Reviews

An ecosystem approach to marine aquaculture: a global review

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ABSTRACT

The general objective of this global review is to assess progress at various levels of aquaculture development towards an ecosystem approach to marine aquaculture[1]. The specific objectives are to: Review research and development progress at the farm, major species, and selected major aquaculture farming countries; identify main barriers to implementation of an EAA, and to identify priority needs and recommended actions.

Review of research and development progress towards an ecosystems approach to aquaculture was presented using two frameworks: (1) using the three principles and levels detailed by Soto *et al.* (2008) in three steps as a global review of research and development progress: first, at the farm level; second for molluscs and shrimp – where substantial industrial/commercial progress has been made towards an EAA; lastly, for the world's major farmed finfish; and (2) a governance framework using an "orders of outcomes" approach. Reviewing the status of marine aquaculture using the Soto *et al.* (2008) framework shows that, overall, there is a great deal of global, multidisciplinary research and development information and good progress on an EAA at the farm research and development (R&D) level which can inform managers. At the industrial/commercial level, there has been a notable transition globally towards an EAA for two, major commodities – molluscs and shrimp - over the past 10 years (more so for molluscs). Analyses in this review chart a rapid trajectory of parts of these sectors towards an ecosystem approach to aquaculture, and capture a clear "innovation portfolio" in these industries. At the commercial scale for marine finfish, there is some progress toward an ecosystem approach globally. For salmon and other marine finfish, analyses of practices in the selected major aquaculture farming countries show good progress towards an EAA for salmon in Canada, some progress in the United Kingdom and Norway, but very little in Chile. There are major concerns in the development portfolio for other marine finfish, with little to no progress towards an EAA, especially in modern cage

[1] The ecosystem approach should ensure *sustainable development.* This is defined as: management and conservation of the natural resource base and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development (in the agriculture, forestry, and fisheries sectors) conserves land, water, plant, and animal resources, is environmentally non-degrading, technically appropriate, economically viable, and socially acceptable, (FAO, 1995).

culture developments in China and Southeast Asia. Applying the governance framework analysis globally, it was found that no aquaculture industry anywhere in the world for any commodity has put into the place all of the enabling conditions described by Olsen (2003), thus there are very few "first order outcomes" to measure in regards to the governance progress towards an EAA globally. The main constraints to an EAA in Asia are sectoral integration, especially lack of consideration for social issues and governance (legislation, enforcement, compliance, and use of economic instruments). Implementation of an EAA in Asia is also slowed by the poor connections of aquaculture to the public, with very weak public participatory processes, less than optimal organization of research and development, especially at the commercial scale, and lack of active true partnerships between government/universities and industry participation in the R&D (and innovation) processes. There are few technological or scientific issues remaining to implement an EAA. This review finds that participatory processes, social sustainability, and poor governance hinders the widespread adoption of an ecosystem approach to aquaculture (EAA), which will require a much tighter coupling of science, policy, and management.

INTRODUCTION

Origins and nature of the ecosystem approach

More comprehensive planning for the future of aquaculture is needed to reorient the "blue revolution" since what is required is an "evolution", not a "revolution". This aquaculture evolution will be a modern, twenty-first century, knowledge-based process to pioneer the development of sustainable, ecologically integrated aquaculture systems that have positive impacts on both natural and social ecosystems (Costa-Pierce, 2002).

The FAO Fisheries and Aquaculture Department (2006) suggested a definition of an ecosystem approach to aquaculture (EAA) would: "strive to balance diverse societal objectives, by taking account of the knowledge and uncertainties of biotic, abiotic and human components of ecosystems including their interactions, flows and processes, and applying an integrated approach to aquaculture within ecologically and operationally meaningful boundaries. The purpose of EAA should be to plan, develop and manage the sector in a manner that addresses the multiple needs and desires of societies, without jeopardizing the options for future generations to benefit from the full range of goods and services provided by aquatic ecosystems." The Convention on Biological Diversity described an "ecosystem approach" to the management of land, water and living resources as matters of societal choice (UNEP, 2000).

BOX 1

All of the world's marine and terrestrial environmental challenges for the 21st century are colored by the explosive growth of the world's population. We live on a "human-dominated planet" where there are no wild areas on Earth yet untouched by humans (with the possible exception of the deep, mid-oceanic realm). The world's nature "reserves" and "wilderness" areas will lose their ecological integrity unless these ecosystems are managed by humans! As a result, for the first time in the history of our species the destiny of the Earth's natural ecosystems is in the hands of our scientific, political, and social institutions

Source: Costa-Pierce (2002)

At an FAO/UIB Workshop on EAA in Mallorca, Spain in 2007, an EAA was defined as: "A strategy for the integration of the activity within the wider ecosystem such that it promotes sustainable development, equity, and resilience of interlinked social-ecological systems".

"An ecosystem approach, like any system approach to management accounts for as complete range of stakeholders, spheres of influences and other interlinked processes. In the case of aquaculture, applying an ecosystem-based approach must involve physical, ecological, social and economic systems, in the planning for community development, also taking into account stakeholders in the wider social, economic and environmental contexts of aquaculture".

"This is essentially applying the ecosystem based management as proposed by CBD (UNEP/CBD/COP/5/23/ decision V/6, 103-106) to aquaculture and also following Code of Conduct for Responsible Fisheries (CCRF) indications".

GESAMP (2001) developed guidelines and tools for the planning and management of coastal aquaculture development. FAO Fisheries and Aquaculture Department (2006) suggested an EAA would have three main objectives: human well-being; ecological well-being and the ability to achieve both via effective governance, within a hierarchical framework that is scalable: farm level; regional level; and global level.

ECOSYSTEM APPROACH TO AQUACULTURE

Selected key issues from EAA principles

Soto *et al.* (2008) developed the following three principles and key issues of an EAA at the different scales.

Principle 1: Aquaculture should be developed in the context of ecosystem functions and services (including biodiversity) with no degradation of these beyond their resilience capacity.

Key issues

The key issue is to estimate resilience capacity or the limits to "acceptable environmental change". A range of terms has been used to estimate the limits to environmental change, including "environmental carrying capacity", "environmental capacity", "limits to ecosystem function", "ecosystem health", "ecosystem integrity", "fully functioning ecosystems", all of which are subject to a specific social/cultural/political context (Hambrey and Senior 2007). Soto *et al.* (2008) mentioned that "in the case of biodiversity, local declines may be acceptable (e.g. below fish cages) as long as such losses can be compensated and restored, at least at the waterbody scale, in order to preserve ecosystem function and services. For example, after a cage farm operation is halted it is expected that the relevant biodiversity recovers if there is enough "green infrastructure", that is conservation areas or more pristine areas to provide relevant colonization and restoration. Many environmental impact assessments will touch on these issues and yet the tools to address them are either not well developed or used; a promising one is that offered by risk assessment (Black, 2006). Relevant questions remain: How much biodiversity are we willing to loose?; at what scale levels?; at what costs?; and how are costs balanced with the benefits from aquaculture? On the other hand, aquaculture effects have to be seen in context by comparing them with those from other food producing sectors such as agriculture and livestock farming. Most terrestrial food producing systems, and especially intensive systems, have drastically transformed the landscape, e.g. cleared native forests and grasslands for agriculture, with permanent impacts on the original biodiversity; but we historically grew used to those impacts; however, intensive aquaculture is a new development worldwide. Efforts need to be made in order to permanently monitor aquaculture effects on biodiversity to make sure that such effects do not result in significant losses of ecosystem functions and services. In this respect values of ecosystem goods and services should be integrated into micro and macro environmental accounting."

Principle 2: Aquaculture should improve human-well being and equity for all relevant stakeholders.

Key issues
This principle seeks to ensure that aquaculture provides equal opportunities for development and its benefits are properly shared, and that it does not result in any detriment for any societal sector, especially for the poorest. It promotes both food security and safety as key components of well being" (Soto *et al*., 2008).

Principle 3: Aquaculture should be developed in the context of other sectors, policies and goals

Key issues
"This principle recognizes the interactions between aquaculture and the larger system, in particular, the influence of the surrounding natural and social environment on aquaculture practices and results. Aquaculture does not take place in isolation and in most cases is not the only human activity - often leading to a smaller impact on water bodies than other human activities e.g. agriculture and industry. This principle also acknowledges the opportunity of coupling aquaculture activities with other producing sectors in order to promote materials and energy recycling and better use of resources in general" (Soto *et al*., 2008).

Aquaculture sites are not only economic engines of primary production that meet the regulations of a society, but can be sites of innovation and pride if they can be well designed as community-based, farming ecosystems. A review of the progress towards such an ecosystems approach to aquaculture is necessary to inspire planners and environmental decision-makers at many societal scales (national, regional, local) to use new, innovative approaches. Sophisticated site planning of aquaculture can occur so that farms "fit with nature" and do not displace or disrupt invaluable natural, aquatic ecosystems or conservation areas; but also contribute to the local economy and society.

EAA principles at different scales/levels

Spatial scales
There are three physical scales of interest in this review regarding the planning for and assessment progress towards an ecosystem approach to marine aquaculture: farm scale, watershed/aquaculture zone, and global. This breakdown is indicative, since issues at each scale are overlapping and there are many important similarities amongst different scales but it helps illustrate potential differences and opportunities.

Farm scale
Planning for the farm scale is easily defined physically and could be few meters beyond the boundaries of farming structures; however, the increasing size and intensity of some farms (e.g. large scale shrimp farming or salmon farming) could affect a whole waterbody or watershed. Most research and development planning for an EAA has been conducted at this scale.

Assessment of an EAA at the farm scale entails an evaluation of planning and implementation of ecological, economic and social programs that account for the wider ecosystem and social impacts of farm-level aquaculture developments, including impact assessments, use of better management practices, and use of restoration, remediation, and mitigation methods. Proper site selection, attention to levels of production intensity, use of species (exotic vs. native), use of appropriate farming systems and technologies, and knowledge of economic and social impacts at the farm level should be considered.

Watersheds/aquaculture zone

Planning and assessment of progress towards an EAA for the waterbody and watershed scale, in the context of this marine aquaculture review, will address circumscribed coastal/marine areas as well as impacts on aquaculture zones/regions and watersheds, including impacts inland.

Planning for an EAA at watersheds/aquaculture zone level is relevant to social, economic and political issues, but there may be some common ecosystem issues; for example, diseases, seed and feeds trade, climatic and landscape conditions, etc. In practical terms, many issues and management issues are similar at the watershed and aquaculture zone, therefore these are considered together in the review.

A model for the practical implementation of EAA at this scale is in practice in Australia, where an Ecologically Sustainable Development (ESD) approach to aquaculture is being implemented (Fletcher *et al.*, 2004). The approach combines analytical and participatory methods and aims to achieve ecosystem and human well-being through effective governance.

Assessment of an EAA at this scale will assess aquaculture's inclusion as a part of governance frameworks, e.g. as a part of, or separate from, an overall framework of integrated coastal zone management or integrated land-water resource management planning and implementation. Assessment should consider regional issues such as escapees, disease transmission, contamination to/from aquaculture, and user competition/conflicts for land and water use. Social considerations at the regional scale would be, for example: aquaculture's role in rural development, comprehensive planning for the beneficial multiplier effects of aquaculture on jobs and the regional economy, and considerations of aquaculture's impacts on indigenous communities.

A watersheds/aquaculture zone ecosystem approach to aquaculture also needs to consider the governance of aquaculture developments, including existing scenarios and alternatives for human development. While an EAA should be the responsibility of a lead aquaculture agency, its full implementation will require government to consider alternative methods of governance and use innovative approaches so that agencies responsible for managing activities impacting aquatic ecosystems (e.g. capture fisheries, coastal zone development, watershed management organizations, agriculture, forestry and industrial developments) can regularly communicate, cooperate, and collaborate. The design of aquaculture management zones could be a relevant tool, particularly when the benefits of integrated aquaculture, polyculture or integrated aquaculture–fisheries initiatives are being considered.

Global

Planning for an EAA at a global scale considers aspects of transnational and multinational issues for global commodity products (e.g. salmon and shrimp). Assessment of progress towards an EAA at the global level entails evaluation of issues such as availability of agriculture and fisheries feedstocks for aquaculture feeds, and impacts on the broader marine ecosystem, economic and social impacts of aquaculture on fisheries and agriculture resources, and societies' infrastructure. Applications of tools such as lifecycle assessments of aquaculture commodities are useful at this level. Other relevant issues include impacts of aquaculture on markets, and impacts of globalization on social sustainability (social capital, goods and social opportunities); and the use or not of innovative social enterprise management guidelines and tools (Dees and Backman, 1994) in the aquaculture industry.

Indicators relevant to the EAA

Sustainability indicators for environmental and social issues in aquaculture are still in the early stages of development. Sustainability is an iterative process of improvement of management practices and procedures. Sustainability indicators must be able to detect the linkages between the 3Ps – people, profit, and planet. Hammond *et al.* (1995) questioned whether or not sustainability is a "bounded concept with measurable goals and objectives". Evaluations of an ecosystem approach to aquaculture (and evaluations of the "sustainability of aquaculture") cannot be defined in a stark black and white manner – labeling an aquaculture operation as "sustainable or not sustainable" adds little to the overall goal to make aquaculture compatible with the modern ecosystems and societies.

