and rice/mitten crab or swamp crayfish in China, no doubt because of the higher market value of these crustaceans than the omnivorous and herbivorous species of fish traditionally stocked in rice fields. The trend of conversion of rice fields to inland fish ponds is likely to continue; and especially so in countries in which aquaculture is relatively new rather than those with a well developed aquaculture sector where there is concern to maintain a minimum area of rice land for national food security. However, even in countries with a well developed aquaculture sector such as China and Vietnam, there is a need to assess the relative merits of using land and water for aquaculture rather than rice cultivation in specific areas, especially those in which rice production is sub-optimal because of poor soils or frequent drought or flooding. Research is required on the merits of conversion of at least marginal, low-yielding rice fields to fish ponds, rice fields in which poor soil and/or unstable water regimes leading to drought and/or flooding lead to low production and often a single annual harvest.

Cage technology has great potential for expansion, especially in inland and coastal waters in some countries although from an environmental sustainability point of view it needs to be within at least the physical carrying capacity of confined water bodies such as inland reservoirs and coastal bays because without adequate control of cage density there is a threat from auto-pollution causing eutrophication of the water and frequent mass fish kills as frequently reported.

There does not appear to be a panacea on the horizon, relatively simple and universally applicable technological solutions for environmentally sustainable aquaculture, to meet the increasing demand for aquatic food. This is more likely to be met mainly through various combinations of technological developments, improvements in existing technology, better management practices, and better site selection so that aquaculture remains within the carrying capacity of ecosystems. Progress in R&D is being made in the reduction of the adverse environmental impacts of intensive aquaculture effluents.

Promising aquaculture practices for sustainable intensification such as modern polyculture systems, and cage-in-pond and raceway-in-pond systems with zero effluent discharge, are likely to become increasingly important. Although the cage-in-pond and raceway-in-pond systems will have a higher capital and operating costs than conventional aquaculture systems, they are likely to be more profitable through considerable intensification of the land area used for construction. Aquaculture technologies currently receiving considerable R&D attention such as recirculating systems, aquaponics, and open-water IMTA and land-based IMTA are unlikely to make a significant contribution to future global fish supply.

It is beyond the scope of this mainly technical overview to consider institutional aspects of the development of environmentally sustainable aquaculture but there need to be greater implementation of BMPs and the ecosystem approach to aquaculture (EAA) to better integrate aquaculture into inland watersheds and coastal zones with more efficient use of land and water. The overall goal of the EAA is to promote ecologically but also socially responsible planning and management of aquaculture to ensure that the aquaculture sector is sustainable through participatory processes with local communities and other stakeholders, and the integration of aquaculture with other sectors and users of the same environmental resources (FAO, 2010). A major constraint to the development of economically sustainable aquaculture is the lack of costing of environmental services to date with aquaculture only considered in terms of financial benefits to farms and companies and not to socio-economic benefits to society to date (Chopin et al., 2010; Troel, 2009). Substantial change towards more widespread ecologically sustainable aquaculture could be driven by more enlightened politics to bring 'realistic external costs of environmental services into company accounts' (Bostock, 2010).

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