Useable indicators must be more than just a description of state and should have diagnostic properties that lead to some insights into the processes taking place, while also providing in-depth understanding of temporal and spatial variabilities. A European Union project titled, "Ecosystem Approach for Sustainable Aquaculture" (ECASA) is evaluating the ability of ecosystem indicators to discriminate between aquaculture and other anthropogenic sources of perturbation in the marine environment. Annual meetings with stakeholders are being held to allow two-way interactions ensuring the practical relevance of the work, and also to ensure that the "user community" has ownership of the project's outputs.

Objectives of the EU project are to:

- identify quantitative indicators of the effects of aquaculture on ecosystems through a process of expert working groups, workshops, and meetings;
- identify indicators of the main drivers of ecosystem change affecting aquaculture, including natural and environmental pressures;
- assess sets of indicators using existing datasets – project partners collectively have extensive data archives – considering each in the context of appropriate selection criteria;
- develop a range of tools, particularly models, that encapsulate understanding of best practices at a wide range of scales;
- test models and indicators in a wide variety of field locations across Europe (~10 locations) that encompass major cultured species and technologies, and covering a wide spectrum of environment types that were selected according to criteria developed during the project; and
- use the collected data to test and select the final tool kit of models and indicators, including appropriate decision support tools to guide users to effective implementation.

To date, ECASA has evaluated 53 indicators of ecosystem change and is conducting fieldwork to select the best environmental indicators in many ecological/ecosystem categories.

Bertollo (1998) expressed the concern that codes of conduct and guidelines for certifying sustainability in environmental management are much too complex. Along with concerns about too much complexity, there are concerns about the costs associated with monitoring multiple indicators that could be irrelevant to managers and the public. Pullin, Froese and Pauly (2001) suggested a simple set of easily quantifiable indicators for sustainability in aquaculture:

- Biological: domestication, trophic level, nutrient/energy conversion;
- Ecological: footprint, emissions, escapes;
- Intersectoral: water-sharing, diversity, cycling, stability, and capacity.

However, both the ECASA and Pullin, Froese, and Pauly (2001) approaches do not address social indicators important for charting progress towards an EAA.

The Delphi approach was started by the Rand Corporation in 1948 to develop strategy and forecasts during the Cold War (Sackman 1975; Schmidt 1997), and has been applied to a range of fields from agriculture (Walter and Reisner 1994) to fisheries (Zuboy 1981). Caffey *et al.* (2001) used a Delphi survey technique to develop sustainability indicators for aquaculture in the southeastern United States of America. This study yielded 31 indicators of aquaculture sustainability: 12 environmental, ten economic, and nine social indicators. Respondents identified two paramount environmental indicators: resource use and pollution. Resource use indicators included: conservation of land, energy, protein, water, and wetlands. Pollution (considered an "environmental externality") indicators included: reduction of chemical use, effluent BOD control, controls of ammonia-nitrogen, phosphorus, suspended solids, and use of non-native species in aquaculture. Top economic indicators were profitability, risk, efficiency, and marketing issues. Social indicators of top importance were job availability, compensation rates, benefits, and worker safety.

The European Commission (EC) presented in 2002 a report to the European Parliament on a strategy for the sustainable development of European aquaculture with the aim of creating conditions to ensure, environmental, economic and social sustainability by:

- creating secure employment focusing upon a number of different initiatives designed to increased production, tackle competition for space, stimulate the market, consider social considerations and improving governance;
- promoting safety of aquaculture products and animal welfare to ensure high standards for public health, animal health and animal welfare; and
- reducing the impacts of wastes, tackling the risk from alien species and genetically modified organisms, pollution prevention and control, environmental impact assessment, and promoting research.

This EC strategy has been designed to ensure greater biodiversity protection and has taken the form of proposals to regulate the introduction of non-native species in aquaculture.

REVIEW OF PROGRESS TOWARDS AN EAA

This global review is a "research and development progress" assessment towards an ecosystem approach to aquaculture (EAA). This assessment is developed using the three principles and levels described above and assembled in a table format. The perspective of this review is global, as a result, and at a glance, the reader can review key examples of ecosystem-based approaches in order to assess progress towards an EAA implementation for the world's major and emerging marine aquaculture commodities. This analysis is done in three steps as a global review of research and development progress: first, at the farm level; second for molluscs and shrimp - where substantial industrial/commercial progress has been made towards an EAA; lastly, for the world's major farmed finfish.

> BOX 2
>
> An ecosystem approach to aquaculture should maximize not only economic but also environmental and social profit.

Farm scale

Selected/key references on research and development projects at the farm level using an EAA are summarized in Tables 1 and 2. This summary represents a compilation of key technologies and management approaches of important mitigation strategies that can be applied to existing farms.

At the farm level, numerous research and pilot scale commercial initiatives have documented a comprehensive ecological approach to aquaculture, water-based, and land-based aquaculture systems developed and operated using an EAA are summarized in Tables 1 and 2 respectively. The available literature clearly indicates that merger of multiple trophic levels can provide waste treatment, nutrient and solids remediation, and higher economic benefits, as found some 25 years ago by Shang and Costa-Pierce (1983). Systems are very diverse, and comprise combinations of species both within and outside of the systems in which the target culture species grown. These studies also show that a merger of diverse technologies will require much more management attention than monoculture systems, necessitating the need to develop new strategies and incentives to decrease costs and expand the use of ecological approaches on existing

TABLE 1
Descriptions of land-based marine aquaculture systems developed and operated using an EAA

Ecosystem Descriptions	Ecosystem Impacts	References
Shrimp-Shellfish Combinations Integration of shrimp, oysters and *Gracilaria edulis*	Laboratory study demonstrated that integrated treatment in 3 stage system with: (1) sedimentation; (2) oysters and (3) seaweed significantly improved water quality of shrimp farm effluents	Jones, Dennison, and Preston (2001)
Integration of shrimp and oysters	Oysters increased total economic yields and increased ecological efficiencies	Wang (1990)
Integration of shrimp and bay scallops	Bay scallops grew quickly in shrimp pond waters at intermediate densities	Walker *et al*. (1991)
Shrimp- Shellfish-Fish Combinations		
Shrimp with mullet and oysters	4-ha modular shrimp system produced 40 t whole shrimp, 7 t mullet, 0.5 mil oysters/year	Sandifer and Hopkins (1996)
Shrimp-Plant (Seaweeds and Mangroves) Combinations		
Integration of shrimp and *Ulva pertusa*	Water quality improved but economics questionable	Danakusumah, Kadowaki, and Hirata (1991)
Integration of shrimp and Gracilaria	Improvements in systems economics	Nelson *et al*. (2001); Phang *et al*. (1996)
Shrimp and mangroves	Devoting 30-50% of shrimp pond area to mangroves gave highest annual economic returns	Binh, Phillips and Demaine (1997)
Shrimp-Seaweed-Shellfish		
Shrimp integrated with oysters and seaweed (*Gracilaria*)		Jones, Dennison, and Preston (2001)
Fish-Seaweed Combinations		
Seabream culture with Ulva	Improved water conservation and water quality of discharged water, and improved economic yields	Jimenez del Rio, Ramazanov, and Garcıa-Reina (1996); Neori, Cohen, and Gordin (1991); Neori *et al*. (1993, 1996);
Salmon culture with Gracilaria, Laminaria	Nutrient absorption by seaweeds may lead to improvements in water quality	Buschmann *et al*. (1994, 1996); Martinez and Buschmann (1996)
Integration of salmon and Gracilaria	Integration improved water quality in the systems and the effluents, with increased economic yields	Buschmann *et al*. (1994, 1996); Troell *et al*. (1997); Troell, Kautsky, and Folke (1999)
Fish-Shellfish Combinations		
Tubot, seabass, sole and bivalves (clams, oysters)	Higher economic yields achieved experiementally	Jara-Jara *et al*. (1997); Lefebvre *et al*. (2000)
Fish-Shellfish-Seaweed Combinations		
Seabream, bivalves (Crassostrea gigas, Tapes semidecussatus, *Haliotis tuberculata*) and seaweeds (*Ulva lactuca*, Gracilaria)	Improvements in whole system productivity, economics, but higher capital and marketing costs	Shpigel *et al*. (1993, 1996); Neori (1996); Neori, Ragg, and Shpigel (1998); Shpigel and Neori (1996)
Integration of seabream and Ulva fed to abalone	Production of 22 kg of seabream, 64 kg of Ulva & 10 kg of abalone per m^2 per year	Neori *et al.* (2004)
Fish-Shellfish-Urchin-Seaweed Combination		
Fish, oysters, sea urchins and seaweeds	Incorporation of urchins not promising	Chow *et al*. (2001)

farms. In addition, studies show a marked lack of multidisciplinary scholarship - e.g. there is a lack of reporting on social impacts – or planning for social benefits – in the vast majority of the R&D studies.

Molluscs and shrimp

Over the past 10 years, substantial industrial/commercial progress has been made towards an EAA for molluscs and shrimps. Tables 3 and 4 chart the trajectory of these commodities towards an ecosystem approach to aquaculture, and try to capture the “innovation portfolio” in these industries.

There has been much progress towards an ecosystem approach to mollusc aquaculture over the past 10 years (Table 3). These advances are apparent not only technologically (e.g., for example, the development of submerged culture systems),

TABLE 2

Descriptions of water-based marine/coastal aquaculture systems developed and operated using an EAA

Ecosystem Descriptions	Ecosystem Impacts	References
Fish-Fish Species Combinations		
Integration of grey mullet confined in bottom cages underneath commercial seabream cages	Grey mullet reduced organic matter accumulations and oxidized bottom sediments	Angel *et al*. (1992)
Fish-Molluscan Shellfish Species Combinations		
Integration of blue mussels with salmon cage aquaculture	Blue mussels grew well on salmon detrital matter; economic potential demonstrated.	Folke and Kautsky (1989, 1992); Kautsky, Troell, and Folke (1997); Troell *et al*. (1997); Troell, Kautsky, and Folke (1999)
Scallops (*Pattinopectin yessoensis*) and oysters (*Crassostrea gigas*) with salmon cage aquaculture	Preliminary results show higher economic potentials with integration	Cross (2004)
Fish-Seaweed Species Combinations		
Cultivation of seaweeds (*Laminaria saccharina, Nereocystis luetkeana, Gracilaria* spp., *Porphyra* spp.) with salmon cage aquaculture	Demonstration of improvements in water quality parameters and economics with increased management and marketing expertise needed	Ahn, Petrell, and Harrisin (1998); Buschmann *et al*. (1994a,b, 1995, 1996, 2001); Chopin *et al*. (1999, 2001); Chung *et al*. (2002); Petrell and Alie (1996)
Fish-Other Invertebrate Species Combinations		
Sea cucumbers underneath fish cages	Sea cucumbers grew well, but questions about product quality	Ahlgren (1998)

TABLE 3

Trajectories towards an ecosystem approach to aquaculture: the innovation portfolio in molluscan aquaculture

Development Concerns	Negative Impacts on Natural and Social Ecosystems Goods and Services	Principle 1: Ecosystems	Principle 2: Society	Principle 3: Sectoral Integration
Massive, floating and vertical arrays in nearshore areas	Localized depletion of food (phytoplankton). Excessive benthic loadings from feces resulting in anoxia and habitat losses[1]	**Farm:** Limit biomass/ha to below pelagic/benthic carrying capacities; informed by carrying capacity research and the precautionary approach[2] **Region:** Shellfish aquaculture returns vital ecosystem functions to marine bays lost by development[3]	**Farm:** Most farms are small, owner operated with large societal benefits[4] **Global:** Increased R&D field and lab investments worldwide demonstrate shellfish arrays benefit water quality, establish new habitats, and benefits marine restoration[5]	**Farm:** Farmer adoptions of regulatory controls to limit spread of diseases and limit introductions of non-native species **Region:** Government regulations to control and limit spread of diseases and to limit introductions of non-native species[6] New conflict resolution and decision-support systems developed for officials[7] Shellfish aquaculture benefits weighed in a nutrient trading scheme[8]

[1] Alvarez-Salgado (1996); Kaiser *et al.* (1998); Cranford *et al*. (2003); Crawford, Macleod, and Mitchell (2003)
[2] Grant *et al*. (1995); Heral (1993); Gibbs (2004); Jiang and Gibbs (2005); McKindsey *et al*. (2006)
[3] Ruesink *et al.* (2006)
[4] Environmental Defense (1997)
[5] DeAlteris, Kilpatrick, and Rheault (2004); Deslous-Paoli *et al*. (1998); Han Jie *et al*. (2001); Newell (1998, 2004); Newell, Cornwell, and Owens (2002); Peterson and Heck (1999, 2001); Ragnarsson and Raffaelli (1999); Tallman and Forrester (2007)
[6] Crawford (2003); U.S. Army Corps of Engineers (2007) stated that "Commercial shellfish operations do not have more than minimal adverse impacts on the aquatic environment and contribute benefits to the ecosystem that balance any adverse impact. Since shellfish improve water quality and increase food production, we believe that there is generally a net increase in aquatic resource functions in estuaries and bays where shellfish are produced." Federal Register 72(47): 11144-11147.
[7] Hamouda, Hipel, and Kilgour (2004)
[8] Lindahl *et al*. (2005)

but also socially and politically where mollusc aquaculture is now being promoted by communities and policy-makers not only for its productive capacity and potential economic benefits, but also for its beneficial impacts on water quality, essential fish habitats, and social benefits in fishing communities (Table 3).

There is much less progress globally towards an EAA in shrimp aquaculture (Table 4). The FAO/WWF international guidelines for shrimp aquaculture are a

TABLE 4
Trajectories towards an ecosystem approach to aquaculture: innovation portfolio in shrimp aquaculture

Development Concerns	Negative Impacts on Natural and Social Ecosystems Goods and Services	Principle 1: Ecosystems	Principle 2: Society	Principle 3: Sectoral Integration
Massive destruction of mangrove ecosystems; discharge of polluted waters into coastal ecosystems; negative groundwater impacts; bycatch of juvenile finfish in collection of shrimp post-larvae (PLs); transfer and spread of shrimp diseases; introduction of exotic species	Loss of valuable coastal buffer strips for storm protection; loss of coastal biodiversity and nursery areas; localized depletion of coastal finfish juveniles; displacement of traditional livelihoods in coastal communities and associated social capital[1]	**Farm:** Limit stocking densities; use native species; zero discharge/ recycling pond and tank systems; widespread use of small-scale and regional hatcheries; use of specific pathogen free broodstock and better disease/stock management and PLs[2] **Region:** Regional hatcheries **Global:** Use of innovative pond management to reduce feed costs; development of alternative, detrital-based and low fish meal based feeds[3]	**Farm:** Thailand and Vietnam assist smaller, owner-operated farms with low costs loans and credit programs that have larger societal benefits than multi-national, corporate farms[4] **Region:** Better planning for localization of hatchery, feed and infrastructure needs that maximize societal benefits[5]	**Farm:** Farmer adoptions of regulatory controls and better management practices to limit spread of diseases and limit introductions[6] **Region:** Government regulations to control clearing of mangroves and to limit spread of diseases and introductions of non-native species **Global:** International conventions on better practices on farm sitting, mangrove preservation/ restoration, farm design, water use, broodstock, PLs, feed, health management, food safety and social responsibility adopted in global partnership[7]

[1] Widely known and abundant literature well summarized in the 1997-2000 FAO Consultations on Policies for Sustainable Shrimp Culture (n.d.); The Shrimp Farming and Environment Consortium of FAO/NACA/UNEP/World Bank/WWF (n.d.); Larsson, Folke, and Kautsky (1994); Gammage (1997); FAO (1998); World Bank (1998); Tacon (2002)
[2] Rönnbäck (2002); Balasubramanian, Pillai and Ravichandran (2005); Lightner (2005); Moss, Doyle. and Lightner (2005); Moss *et al.* (2005); Arnold *et al.* (2006); Amaya, Davis and Rouse (2007)
[3] Tacon (2002); Burford *et al*. (2004); Amaya, Davis and Rouse (2007)
[4] SAPA (2000); Hall (2003); Nguyen, Momtaz and Zimmerman (n.d.)
[5] Barg *et al.* (1999)
[6] Boyd, Hargreaves and Clay(2003); Haws and Boyd (2005)
[7] FAO/NACA/UNEP/World Bank/WWF. 2006. International Principles for Responsible Shrimp Farming. Network of Aquaculture Centres in Asia-Pacific (NACA). Bangkok, Thailand. 20 pp.

major step forward in principle, but less so in practice. However, the few examples of commercial shrimp aquaculture using an EAA that do exist point the way for commercial success.

Salmon and other marine finfish

Next, analysis of progress towards an EAA is accomplished for the world's major farmed finfish products – salmon and other marine finfish – in selected aquaculture countries is accomplished, identifying main barriers to implementation of an EAA, and some recommended actions (Tables 5 and 6). For each of these analyses, data are collected on each of the three EAA principles at the farm, watersheds/aquaculture zone and global levels.

Analysis of progress towards an EAA for salmon and other marine finfish in the selected major aquaculture farming countries indicates that technology is not the main barrier to implementation of an EAA; rather, lack of demonstration of economically viable alternative systems at the commercial level, lack of markets for alternative products from polyculture systems; and poor planning for the social multiplier effects of aquaculture are limiting factors (Tables 5 and 6). The few commercial-scale ecological aquaculture farms are in Asia and the Mediterranean Sea region where integration is easier to develop from historically profitable, community-based extensive systems that exist, such as the integration of shrimp, molluscs and seaweeds in coastal lagoons in Southeast Asia and China and the "valliculture" system in southern Europe. However, many of these systems are under great threat from coastal development and pollution.

TABLE 5
Analysis of progress towards an ecosystems approach to aquaculture for selected aquaculture commodities in major aquaculture farming centers: salmon (*salmo salar*) in marine cages

Major Nations and Status	Principle 1: Ecosystems	Principle 2: Society	Principle 3: Sectoral Integration	Main Barriers to Implementing an EAA	Recommended Actions
Norway 582 043 tonnes; ~3 700 jobs	**Farm:** Open water cage systems have localized benthic impacts; high technology and monitoring systems in place; antibiotic use down 98% from 1987, use of cleaner wrasse widespread for lice treatment **Regional:** MOM system for assessment informed by research on interactions of cage operations in a waterbody[1]; establishment of protected areas for wild salmon, fish farms to move out of these places by 2011[1] **Global:** A global leader in marine protein and oils substitution in feeds[4]	**Farm:** EU farm labour, benefit, wage, and health standards **Waterbody:** Some planning for ameliorating user conflicts	**Farm:** Norwegian regulations on cage sitting, production[1] **Waterbody:** Government oversight, legal and regulatory framework, industry compliance and enforcement on cage locations, numbers, production[1]; Mandatory disease monitoring and control actions[3] **Global:** Concerns about Norwegian salmon companies as multi-nationals in Chile	User conflicts; adverse impacts of cultured salmon on wild salmon runs/stocks[3]	Additional research needed on carrying capacity and hydrodynamics[2]; Ameliorate impacts of cultured salmon on wild salmon runs/stocks that are at risk[3]
Chile 374 387 tonnes; ~35 000 jobs	**Farm:** Open water cage systems have localized benthic impacts; high technology used **Waterbody:** Cages are densely located, so open water systems can have cumulative nutrient impacts; benthic impacts well documented **Global:** Increasing concerns about costs and availabilities of fish feeds[8]	**Farm:** No uniform farm labour, benefit, wage and health standards **Waterbody:** No local planning for ameliorating user and NGO conflicts; international mediation through the WWF Salmon Aquaculture Dialog **Regional**: Worker strikes at several salmon factories in 2006[6]; Impacts on regional labour markets unknown	**Farm:** Adequte legal and regulatory framework[5] **Waterbody:** Poor compliance and enforcement on expansion and location, cage locations, numbers, production, and wastes **Global:** Societal concerns over expansion into ecologically sensitive southern region XII	Strong legal framework, but poor compliance and enforcement; low level and poor organization of institutional research capacity to inform decision-makers of aquaculture and environmental interactions and solutions[7]	Improved compliance and enforcement of areal extent, carrying capacities, expansion into sensitive ecosystems, and environmental remediation
UK (Scotland) 129 823 tonnes	**Farm:** Open water cage systems have localized benthic impacts; high technology and monitoring accomplished **Regional:** Scottish Environmental Protection Agency (SEPA) regulates and monitors impacts of industry[10]; Poor protection for wild stocks and disease outbreaks[3]	**Farm:** EU farm labour, benefit, wage and health standards **Waterbody:** Innovative SEPA planning for ameliorating visual impacts **Regional:** Impacts on regional labour markets known	**Farm:** EU farm labour, benefit, wage and health standards **Waterbody:** Area Management Agreements to integrate aquaculture, fisheries and regulations on sea lice **Regional/Industry:** Strategic Framework for Scottish Aquaculture[9]; Salmon producers develop and adhere to Code of Good Practice for Scottish Finfish Aquaculture	Poor protection for wild stocks and disease outbreaks[3]; Strong opposition by WWF Scotland, Salmon Farm Protest Group who favour land-based containment systems	Ameliorate impacts of cultured salmon on wild salmon runs/stocks that are at risk; Accelerate research on economically-viable land-based containment systems

TABLE 5 (Continued)

Analysis of progress towards an ecosystems approach to aquaculture for selected aquaculture commodities in major aquaculture farming centers: salmon (*salmo salar*) in marine cages

Major Nations and Status	Principle 1: Ecosystems	Principle 2: Society	Principle 3: Sectoral Integration	Main Barriers to Implementing an EAA	Recommended Actions
Canada 83 653 tonnes	**Farm:** Much research on environmental interactions of open water cage systems[12]; high technology and monitoring accomplished **Waterbody:** Lease system grants three sites for one lease for complete year class segregation, decreases disease transfers **Regional:** Limited sites and high density of farms in New Brunswick (NB)[3]; Concerns over invasive species in BC **Global**: New developments on little studied south coast of Newfoundland; Impacts of rapid climate change	**Farm:** High Canadian farm labour, benefit, wage and health standards **Regional:** Significant positive impacts on regional labour markets, esp. in Charlotte County, N.B.	**Waterbody:** Diseases (ISA, BKD, Furunculosis) major concerns but practices and procedures excellent[3]; Heavy use of Slice to control sea lice and concerns about resistance[12]; Tight regulations on cage locations, numbers, production **Regional:** Fisheries and Oceans Canada and Provinces oversee aquaculture and have rigorous approval, monitoring programs such as Aquaculture Bay Management Areas and Bay Management Agreements and Marine Fish Health	None, recent Canadian US$70 million for government aquaculture support, environmental impacts and remediation aspects	Implementation of integrated multitrophic aquaculture to ameliorate environmental impacts since new NB research shows sensitivity of NB environment and farms impacting environment on scales of sq. km, possibly due to high feed wastes[14]

[1] FIRI (2004); Stigebrandt *et al*. (2004)
[2] Stigebrandt *et al*. (2004); Olsen (2007)
[3] Porter (2005)
[4] Tacon (2005); Holm *et al*. (2003)
[5] Subpesca (2003); D'Andrea, 2005)
[6] Fishupdate.com (2006) reports that strikers demanded better safety, health benefits and higher wages. Carvajal (2007) and PDM (2001) cites diver safety, insurance, poor sanitation, and lack of drinking water for workers.
[7] Buschmann *et al*. (2006)
[8] Carvajal (2006); Tacon (2005)
[9] Scottish Executive (2003)
[10] SEPA (2000)
[11] Huntington (2004)
[12] Westcott, Hammell, and Burka (2004)
[13] GNB (2007); NBSGA (2004); DFO (2002)
[14] Hargrave (2005)
[14] Strain and Hargrave (2005)

TABLE 6

Analysis of progress towards an ecosystems approach to aquaculture for selected aquaculture commodities in major aquaculture farming centers: other marine finfish (many spp.[1]) in coastal ponds and cages

Major Nations, Status, Systems (2005)	Principle 1: Ecosystems	Principle 2: Society	Principle 3: Sectoral Integration	Main Barriers to EAA	Recommended Actions
China 588 060 tonnes total from ponds and coastal cages (est. 287,301 tonnes; 1 million cages)[2]	**Farm:** Advances: integrated farming ; fish & mussels being practiced in coastal zones Problems: Use of wild caught juveniles and trash fish in cage aquaculture **Regional:** Problems: Environmental pollution from cage farms a serious problem; economic/social equity and worker justice issues[3,4] **Global:** Overfished marine systems provide trash fish for cages/ponds[2]	**Farm:** Few internationally recognized labour standards; human wastes from vast floating fish culture sites (Shenao Village on the Sea)[2]	**Regional:** Little regional planning for aquaculture's beneficial multiplier effects **Global:** Global concern over China's increasing demands of fish meals/oils; as a direct result of environmental pollution, increasing global concern for food safety and environmental contaminants	Aquaculture in open cages where large discharges of societal wastes have deteriorated coastal water quality and caused HABs threatening aquaculture[4] Lack of compliance and enforcement of regulations Lack of monitoring and regulation for aquaculture zones or regions Lack of understanding and valuation of ecosystem services Population and economic growth and continuous pressure on economic resources	Need for comprehensive control plus management strategy[2] Enforce compliance of environmental laws and regulations Improve site selection and zoning using Geographic Information Systems Development of coastal hatcheries Development of fishmeal replacements in fish feeds[5] Speed the integration of seaweeds into finfish and mollusk cultivation, as occurs in North China[6]
Vietnam 374 387 MT, mostly freshwater cage culture, but a growing amount of grouper, snapper and cobia culture	**Farm:** About 70 % of grouper production relies on wild fish juveniles for stocking and trash fish for feeds[7] **Region:** Groupers and snappers are used as stocking materials (fry and juveniles) are heavily overfished in nearshore areas	**Farm:** Few internationally recognized labour standards **Regional:** Little regional planning for aquaculture's beneficial multiplier effects	**Global:** Global concern over Vietnam's increasing demands of fish meals/oils; as a direct result of environmental pollution, increasing global concern for food safety and environmental contaminants	Aquaculture in open cages where large discharges of societal wastes have deteriorated coastal water quality[8] Lack of compliance and enforcement of regulations	Grouper culture is expanding rapidly, driven by high prices in the live fish markets of Hong Kong SAR and China
Japan 268 921 tonnes from cages	**Farm:** Open water cage systems for yellowtail have localized benthic impacts; high technology and monitoring systems in place[8]	**Farm:** High farm labour, benefit, wage, and health standards **Waterbody:** Widespread planning for ameliorating user conflicts	**Waterbody:** Government oversight, legal and regulatory framework, industry compliance and enforcement on cage locations, numbers, production; Mandatory disease monitoring and control actions	None, Japan has potential for widespread adoption of an EAA	
Philippines 129 823 tonnes from cages; milkfish est. 161 426 tonnes from ponds, and some cages and pens	**Farm:** Milkfish based on wild fry with some hatchery-production and systems under development[9] **Region:** Milkfish, groupers and snappers are used as stocking materials (fry and juveniles) are heavily overfished in nearshore areas **Global:** Milkfish based on cultivated algae; some development of semi-intensive culture and use of low protein formulated feeds	**Farm:** Few internationally recognized labour standards **Regional:** Little regional planning for aquaculture's beneficial multiplier effects	**Region:** Fry/fingerlings trade with Indonesia is concern to nearshore ecosystems in that nation due to high juvenile finfish bycatch **Global:** Milkfish feeds on cultivated algae, little pressure on global fish meals/oils	Large discharges of societal wastes have deteriorated coastal water quality and caused HABs threatening aquaculture[10] Use of wild caught juveniles and trash fish in cage aquaculture Lack of compliance and enforcement of regulations	Milkfish broodstock genetic management and assurance of fry quality are needed[11] Examination of the production, market and policy structures of the milkfish industry are required[11] Assessment of the economic efficiency of the commercial milkfish and grouper hatcheries and grow-out systems will provide guidance on how to improve and enhance broodstock and fry industries and reduce dependence on imports[11]

TABLE 6 (Continued)

Analysis of progress towards an ecosystems approach to aquaculture for selected aquaculture commodities in major aquaculture farming centers: other marine finfish (many spp.[1]) in coastal ponds and cages

Major Nations, Status, Systems (2005)	Principle 1: Ecosystems	Principle 2: Society	Principle 3: Sectoral Integration	Main Barriers to EAA	Recommended Actions
Indonesia 83 653 tonnes from cages, principally groupers and snappers	**Farm:** Wild caught juveniles and trash fish are used, while hatchery techniques and formulated feeds are well known since the mid-1980's and were once uneconomic, but that has changed towards profitability in 2004, esp. in Bali where there are hundreds of small-scale hatcheries[12] **Region:** Stocking materials (fry and juveniles) are heavily overfished in nearshore areas but hatchery development has largely replaced wild sources	**Farm:** Few internationally recognized labour standards **Regional:** Little regional planning for aquaculture's beneficial multiplier effects		Large discharges of societal wastes have deteriorated coastal water quality and caused HABs threatening coastal aquaculture Lack of compliance and enforcement of regulations	Enforce compliance of environmental laws and regulations Better site selection and zoning Accelerated development of coastal hatcheries Development of fishmeal replacements in fish feeds Speed the integration of seaweeds into finfish and mollusk cultivation (IMTA, IAA) as occurs on small-scale in many provinces
Greece 76 577 tonnes mostly from cages	**Farm:** Area under cage cultivation of sebass/bream and other species stable[13] **Regional:** Little evidence of adverse impacts, esp. pollution from cages[13]	**Regional:** Employment in mariculture was 2,910 15% female) in 1997[14]		Little/no R&D in marine systems integration (e.g. IAA or IMTA)	Development, compliance and enforcement of better management practices Zoning to better plan for future growth
Turkey 68 173 tonnes mostly from cages	**Farm:** Area under cage cultivation of seabass/bream and other marine species growing[15] **Global:** Turkey produces about 10,000 tonnes/y of fish meal, and imports about 25,000 MT from Chile and Peru, and is self-sufficient in fish oil with about 2000 tonnes/y[15]	**Regional:** Estimated that more than 5,000 mariculture employees[15] Secondary support services (feed, equipment, consultancies, etc.) developing rapidly, but largely unplanned for	**Regional:** Ministry of Agriculture and Rural Affairs regulates aquaculture, but overlapping jurisdiction between authorities, estimated involvement of 11 ministries	Little/no R&D in marine systems integration (e.g. IAA or IMTA)	Streamlining governance Development, compliance and enforcement of better management practices Zoning to better plan for future growth

[1] Main species are: Japanese amberjack, Red seabream, Yellow croaker, European seabass, Gilthead seabream, Cobia, Snappers, Groupers, Barramundi (Asian seabass), Mullet and Milkfish (*Chanos chanos*).
[2] Feng *et al*. (2004; Chen *et al.* (2007)
[3] Lam (1990); Liu and Liu (2001); Duqi and Minjie (2006); Honghui *et al*. (2006); Xiao, Shaobo, and Shenyun (2006); Chen *et al.* (2007)
[4] Qian, Wu, and Ni (2001); Chen *et al.* (2007)
[5] Zhou *et al*. (2005); Chen *et al*. (2007)
[6] Fei, Bao, and Lu (1999); Chen *et al.* (2007)
[7] Halwart, Soto, and Arthur (2007)
[8] Pillay and Kutty (1998)
[9] Tanaka *et al.* (1990)
[10] Halwart, Soto, and Arthur (2007)
[11] World Fish Center (2006)
[12] Tookwinas (1989); (P. Edwards, personal communication, 2008)
[13] Klaoudatos (1998)
[14] MacAlister Elliott and Partners Ltd. (1999)
[15] Okumus (2003)

PRIORITY NEEDS FOR AN EAA

Farm scale

Social sustainability

The social benefits associated with the development of an EAA to marine aquaculture include: (1) increasing aquaculture opportunities in coastal areas with many user conflicts; (2) increasing aquaculture development opportunities in remote coastal regions constrained by logistical challenges; (3) economic diversification of coastal communities to develop more diverse secondary industry support systems; and (4) improving public approval of aquaculture, and aquaculture "environmental accountability".

The notion of social sustainability has been discussed by McKenzie (2004), who states that social sustainability occurs when formal and informal processes, systems, structures and relationships actively support the capacity of current and future generations to create healthy and livable communities. Socially sustainable communities are equitable, diverse, connected and democratic, and provide a good quality of life. Principles by which social sustainability may be achieved according to McKenzie (2004) are:

1. Equity: the community provides equal opportunities and outcomes for all its members; particularly the poorest and most vulnerable (equal opportunity for all community members; equity for indigenous people; equity in relation to human rights). In general, there is equity in relation to disadvantaged members of a community.
2. Diversity: the community promotes and encourages many points of view to develop a broader vision.
3. Interconnectedness: the community provides processes, systems and structures that promote connectedness within and outside the community at the formal, informal and institutional level.
4. Quality of life: the community ensures that basic needs are met and fosters a good quality of life for all members at the individual, group, and community levels.
5. Democracy and governance: the community provides democratic processes, and open and accountable governance structures.

Farmed salmon in rural New Brunswick, Canada earns an estimated US$200 million annually, with significant benefits to society from rural employment income, much of what is valuable, full-time time employment income, and tax revenues which have led to a clear revitalization of a large, rural, coastal county where there are few alternative employment opportunities. The salmon industry employs about 1 700 people directly and 2 900 indirectly (Stewart, 2001). In contrast, Barrett *et al.* (2002) reported that while salmon farming in the X and XI regions of Chile had created about 30 000 rural jobs, but that the poor had been socially dislocated and marginalized, and that the fish processing work created by salmon aquaculture was transient. Others debate these findings. However, the lack of studies in this area points out the priority need for social monitoring systems; and the need for regular reviews as to obtain accurate social data on the social impacts of aquaculture.

Stakeholder engagement

Technical innovations alone are inadequate to direct the sustainability trajectory of complex, knowledge-based farming enterprises such as aquaculture. What is needed is an improved, multi-disciplinary, and much more participatory aquaculture research processes tightly connected to informed aquaculture extension approaches.

Pioneering agriculture research in agroecology and agroecosystems, and the increasingly widespread use of farming systems and participatory technology development (PTD) frameworks have led to many recent innovations in sustainable and

BOX 3

PTD approaches are needed because:

1. What works in one place, time and circumstance will not necessarily work in another,
2. What suits one farmer may not suit another with different ideas and constraints,
3. The complexity of a farming situation and livelihoods affects the adoption of interventions,
4. The message-based approach is the least effective teaching method.

Source: Scarborough *et al.* (1997)

BOX 4

Adoption of innovations is a three-step process.

1. Evolutionary Learning: step-by-step, cumulative participatory learning by stakeholders,
2. Multiple Perspectives: many ways of describing a situation,
3. Iterative Group Learning. the complexity of the world can only be learned by an iterative process of group inquiry and learning.

Source: Pretty (1995)

organic agriculture and attention to the importance of local food production in many developed nations. In the developing countries, PTD has created a valuable information basis for innovative "farmer first" extension and outreach methodologies. These "engagement innovations" have provided a road map for engaging farmers to plan and implement a participatory, ecosystem approach to aquaculture that could evolve more sustainable aquaculture farming ecosystems.

The approach is to use the wisdom of ecology and its underlying principles of hierarchies, complementarity, redundancy, cycling, and diversity to not only meet environmental goals, but also to improve farmer livelihoods by increasing whole farm efficiencies and product values. PTD seeks to demonstrate that the complementarity of systems and enhancement of recycling pathways of farm resources will lead to greater resource efficiencies, long-term sustainability, and environmental protection (Lightfoot, 1990).

Farmers are skilled innovators who have developed ways of experimenting through trial and error. Farmers know best about their own ecosystems, and their social and economic realities. Trust must be built up with farmers by respecting local values and working together in the spirit of equality.

For research scientists this can be a challenge—and a revelation—since they have to reorient their world views about the meaning of knowledge, science, the economy, gender roles and relations, communities and the required methodologies needed in order to get buy-in to a participatory research and learning process. In participatory technology development (PTD), farmers can design and experiment using strategies they have developed themselves which they feel are appropriate to conditions they experience on their own farms. Such participatory experimentation promotes empowerment and accountability. These processes lead to institution building, market reforms, and the farmer-based advocacy needed to secure policy reforms and rural economic development (Veldhuizen, 1998).

The principal idea behind a PTD framework is that farmers have to involved in the process of technology research development and dissemination from the outset. Instead of scientists developing one fixed set of techniques in isolation on a research station then disseminating them as a "technology package" to farmers, ideas from farmers are elicited first; then researchers and farmers work to perfect technologies that suit the farming systems of the target group. Farmers take part in the technological identification, research and development and extension processes from the outset of the process in contrast to being a passive recipient of innovative technologies developed elsewhere. Farmers can comment on and criticize as much as they want; they can test new technologies on their own farms or at research stations; and they can modify technologies if they think necessary as long as the process of technological modifications/innovations is monitored and recorded.

With the PTD framework, responsibility for adopting a new technology rests entirely with the farmer. The farmer decides whether or not to try a new technology on the farm. Farmer refusal to implement a technology is an important signal to the research or extension worker that something is wrong. Farmers do not receive any financial assistance or other subsidies besides information and engagement by the research and extension workers, and are not in a dependent position. The relationship between farmers, extension agents and researchers is more on an equal footing.

Another characteristic of the PTD approach is that the responsibility for adopting a new technology rests entirely with the farmer. The farmer decides whether or not to try a new technology on the farm. Farmer refusal to implement a technology is an important signal to the research or extension worker that something is wrong. Farmers do not receive any financial assistance or other subsidies besides information and engagement by the research and extension workers, and are not in a dependent position. The relationship between farmers, extension agents and researchers is more on an equal footing.

Economics benefits

The economic benefits of an EAA are based on evaluations of not only opportunity, but of economic risks in terms of associated capital/operational costs, performance certainties, impact and integration of multiple products to existing markets and sales pathways, additional management and personnel requirements, differential/fluctuating component species pricing, and profitability. The widespread commercial development of an EAA by industry has not yet occurred most likely due to a number of these business uncertainties. The remaining challenges facing future research and development of an EAA include initiatives that will address the practical aspects of commercial-scale facilities so that results can be assessed at that scale by the investment and corporate community, and the true development risks quantified and analyzed. The economic benefits offered by the commercial development of an EAA will need to be evaluated using factors that contribute directly to the cost-effectiveness of these aquaculture systems over current monoculture approaches; such evaluations will have important implications to EAA system design and engineering. For example, Neori, Shpigel, and Ben-Ezra (2000) indicated that a farm producing 1,000 tonnes/year of seabream would need around 15 ha of Ulva and 7 ha of tanks supporting the production of 660 tonnes of abalone. Comparable pilot scale experiments in southern France (Deviller *et al*., 2004) were not as successful, since seaweed growth was lower due to seasonal variations.

In more northerly regions, phytoplankton could be used for bioreactors and bivalves for secondary production (Hussenot, 2003). In this system, the main revenue was from abalone. The initial investment would be 1.3 million Euros, comparable to revenues from a similar production from a cage farming system. Farm income was estimated at 1.05 million Euros from the sea bream and 6.5 million Euros from abalone. The farm would be just as profitable without producing abalone, whose addition raised the expected profit from ~0 to 2.5 million Euros. Labour costs were predicted to be high, mainly for the abalone unit, with 10–12 permanent employees needed. According to Neori *et al*. (2004), the production costs were comparable to cages if the cost incurred for water treatment would be added in the form of taxes (according to the polluter-pays principle).

Profitability, versus system function (potential interferences among components), operational logistics, capital expense, and training requirements (complexity of employee knowledge-base), will jointly determine the level and acceptability of investments and commercial development risks. In remote coastal areas, operational efficiencies become critical in determining the economic viability of a proposed aquaculture facility, and are often cited as the economic constraints to such development (despite optimal growing conditions). The development of an EAA provides the opportunity to capitalize on the infrastructure and operational activities/schedules available through polyculture with other complementary aquaculture components. In particular, transportation costs (e.g. for crew, feed delivery, supplies, seed, harvests) represent a significant, and usually limiting factor for developing innovative EAA operations in remote coastal regions. Cross (2004) developed an integrated finfish-shellfish aquaculture system based on a modified (stretched) 12-cage steel net-cage facility and estimated that the capital and operational costs realized by the shellfish component of the system to be between 66 and 79 percent of that of an independent shellfish operation of similar size. Furthermore, his projections suggested that profitability of the shellfish aquaculture component ranged from 0.8–20 percent (net profits), compared to that of an independently operated shellfish operation of similar size that would otherwise realize a net loss. Margins would vary depending upon distance from an operational base (port).

BOX 5

Aquaculture production in the United States of America accounted for only 16 500 jobs and just 8 percent of the income. Aquaculture goods and services (feeds, fertilizers, processing, transport, equipment, supplies, etc.) accounted for 92 percent of the income and about 165 500 jobs.

Source: Dicks, McHugh and Webb (1996)

Better planning for aquaculture production networks

An ecosystem approach to aquaculture would integrate people in communities with technologies in new synergies to create new biotechnical and ecological engineering advances, and plan for maximal job creation and knowledge-based employment, integrating the applied ecological sciences to develop technological information with innovation in both the local, regional and global marketplaces.

The success of aquaculture is dependent not only on its technical needs for hatcheries to produce seed, and feed mills to produce feeds, but also on markets, equipment, and the capacities and capabilities of the entire seafood infrastructure. To date, macro-economic factors have been the main controllers of aquaculture developments, with environmental and social costs externalized.

The future challenge for planning and implementing an ecosystem approach to aquaculture is to operate more holistically and plan for aquaculture production—not only technically, but also as community development—and consider the social ecology of aquaculture developments. Proper planning for ecological aquaculture internalizes all of nature's and society's costs as part of an entire regional development activity, or "aquaculture production network" that connects aquatic seed and feed production centers and markets in order to maximize local economic multiplier effects.

If aquaculture is planned as grow-out operations only—and using a feedlot concept—then the benefits to communities are small. However, if aquaculture is planned as community-based development of a highly integrated, local operation, then employment opportunities and the potential for positive community impacts increase dramatically. Aquaculture can play an important economic role by creating new economic niches—generating employment in areas where there are few alternate job choices—and providing local sources of high quality food, and opportunities for attractive investments for local entrepreneurs to invest in the local economy, thereby increasing local control over economic development. Aquaculture depends upon inputs from various food, processing, transportation and other industries, and can produce valuable, uncontaminated waste waters and fish processing wastes, all of which can be a vital part of an ecological system that can be planned and organized for community-based aquatic foods production—and natural ecosystem rehabilitation, reclamation and enhancement—not degradation.

In order to change the public perception of aquaculture as "outsiders" or "industrial polluters", an ecosystem approach to aquaculture would be technically sophisticated and knowledge-based, but foremost ecologically and socially responsible. An ecosystem approach to aquaculture would plan for aquaculture to be an integral part of a community and a region, and have a wider plan for community development that works with policy-makers to: create a diversity of unprocessed and value-added products, and to provide local market access to provide needed inputs; recycle wastes; and to plan for job creation and environmental enhancement on local and regional scales. In this regard, the FAO Code of Conduct for Responsible Fisheries contains a key recommendation that: "States should produce and regularly update aquaculture development strategies and plans, as required, to ensure that aquaculture development is ecologically sustainable and to allow the rationale use of resources shared by aquaculture and other activities."

Improved governance – *orders of outcomes approach*

FAO Fisheries and Aquaculture Department (2006) found that one of the key trends in aquaculture development and management is enhanced regulation and better governance. The future of an EAA will be highly dependent on government actions. For example, Kenya has fostered a participatory policy formulation for aquaculture, providing a legal and investment framework, establishing public–private partnerships, providing basic infrastructure support, promoting self-regulation, providing a research platform, undertaking zoning for aquaculture and providing monitoring and evaluation support (FAO, 2006).

An EAA should be the responsibility of a lead aquaculture agency; its full implementation will require government to consider alternative methods of governance and use innovative, ecosystem-based management approaches (Table 7). There will be a need to facilitate an operational definition of ecosystem boundaries for management, for example to assess carrying capacity or water-management needs and to clarify administrative and legal jurisdictions. This will require the use of different tools and methodologies (e.g. geographic information system tools (Kapetsky and Aguilar, 2007), environmental impact assessments, etc). The design, implementation and enforcement of aquaculture management zones could be a relevant tool, particularly when the benefits of integrated aquaculture, polyculture, or integrated aquaculture–fisheries initiatives are being considered.

Sectoral agencies responsible for managing activities impacting aquatic ecosystems (e.g. capture fisheries, coastal zone development, watershed management organizations, agriculture, forestry, industrial developments) will have to develop new ways of interacting to regularly communicate, cooperate, and collaborate. The need for innovative governance to implement an ecosystem based approach to aquaculture can be seen as an obstacle but can also be seen as an opportunity to increase the social benefits that are likely to develop through synergies among food production sectors.

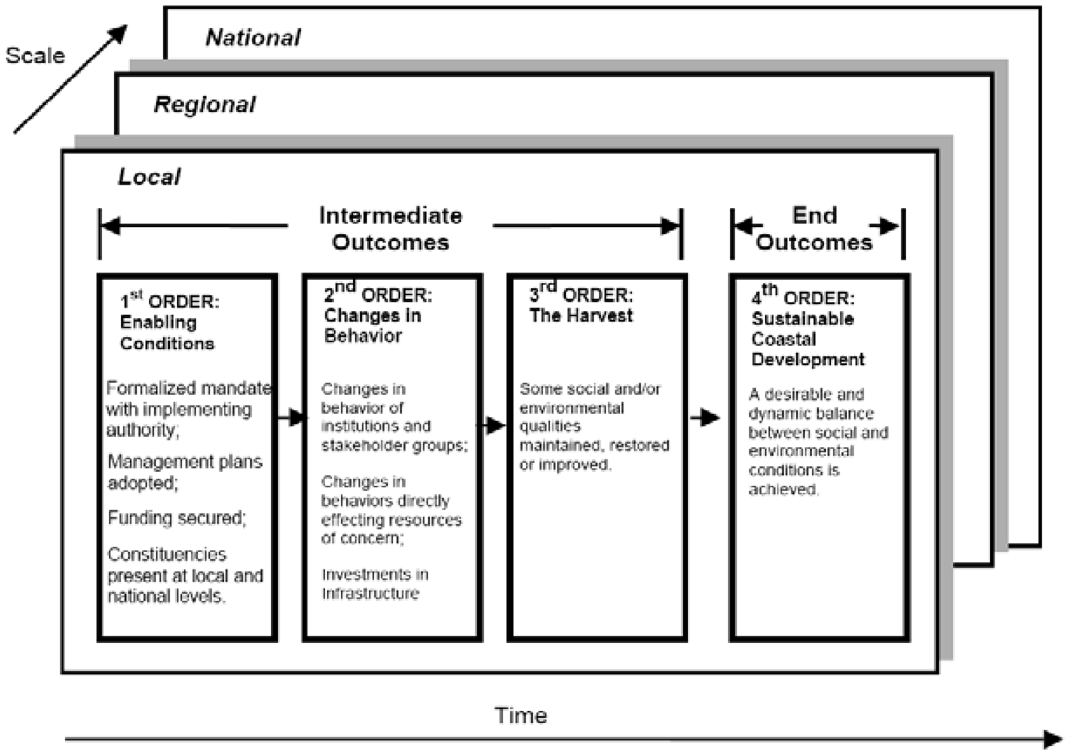
Adaptation of frameworks used to evaluate the needs and progress of governance on coastal management plans could be very useful to evaluate progress towards an ecosystem approach to aquaculture (Figure 1). As described by Olsen (2003), this adaptation framework recognizes not only the importance of changes in practices (such as the changed aquaculture farming system) but also recognizes that for each

TABLE 7
Ecosystem-based management involves a transition from traditional sector-by-sector planning and decision making to a more holistic approach

From	To
Individual species	Ecosystems
Small spatial scale	Multiple scales of different dimensions
Short-term perspective	Long-term perspective
Humans independent of ecosystems	Humans as integral parts of ecosystems
Management divorced from research	Adaptive management
Managing commodities	Sustained production potential for ecosystem goods and services

Source: Lubchenco (1998)

FIGURE 1
Four orders of coastal governance outcomes



Source: Olsen, Tobey, and Hale (1998); Olsen (2003).

change, there are correlated changes in the behaviour of key partners and stakeholders within the sphere of influence of the management activity, and that these changes can be measured at local, regional and national levels (Table 8).

Public perception

In the EU Genesis project, “Development of a generic approach to sustainable integrated marine aquaculture for European environments and markets” a study was conducted to estimate the awareness of consumers to eat shellfish and fish coming from integrated aquaculture systems based on the “focus group” methodology. While French and UK consumers did not have any difficulties consuming the fish, French consumers showed some reluctance to consume shellfish grown downstream of a fish farm when compared to shellfish cultivated in the usual culture environments (Monfort, 2007).

Barrington *et al*. (2005) compiled responses to a survey/questionnaire that queried respondents as to their opinions regarding the benefits of an integrated multitrophic aquaculture (IMTA) approach. Once educated as to what and how IMTA works, study respondents were supportive of the idea and of the inherent environmental and socio-economic benefits of IMTA. All of the study participants (100 percent) showed a willingness to eat seafood products grown in proximity to salmon, yet most felt that appropriate testing be conducted on the harvested products (particularly trace metals, antibiotic residues, and potential pathogens).

Global scale

Better management and ecocertification

Ecosystem approaches to aquaculture can be used to better plan and develop aquaculture production networks for multiple species to create a highly diversified, segmented network, planning for maximal job creation, by creating numerous interconnections supplying inputs and outputs using local resources and recycled wastes and materials

TABLE 8
Orders of governance outcomes (Olsen, 2003) applied to an ecosystem approach to aquaculture (EAA)

Orders	Explanations	Indicators
First Order	Government at the national level commits to a plan of action designed to adopt an ecosystem approach to aquaculture (EAA) by issuing a formalized commitment to an EAA by putting in place the "enabling conditions"	• New laws, programs and procedures that provide the legal, administrative, and management mechanisms to achieve the desired changes in behaviour by: • Building constituencies that actively support EAA within the user groups that will be most affected; within government institutions involved; and within the general public; • Developing a formal government mandate for an EAA with the authority necessary to implement actions in the form of laws, decrees, or other high level administrative decisions creating an EAA as a permanent feature of the governance structure of aquaculture; creation of commissions, working groups, user organizations and nongovernmental organizations (NGOs) dedicated to the advancement of an EAA agenda; designation of EAA zones; • Resources, including sustained annual funding, adequate to implement an EAA; • A plan of action to develop an EAA constructed around unambiguous goals; • The institutional capacity necessary to implement the new EAA plan of action.
Second Order	Evidence of successful implementation of an EAA	• Changes in the behaviour of institutions and interest groups (collaborative planning and decision making through task forces, commissions, civic associations, etc.); successful application of conflict mediation activities; evidence of functional public-private partnerships; collaborative actions by user groups; use of new school curricula incorporating an EAA; • Changes in behaviours directly affecting ecosystem goods and services (elimination of socially and environmentally destructive aquaculture practices); • Investments in infrastructure supportive of EAA policies and plans.
Third Order	Evidence of sustained achievements in institutional and behavioural change due to an EAA: the environment and indicators for the quality of life, income or engagement in alternative livelihoods improve in target communities	• Improvements in marine ecosystem qualities, such as sustained conservation of desired ecosystems and habitats; halting or slowing undesired trends such as nutrient and sediment releases; restoration of damaged benthic ecosystems, benefits to corals or sea grass beds; • Improvements in society as evidenced by monitoring of some social indicators (see Section 7.1, for example, increases in indices of quality of life; reduced poverty; greater life expectancy; better employment opportunities; greater equity in access to coastal resources and the distribution of benefits from their use; greater order, transparency and accountability in how planning and aquaculture development decision-making processes occur; greater security, including food security; greater confidence in the future and hope.

and expertise and closing leaky loops of energy and materials that can potentially degrade natural ecosystems.

Behavioural changes will be required by industry to better plan and to implement an ecosystem approach to aquaculture. Social investments, strategic incentives/subsidies, and innovative market mechanisms can help facilitate change in behaviours. Self-regulation by the aquaculture industry has led to codes of practice and better management practices.

An EAA goes beyond "meeting the regulations", and to be successful economically, an EAA will necessitate the use of ecolabels. This rationale comes for the success enjoyed by the Marine Stewardship Council label for environmental standard for well-managed and sustainable capture fisheries, which is based on the FAO's Code of Conduct for Responsible Fisheries (FAO, 1995), having three main criteria: "a) the health and productivity of the fish stock; b) the function of the ecosystem surrounding the fishery; and c) effective fisheries management." The logic behind this is that informed consumers who care about an EAA will demand aquaculture products that carry a label or fit into the "green" (buy) area of a watch card, as opposed to those products which don't have the label, sending a market signal back to aquaculture industries that only products from farms using an EAA is preferred. Independent certification programs have developed ecolabels and "seafood watch cards" to provide consumers with additional information from non-governmental organizations on whether or not the regulatory bodies are actually protecting the environment and

TABLE 9
Examples of standards developed to enhance product safety and consumer awareness

Examples	References
Better Management Practices	Tucker and Hargreaves (2008) Environment Best Management Practices for Aquaculture. Blackwell Publishing, Ames, IA, United States of America
Clean Production Agreements	Clean Production Agreement for Chilean Aquaculture (Barton, 2006)
Principles for Responsible Aquaculture	FAO/NACA/UNEP/WB/WWF. 2006. International principles for responsible shrimp farming. NACA, Bangkok, Thailand
Certification and Environmental Labeling Programs	Global Aquaculture Alliance and the Aquaculture Certification Council www.aquaculturecertification.org/accmiss.html
Aquaculture Quality Standards	Boyd *et al.* (2007)

society, and go beyond. For example, there are ecolabels that not only examine best management practices in culturing marine organisms they also include social criteria on whether products are raised in conditions in which the workers are paid with fair wages. Consideration of consumers' increasing awareness of environmental and food safety issues has led farmers' associations/consortia to adopt a variety of standards and labels, most of which are specifically intended to allay consumers' concerns about negative environmental consequences (Table 9).

Ecolabeling as been defined by Salzman (1991) is the "voluntary granting of labels by a private or public body in order to inform consumers and thereby promote consumer products which are determined to be environmentally more friendly than other functionally and competitively similar products" . Most ecolabeling guidelines follow the International Organization for Standardization (ISO) guidelines which prescribe that "the development of environmental labels and declarations shall take into consideration all relevant aspects of the life cycle of the product" (ISO, 1998).

Certification of plant and animal protein products as being produced or harvested in a sustainable, ecological manner is gathering attention from both producers and consumers, led by the UK Soil Association, the International Federation of Organic Agriculture Movements (IFOAM), Sweden's KRAV, Germany's "Naturland", and FAO's Codex Alimentarius Commission. However, Roheim (2001) point out concerns over ecolabeling, especially the lack of transparency and opportunity for participation in the development of standards, and concerns of developing countries that ecolabeling schemes are an attempt at disguised protection of domestic industries to restrict market access and erode competitiveness. In addition, Wessels, Johnston, and Donath, (1999) found that successful ecolabeling programs must accelerate consumer education programs so that consumers become more aware of differences in species, geographic regions, and certifying agencies.

Roheim (2001) states that ecolabels require traceability. Traceability is the ability to follow the movement of a food through specified stages of production, processing and distribution. Essentially, it is a record-keeping system that identifies and tracks products, transportation of products, and ingredients of products from origin to consumption, while providing the ability to quickly trace back products at any point along the supply chain. It is necessary for food safety purposes, in order to track backwards in the food chain the source of food which made consumers ill, so products could be removed from store shelves. Thus, ecolabeling for an EAA will require that aquaculture products produced using an EAA be kept separate from uncertified ones, and that a chain of custody certification be given. To implement that chain of custody, traceability is used. One of the benefits of traceability, and ecolabeling, is that consumers are ensured that farmed products produced using an EAA actually come from such farms.

Policy and regulatory constraints

The legal instruments (policies and regulations) that currently apply to the aquaculture industry, in most jurisdictions, are considered sufficiently flexible as to accommodate the development of an EAA. In a comparative legal analysis, White and Glenn (2005) conclude that the legal frameworks that govern aquaculture across Europe can, in most cases, apply to the installation and subsequent management of biofiltration components (e.g., shellfish, macrophytes, sea cucumbers) with little or no significant modification. The current European legal frameworks will allow the introduction of biofilters in order to facilitate environmental impact mitigation (waste reduction), but are also viewed as being able to consider the regulatory issues associated with harvest of these biofilters (e.g., shellfish) as a secondary (or tertiary) level of production within an integrated aquaculture system.

The dilemma faced in regulating the introduction of biofilters to a finfish monoculture system relates to governance procedures that: (i) define waste discharge limits/standards through a permitting process; and (ii) establish specific levels of farm site production. When introducing biofilters, this culture component presumably reduces (changes) organic loading (waste impact mitigation) but at the same time increases site production, albeit across more than a single species. How to accommodate this apparent contradiction has thus become the focal point of regulatory reform discussions in countries considering commercialization of Integrated Aquaculture, yet currently operate using these regulatory procedures.

In Europe, aquaculture permits and the overall regulatory environment varies widely amongst countries, with the regulatory system being the most complex in Germany and easiest in Spain (Buck, Krause and Rosenthal, 2004). In some countries aquaculture is defined and regulated under agricultural laws, while in others there is no lead agency and responsibilities are dispersed among many government bodies. Additionally, international as well as national regulations and conventions concerning aquaculture within the EU are yet to be completed (Buck, Krause, and Rosenthal, 2004). Thus, an EAA would need to be considered at many levels, internationally as part of conventions such as at the EU level, and nationally by states.

In North America, regulation of the environmental impacts of aquaculture has moved towards a performance-based approach, with operational limitations focused primarily on achieving environmental (benthic, water quality) standards. The inclusion of Integrated Systems within a performance-based paradigm should therefore be less problematic in terms of licensing/operation, assuming that improved environmental performance resulting from the introduction of biofiltration components would continue to satisfy the established standards or performance thresholds (despite increased overall site production).

The need to satisfy jurisdictional and international agreements/regulations regarding seafood safety (i.e. bacterial, antibiotic, chemical contaminant loading in products from an EAA system) will require procedural modifications to reflect polyculture systems. However, given that the use of such treatments in the fish component typically has sufficient procedural safe-guards (e.g., prescribed treatment dosage/applications, required tissue clearance periods, acceptable product tissue levels), it is assumed that these protocols should be adaptable to incorporate the other species of an Integrated Aquaculture system that may be exposed to the residues released during and immediately following treatment. White and Glenn (2005) suggest that while additional administrative protocols or procedures will necessarily evolve in response to the development of an EAA within individual jurisdictions, this added bureaucracy should not be prohibitive. In fact, these adjustments will most likely be determined by regional politics and by the options available given scientific support of their effectiveness, as well as by the economic and financial considerations.

While the policy and regulatory constraints to incorporating an EAA into existing legal frameworks does not appear prohibitive, the premise that this approach to aquaculture attempts to move towards system sustainability should be viewed by society as positive, and an approach that should be encouraged. Robinson (2004) suggests that the role of government, in reforming aquaculture policy to incorporate an EAA (he used the example of Integrated Multitrophic Aquaculture, or IMTA), be one of encouragement for industry sectors that follow these tenets. He further recommends that incentives or penalties, similar to those that have been applied to environmental or health behaviour of people in land-based systems (e.g., fuel or cigarette taxes, higher insurance premiums for high-risk activities, pollution tax, etc.) be considered for integrated aquaculture systems.

CONCLUSIONS

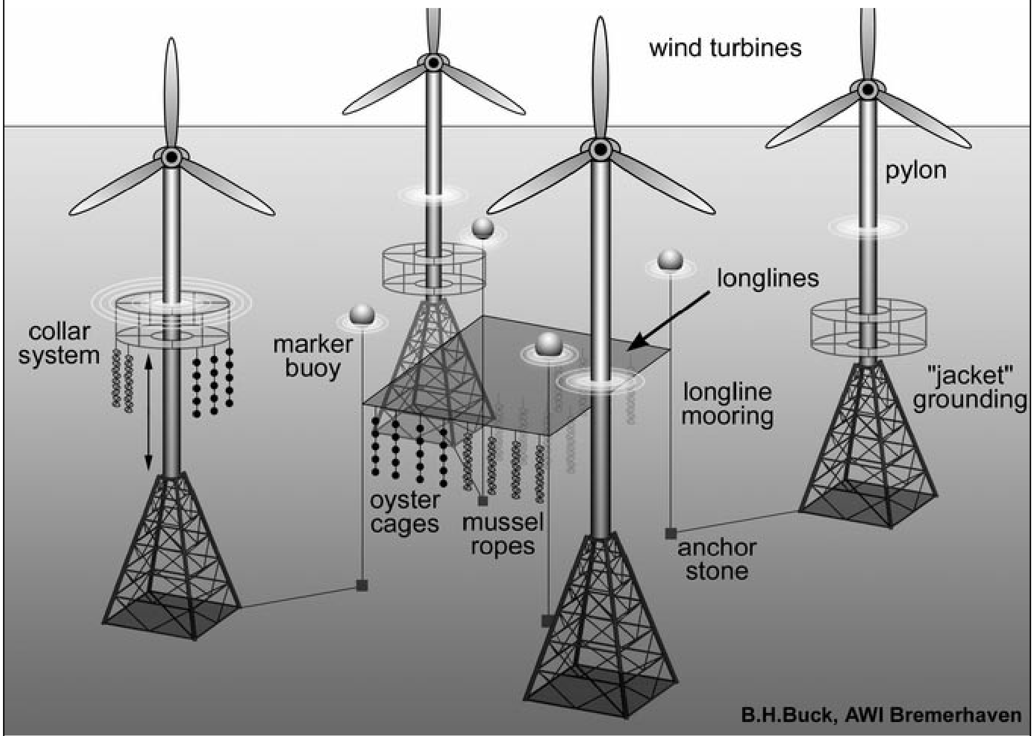
Aquaculture is not a uniform "industry" or a standard set of practices easy to classify—or label—and regulate. There are a wide diversity of systems and species which can be classified in many different ways, and this will grow more complex if an EAA becomes widespread. For example, the integration of aquaculture, agriculture and animal husbandry on small farms in Asia creates definable aquaculture ecosystem types which closely resemble natural ecosystems having their own structure, closely-coupled nutrient recycling pathways and ecological management strategies.

A review of research and development progress towards an ecosystems approach to aquaculture was presented using the three principles and levels detailed by Soto *et al.* (2008) to review the state of the art of planning and to assess progress for the world's major and emerging marine aquaculture commodities. A governance framework was developed using an "orders of outcomes" approach (Figure 1; Table 8). Using the second approach, it was found that, no industry anywhere in the world for any commodity has put into the place any of the enabling conditions described by Olsen (2003), thus nowhere were there even "first order outcomes" to measure in regards to the progress towards an EAA globally.

However, overall, there is a great deal of global, multidisciplinary research and development information and good progress on an EAA at the farm R&D level which can inform managers. This strong research and development baseline has been a major part of a notable transition globally towards an EAA in the industrial/commercial sector for two, major global commodities – molluscs and shrimp – over the past 10 years. Analysis tables chart a rapid trajectory of these commodities towards an ecosystem approach to aquaculture, and capture a clear "innovation portfolio" in these industries. There are few technological or scientific issues remaining to implement an EAA. The principle constraint for marine aquaculture in the coastal zone is user conflicts and limited availability of suitable space, and the many legal issues that arise from the use of public resources for private developments. One advance in this regard, is the type of works being done by the Alfred-Wegener Institut fur Polar und Meeresforschung who have designed aquaculture into platforms for offshore wind farms; these are now being considered throughout the world are perfect places for sitting integrated aquaculture operations (Buck, Krause, and Rosenthal, 2004) (Figure 2). However, overall, there is little consideration of social sustainability in marine aquaculture research and development; little social monitoring, data collection or planning; this is a major gap in the global movement towards an EAA.

A global analysis of progress towards an EAA for finfish – salmon and other marine finfish – in the selected major aquaculture farming countries shows good progress towards an EAA for salmon in Canada, some progress in the UK and Norway, and very little in Chile. There are major concerns in the development portfolio for other marine finfish, with little to no progress towards an EAA, especially in modern cage culture developments in China and Southeast Asia. The main constraints in Asia are sectoral integration, especially lack of consideration for social issues and governance (legislation, enforcement, compliance and use of economic instruments). In addition, in these important aquaculture centers an EAA is also slowed by the poor connections of aquaculture to the public, with very weak public participatory processes, less than

FIGURE 2
Conceptual arrangement of offshore wind energy facilities, seaweed (kelps) and shellfish (mussels, oysters) aquaculture proposed for the coast of Germany by the Alfred-Wegener Institut fur Polar und Meeresforschung



Source: Buck, Krause, and Rosenthal (2004)

optimal organization of research and development, and lack of active true partnerships between government/universities and industry participation in the R&D (and innovation) processes. As a result, this review has focused on participatory processes, social sustainability issues, and analysis of governance systems, since the widespread adoption of an ecosystem approach to aquaculture (EAA) requires a much tighter coupling of science, policy, and management.

Aquaculture has intimate connections not only with capture fisheries, but also with agriculture, markets, and marine policy, legal and regulatory environments. Accelerated production of aquatic proteins cannot be evaluated in a vacuum separate from other types of land-based animal agriculture or ocean-based capture fisheries since these food systems use similar (and sometimes competing) inputs and outputs, face similar policy and regulatory environments, and have to deal with common consumers and decision-makers. More holistic planning perspectives are needed to ensure the survival of traditional coastal fishing and aquaculture communities, and to link aquaculture science, industry, and society in order to design effective policies, practices and technologies to address the many challenges ahead.

Using an EAA, aquaculture institutions and industries worldwide can be pro-active, promote and develop as the world's most ecologically integrated industry, and adopt a new strategy—that of a community-based, sustainable, ecological aquaculture industry that produces ecologically and socially certified produce—adopting input management strategies and codes of better practices. In this regards, the FAO/NACA/UNEP/WB/WWF (2006) guidelines developed for shrimp farming are a major advance, as are other innovative ecolabeling initiatives that go beyond the use of "watch cards" and include not only production, but also environmental and social criteria for product differentiation.

In the 21st century, aquaculture developers will need to spend as much time on the technological advances coming to the field as they do in designing ecological approaches to aquaculture development that clearly exhibit stewardship of the environment. For aquaculture development to proceed to the point where it will be recognized worldwide as the most efficient contributor to new protein production—clear, unambiguous linkages between aquaculture and the environment must be created, fostered, and communicated—and the complementary roles of aquaculture in contributing to environmental sustainability, rehabilitation and enhancement must be developed and clearly articulated to a highly concerned, increasingly educated and involved public. An ecological approach to aquaculture brings modern sustainability, ecological methods and systems thinking to aquaculture, incorporating social, economic, and planning for its wider social and environmental contexts in fisheries and coastal zone management. Ecological aquaculture will create new opportunities for a more diverse group of professionals and entrepreneurs to get involved in aquaculture since new advances will be needed not only in treatment technologies, production management and feed technologies; but also in energy technologies, information management, public information and outreach, community facilitation and networking.

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An ecosystem approach to freshwater aquaculture: a global review

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ABSTRACT

This papers addresses the relevance of the ecosystem approach to freshwater aquaculture (mainly in Asia) through literature review and eighteen case studies. The case studies include some examples where aquaculture has threatened sustained delivery of ecosystem services including biodiversity. Extensive and semi-intensive systems typically have a lesser effect over a greater area; while intensive systems usually have a more severe but more localised effect. Case studies suggest that inland aquaculture generally improves human well-being and equity. Aquaculture generates employment for the poor, economic activity from the sale of low as well as high-value species in national and in some cases international markets, and low-cost fish for domestic consumption. Benefits generated through employment of the poor in the supply, processing and distribution chain can be substantial and significantly greater than those directly associated with small-scale farming. The authors recognize that to implement the ecosystem approach will require the development of institutions and associated integrated management systems which can deliver such an approach at realistic and practical scales, taking full account of the needs and impacts of other sectors, and this is a huge challenge. The key is to develop institutions capable of integration, especially in terms of shared agreed objectives and standards.

EXECUTIVE SUMMARY

Decision V/6 of the Convention on Biological Diversity defines the ecosystem approach (EA) as "*a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way*".

Freshwater aquaculture has become a key element in many rural economies, especially in East, South and Southeast Asia, contributing to economic growth, poverty alleviation and food security. Production from freshwater aquaculture amounted to 26 million tonnes in 2004 and comprised 43 percent of global aquaculture production.

Through literature review and 18 case studies, this paper addresses the relevance of the ecosystem approach to freshwater aquaculture, and the ways in which freshwater aquaculture development may take place in accordance with the concept, and the three principles developed as part of this initiative.

Principle 1: Aquaculture development and management should take account the full range of ecosystem functions and services, and should not threaten the sustained delivery of these services to society

1. Our case studies include some examples where aquaculture has threatened sustained delivery of ecosystem services. All examples affect biodiversity and ecosystem services to some degree – extensive systems typically have a lesser effect over a greater area; intensive systems usually a more severe but more localised effect. However intensive systems are often associated with greater use of chemicals and these significantly increase the zone of influence, both socially and environmentally. Some of the most intensive systems are more bio-secure, and this may reduce the requirement for chemical use.
2. Principle 1 implies that we can define the point at which environmental change threatens sustained delivery of ecosystem services. In practice this is extremely difficult, especially with respect to changes in biodiversity. The definition of "*acceptable*" will depend on local social and economic conditions and perspectives.
3. It is essential in setting limits to change that some *resilience* is retained in terms of service provision. This implies two things: *firstly, that acceptable limits include a "safety margin"; and secondly, that those factors which strengthen system resilience – such as biodiversity and enterprise diversity – should be promoted as much as possible.*
4. The use of *alien species* is a common feature of freshwater aquaculture throughout the world. There are difficult trade-offs to be made between ecological risk and socio-economic benefit. Management of alien species and their impacts on wild stocks and fishery resources is a *matter of great local concern*, but also requires *national and international policy and regulation,* and has been widely discussed elsewhere. The way forward has to be one of *more openness and thorough risk assessment.* A naïve "precautionary approach" would ban all introductions and modifications because there is always the risk of ecosystem impact, and the associated science is always highly speculative. *A pragmatic precautionary approach would weigh the severity and likelihood of negative impact on the wider ecosystem, and balance this against potential social and economic gain.* However, *the principle must be to use native species wherever possible*, and for government to facilitate this through appropriate research and development.
5. There are *many specific mechanisms and technologies which can serve to eliminate or reduce negative effects on ecosystem function and service*, and these have already been widely reported. Some of these require action by associations of farmers through, for example, best management practices (BMPs); others require better planning, management and regulation by government.
6. *Fish or fishmeal is* a key ingredient in feeds used in many different aquaculture systems. Principle 1 *implies either the need to reduce this dependency* (for example through use of locally sourced nutrients, perhaps from integrated aquaculture), or the need to *ensure that such resource use does not damage provision of ecosystem*

services elsewhere in the world – e.g. through sustainable fishery management practices.

7. *Resource use integration and waste recycling at all levels from local to global can contribute to Principle 1. The use of "green infrastructure" – essentially conserving and/or strengthening ecosystem services through design/retention/protection of green zones or corridors* – can for example increase the capacity of the environment to assimilate waste or enhance water and air quality.
8. Traditional extensive and semi-intensive forms of aquaculture, and *integrated aquaculture*, may be considered to represent an ecosystem approach as they tend to have less immediate impact on the wider environment than more intensive forms. However, many of these systems offer no way out of resource-limited poverty through increased productivity (see Principle 2), and more modern systems may not be economically competitive. *While the opportunities for farm level integration as a mechanism to reduce pressure on the environment should always be considered, they should be evaluated carefully in socio-economic as well as environmental terms, and not promoted as a panacea.*
9. An ecosystem approach would address all the above issues through a *participatory process* involving stakeholders, scientists and economists to both define acceptable limits to environmental change and to agree on the most cost-effective and socially-acceptable mechanisms to eliminate or reduce any negative effects to an acceptable level. Unfortunately, our cases offer only limited experience of using this approach in practice.
10. To implement the ecosystem approach will require the development of *institutions* and associated *management systems* which can deliver such an approach at a realistic and practical scale, taking full account of the needs and impacts of other sectors.

Principle 2: Aquaculture should improve human well-being and equity for all relevant stakeholders especially the more deprived sectors of society

11. There is much evidence from the literature and our case studies to suggest that aquaculture often improves human well-being and equity. Aquaculture generates employment for the poor, economic activity from the sale of high-value species in national and in some cases international markets, and low-cost fish for domestic consumption. Benefits generated through the supply, processing and distribution chain can be substantial and significantly greater than those directly associated with farming.
12. However, as for all successful economic enterprises, there are counter-examples. *Governments must ensure that the economic success of aquaculture does not lead to appropriation of productive resources by the rich and powerful.* It is also essential that the *poor and disadvantaged are included in decision-making* relating to standards for both aquaculture and the wider environment.
13. Unfortunately, it is difficult to escape poverty through traditional integrated aquaculture systems. Poor people typically have access to limited land and/or water. The only way for them to increase their income through aquaculture is to invest in more inputs; this usually leads to a need to specialise in fish production and therefore decrease integration with agriculture and animal husbandry. Certification may generate a premium on products from more traditional/integrated systems but this is no panacea, especially for poor small-scale and widely scattered farmers. The Socialist Republic of Viet Nam offers an alternative but possibly transient example in which the traditional integrated system is still pursued by some farming households while the main source of income is increasingly generated from off-farm employment.

Principle 3: Aquaculture should be developed in the context of other sectors, policies and goals

14. This is essentially a call for more integrated planning and management systems, something which has been advocated for many years – for example *through integrated coastal zone management and integrated watershed management.*
15. Our cases reveal few examples of this approach being implemented and having a clear impact on the nature of aquaculture development in terms of the other two principles. The Water Framework Directive in Europe offers a possible model, but is still in the early stages of implementation. Our case study of Laguna de Bay in the Republic of the Philippines suggests some success and some failure.
16. The difficulty of implementing this ideal approach should not be under-estimated. *The key is to develop institutions capable of integration, especially in terms of shared agreed objectives and standards*. In the past much effort has been put into plans, with insufficient attention given to the institutions and delivery mechanisms.

INTRODUCTION

Origins and nature of the ecosystem approach

The primary policy basis of the ecosystems approach is the Convention on Biological Diversity, adopted following the 1992 United Nations Conference on Environment and Development. Decision V/6 of the Convention defines EA as *a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way".*

The fifth Conference of the Parties to the Convention on Biological Diversity which took place in Nairobi, Kenya, in May 2000 endorsed twelve principles and five points of operational guidance as a framework with which the EA could be enacted. These principles are the foundation of most subsequent interpretations of the EA. In essence, the EA is a management approach consistent with the aims of the CBD, and can be adopted by any organisation (public, private or multilateral) involved in the regulation or management of human uses of the environment (Smith and Maltby, 2003). It is important however to note the caution, spelt out in Decision VII/11 of the convention: There is *"no single correct way to achieve an ecosystem approach… The underlying principles can be translated flexibly to address management issues in different social contexts".*

The EA represents a shift in thinking from development on the one hand and protected areas on the other, to a recognition that humans are an integral part of many ecosystems (Hamerlink and Duvail 2003) and that people and their activities lie at the heart of biodiversity conservation; and our wellbeing is dependent in turn on the quality of the "ecosystem services" we derive from the wider environment. In a sense EA is the flip side of sustainable development. The former starts from the premise of biodiversity conservation but recognises the need to achieve this through modified human behaviour/development; the latter starts from the premise of development but recognises the need to achieve this in part through better environmental management.

The ecosystem approach to aquaculture has also been called "ecological aquaculture" (Costa-Pierce, 2002;2003) to develop linkages between aquaculture, the environment and society to promote complementary roles of aquaculture to contribute towards environmental sustainability, rehabilitation and enhancement. Bartley (2002) pointed out that while the EAA is becoming a "cornerstone of international conservation and development programmes" and acknowledges linkages between ecological and human activity/economic systems, the approach remains to be well defined.

The CBD principles are a rather difficult mix of truisms, aspirations, objectives, and means, deriving from a political negotiating process. Principles 1, 2 and 4 for example are political statements only loosely linked to the core ideas of ecosystem management, and there is substantial overlap/repetition between the principles and operational guidance. Several of the principles amount to what has been considered sound management practice for decades. As Oeschger (2000) suggests, the principles represent: *"An instrument to persuade the largest possible number of interest groups to support the widest possible range of conservation goals".* Notwithstanding these limitations, the principles are important and represent a serious attempt to generate an internationally agreed framework or management approach likely to promote sustainable development.

Most of the principles and associated ideas are not new. They can be found in one form or another in the literature and guidance relating to integrated natural resource management (many examples at different scales), Integrated Coastal Zone Management (ICZM) and Integrated Watershed Management (IWSM). In relation to aquaculture, most can be found in the GESAMP Report "Planning and management for sustainable coastal aquaculture development" (GESAMP, 2001). There are however some additions and shifts of emphasis. In particular, there is a greater emphasis on the constraints and opportunities associated with "ecosystem functioning"; "ecological health or wellbeing"; "resilience"; and equity.

In applying the 12 principles of the ecosystem approach, the five points in Box 2 are proposed as ***operational guidance***.

Interpretations

The core idea – or emphasis – behind the ecosystem approach is that the management of any activity or area must take account of the nature and functioning of ecosystems:

1. EA recognises that humans are an integral part of important ecosystems and people should be at the centre of biodiversity management. This implies the need for integrated, participatory approaches to "ecosystem" management.
2. EA recognises that ecosystems provide services which underpin most human activity, and we need to ensure that we do not threaten the sustained delivery of these services through damage to ecosystem functions. Given our ignorance of the functioning of these highly complex systems this implies the need for a precautionary and adaptive approach.
3. EA recognises that some activities threaten or reduce the quality of ecosystem services available to society at large and therefore represent a cost which should be accounted or internalised
4. EA recognises that waste products from one activity or sector may serve as inputs to another, thus enhancing productivity and reducing pressure on ecosystem functions and services
5. EA recognises that ecosystems function at a range of scales from highly local to global, and we therefore need a "nested" approach with different approaches to management according to scale.

Since the approach was first launched there have been several new "interpretations" and follow up guidance. The IUCN Commission on Ecosystem Management offers 5 main steps toward implementing the approach. The FAO "ecosystem approach to fisheries" (FAO, 2003) emphasises the importance of the management system and participation. The *Tropeca* research programme (Hambrey *et al*., 2005) developed practical guidance for the participatory management of aquaculture within "the capacity of the environment" – encompassing many of the EA principles, though focused in particular on nutrient management. The German Federal Environment Agency reviewed the management of the Wadden Sea against each of 12 principles Ecosystem approach – addressing both the practicalities of the approach, and the quality of its own management approach. WWF has also recently developed guidance.

BOX 1
Ecosystem approach principles and points of operational guidance

Principle 1: The objectives of management of land, water and living resources are a matter of societal choice.

Principle 2: Management should be decentralised to the lowest appropriate level.

Principle 3: Ecosystem managers should consider the effects (actual or potential) of their activities on adjacent and other ecosystems.

Principle 4: Recognising potential gains from management, there is usually a need to understand and manage the ecosystem in an economic context. Any such ecosystem management programme should:
- (a) Reduce those market distortions that adversely affect biological diversity;
- (b) Align incentives to promote biodiversity conservation and sustainable use;
- (c) Internalise costs and benefits in the given ecosystem to the extent feasible.

Principle 5: Conservation of ecosystem structure and functioning, in order to maintain ecosystem services, should be a priority target of the ecosystem approach.

Principle 6: Ecosystems must be managed within the limits of their functioning.

Principle 7: The ecosystem approach should be undertaken at the appropriate spatial and temporal scales.

Principle 8: Recognising the varying temporal scales and lag-effects that characterise ecosystem processes, objectives for ecosystem management should be set for the long term.

Principle 9: Management must recognise that change is inevitable.

Principle 10: The ecosystem approach should seek the appropriate balance between, and integration of, conservation and use of biological diversity.

Principle 11: The ecosystem approach should consider all forms of relevant information, including scientific and indigenous and local knowledge, innovations and practices.

Principle 12: The ecosystem approach should involve all relevant sectors of society and scientific disciplines.

Source: CBD, 2005, Decision V/6 Annex B, pp 587–592

BOX 2
Operational guidance for an ecosystem approach

1. Focus on the functional relationships and processes within ecosystems.
2. Enhance benefit-sharing.
3. Use adaptive management practices.
4. Carry out management actions at the scale appropriate for the issue being addressed, with decentralisation to lowest level, as appropriate.
5. Ensure intersectoral co-operation.

FAO draft principles

FAO is now seeking to develop guidance on the application of the ecosystem approach to aquaculture development and management – a process to which this review will contribute. The following have been proposed as definitions and principles relating specifically to aquaculture:

Definition:
"An Ecosystem Approach for Aquaculture is a strategy for the integration of the activity within the wider ecosystem such that it promotes sustainable development and resilience of interlinked social-ecological systems".

The principles guiding the strategy are:

1. Aquaculture development and management should take account of the full range of ecosystem functions and services, and should not threaten the sustained delivery of these to society.
2. Aquaculture should improve **human well-being and equity** for all relevant stakeholders.
3. Aquaculture should be developed in the context of **other sectors, policies and goals.**

Such definition and the principles guiding the strategy are described in more detail in the first paper of these proceedings (Soto *et al.*, 2008).

This review offers an overview of the nature of freshwater aquaculture systems and management throughout the world, with a view to informing the final development of these principles and any associated guidance.

FRESHWATER AQUACULTURE

Freshwater aquaculture takes place across large swathes of the globe and is a hugely varied economic activity. In this review we have used case studies to represent a range of different types in order to illustrate the possible implications or meaning of "the ecosystem approach".

Production from freshwater aquaculture amounted to 26 million tonnes in 2004 and comprised 43 percent of global aquaculture production. 94 percent of this production is of fish, dominated by cyprinids, contributing 8 million tonnes of production and valued at US$16 billion. Cichlids (mainly Tilapia) are also increasingly important. The bulk of this production is from S and SE Asia, and in many cases in poor and remote rural areas. While a significant proportion of marine and brackishwater production is for export, freshwater aquaculture remains primarily for domestic markets, and is therefore a critical element in food security. Increased production throughout the world has led to modest price falls in many countries, contributing to nutritional benefits. However, prices may begin to rise given the current general trend for food products globally.

More detailed overview of freshwater aquaculture can be found in the "State of world aquaculture" reports (FAO, 2006), and its Fisheries and Aquaculture "Country Profiles")[1]. A useful overview is also provided by the World Bank (2006).

SOME KEY ISSUES

Defining limits to change and the concept of resilience

Principles 5 and 6 of the CBD ecosystem approach imply that there are limits to ecosystem change (or the pressures on them) beyond which ecosystem function

[1] FAO. 2008. Fishery and Aquaculture Country Profiles [online]. Rome, FAO. [Cited 2 June 2008]. www.fao.org/fishery/countryprofiles/search

may be compromised and the delivery of ecosystem services threatened. Principle 9 recognises however that change is inevitable. Proposed principle 1 of the draft FAO guidance relating to aquaculture states that *"aquaculture should be developed in the context of ecosystem functions and services (including biodiversity) with no degradation of these beyond their resilience"*

In some cases defining limits to change is relatively straightforward. For example a certain concentration of nutrients in water may trigger undesirable or toxic algal blooms. This point may be termed a *threshold* – the dividing line between two fundamentally different states (Haines-Young, Potschin and Cheshire, 2006) characterised by significant differences in terms of service provision.

In many cases however, defining or agreeing acceptable limits is more difficult: there is no obvious threshold in terms of the characteristics of the system or in terms of service delivery. There may be very different perspectives as to what constitutes a suitable "acceptable limit" or an adequate level of "precaution". The science may be inadequate to inform these discussions. The institutions required to agree on absolute or precautionary limits are often lacking.

Defining acceptable change in respect of biodiversity is particularly difficult. There are specific examples of established relationships between biodiversity and ecosystem services (Balvanera *et al.*, 2006; Hiscock *et al.*, 2006; Chapin *et al.*, 2000). The loss of just one species or habitat may be enough to trigger failure of a service. A particular tree species may, for example, be vital in preventing erosion. A particular habitat may be vital as a breeding or nursery ground for economically important fisheries. In many cases however, the relationships are poorly specified and the thresholds unclear (Hambrey and Senior, 2007). In some cases we can lose (or change) a great deal of biodiversity before there is any significant loss of ecosystem services. Many agricultural landscapes have developed at the cost of certain kinds of biodiversity without any significant loss of "life supporting" services. Indeed biodiversity is often exceptionally rich in traditionally farmed landscapes, and in some parts of the world old shrimp or fish ponds have now been designated as nature reserves.

Biodiversity is often associated with "resilience[2]", and this concept in turn is closely associated with the issue of precaution. A reduction in biodiversity necessarily "reduces the options", and by implication resilience. There will be fewer species or habitats able to fulfil a particular ecological function, or ready to "spring back" following some shock or change. A precautionary approach would seek to conserve as much biodiversity as possible, because any loss would be deemed to reduce resilience, although this cannot usually be measured.

We are therefore left with two extreme situations relating to "acceptable" limits to change:

1. That in which change is allowed to take place so long as some clearly identified and agreed threshold is not reached;
2. That in which any *change* to biodiversity is seen as likely to be associated with a *reduction* in overall biodiversity, and therefore a *reduction in resilience*.

In the case of 2 there are likely to be as many opinions as to acceptable change, or "acceptable loss of resilience", as there are stakeholders, and the science is rarely adequate to inform this issue in any practical way.

Other variations on the theme of limits to change include the concept of *no net loss* of ecosystem services, or in more practical terms, *no net cost* to other users or society at large. While these terms are undoubtedly useful as a mechanisms to focus minds on the key issue of concern, they still depend on science to quantify the effects (loss of service), and unfortunately the science is rarely robust enough to generate credible cost figures.

[2] According to the Oxford dictionary, resilient means: "recoiling; springing back".

It is clear therefore that the definition of acceptable change is often highly subjective, and re-enforces the need for effective and efficient participation (or representation) in decision-making. At the present time there are few decision-making structures anywhere in the world which are sophisticated enough – in terms of either procedure or supporting science – to fully address issues of resilience and the precautionary approach.

In practice however, many of the key ecosystem services (flood prevention and mitigation, fisheries production, water purification etc) are under direct and immediate threat, and are closely linked to particular habitats/species. The science and rationale for conservation is strong. It is important that we do not become too embroiled in these complex scientific debates, but rather move forward toward effective decision-making. Most people will sign up to "sustained delivery of ecosystem services" and agree to *objectives* for, and acceptable limits to change in services.

In this review we explore how "ecosystem functions" might be safeguarded in relation to the various examples and cases relating to aquaculture.

Equity

The CBD EA operational guidance proposes that EA should seek *to "enhance benefit-sharing".* Proposed principle 2 of the draft FAO guidance relating to aquaculture states that *"aquaculture should improve human well-being and equity for all stakeholders".*

Equity is not something which is clearly and readily identified with ecosystems. Its appearance in the CBD "operational guidance" derives from the moral dimension of "sustainable development", which at its heart seeks to ensure equality of opportunity between generations ("inter-generational equity"). Logically this can be extended to equality of opportunity between different social groups.

FAO has a particular remit to reduce poverty and inequality, and aquaculture can be an important tool to achieve this. However, equity is fundamentally a political issue which is usually tackled through national social and economic policy. It is unclear how a particular sector can, unilaterally, promote equity; although it can contribute to and should not by its very nature reduce equity. We explore this in more detail in the review.

Integration

Integration is a word which occurs repeatedly in discussions of the ecosystem approach and is specifically promoted in the proposed Principle 3 of the EAA.

There are several dimensions to integration:

- **Policy integration** – minimising inter-sectoral conflict; coordinating policy and management measures to ensure consistency and a level playing field.
- **Operational (or enterprise level) integration** – ensuring that the various activities pursued by a particular enterprise are coordinated and mutually reinforcing. This may include recycling of wastes.
- **Ecosystem (or sectoral) integration** – promoting a balance between different activities or sectors within an aquatic system in order to maximise the re-use of nutrients or other materials, thereby increasing efficiency and reducing pressure on the environment.
- **"Green infrastructure"** – maximising the delivery of ecosystem services, including waste assimilation, by ensuring that areas or corridors of a range of habitat types are conserved or re-created and managed appropriately

A particular example of both operational integration and ecosystem integration is "integrated aquaculture" – which is sometimes put forward as the key to implementing the ecosystem approach. While it is undoubtedly one mechanism to reduce pressure on the wider environment, efficient waste treatment systems and/or development and maintenance of "green infrastructure" may be equally effective at maintaining "ecosystem functions". In this review we explore the extent to which integration is desirable and feasible in these various ways at different scales.

Productivity

There is a view that the EAA should involve management to increase ecosystem productivity, in particular through integrated aquaculture. This idea does not derive directly from the principles associated with the CBD. The objective of aquaculture is, surely, *to improve human welfare through sustained income generation and food production, without detriment to other interests or ecosystem services.* The "productivity of the ecosystem" as a whole is not really an issue for the aquaculture sector, and it is difficult to see why it should be an objective for government. Sustaining or increasing the productivity of existing economic activity (including aquaculture) on the other hand is usually an objective of the sector and of government, and it may, in some circumstances, be related to or constrained by the productivity of the wider ecosystem. This should of course be taken into account and we explore its possible meaning in relation to the case studies.

Scale

Scale is a key issue for the implementation of the ecosystem approach to aquaculture.

Scale of influence of aquaculture activities

Like most economic activities in the modern world, the scope of influence of an aquaculture enterprise is typically large – though most of the effects tend to be more thinly spread as we move further away. In our discussion below relating to impact of aquaculture on ecosystem services (impacts on ecosystem functions and services section) we identify several far reaching impacts including effects on water quality (local, regional), biodiversity (local, regional, global), and feed resources (local, regional, global).

Scale at which "no net effect" might be achieved

A key question for the EAA is "to what degree does the approach seek to ensure "no net loss" of ecosystem services, and at what scale should such a principle be applied"?

Impacts on other users and on human health are usually best dealt with through existing government regulatory structures at a variety of scales.

Impacts on water and sediment quality and on biodiversity can be dealt with at farm level, at "farm group" level, or at a higher level corresponding to some identifiable waterbody, watershed or "agro-ecosystem". In relation to the various freshwater aquaculture systems we explore the desirability and feasibility of "no net loss" or "no net cost", and the mechanisms which might be used to deliver this at different scales. These include, for example, reduction of waste through integration of different activities in traditional or modern integrated aquaculture; waste treatment at the farm level; waste treatment infrastructure for groups of farms; or "green infrastructure" for multiple sectors at a range of scales.

We also explore the extent to which the nature and scale of existing or potential management institutions can operate or deliver effectively at these various scales. Clearly the more global issues can only be tackled by organisations such as FAO seeking action and coordination between governments. Local and regional issues are typically best addressed at some level corresponding to an identifiable aquatic system, or agro-ecosystem; but a compromise may have to be struck depending on the nature and scale of existing or potential management systems and associated institutions.

Ultimately there is a strong argument for devolving responsibility for (no net loss) to the enterprise level, but it may be that this is not always the most efficient or cost effective approach, and may be constrained by issues of product demand.

Institutions, knowledge and participation

We have already noted the similarities between the ecosystem approach and integrated coastal zone management (ICZM) and integrated watershed management (IWSM). There is a wealth of experience relating to the implementation of these approaches throughout the world, and it is worth briefly reviewing some of the difficulties which have been encountered. Broadly speaking implementation of both ICZM and IWSM has been patchy and limited for several reasons.

The biggest problem – and evident in both developed and developing countries – is the lack of ***adequate management systems*** through which more holistic and integrated planning and management systems can be delivered.

In developed countries management systems are often well developed, but are *not well integrated*. Management is traditionally along sectoral lines, partly because most professionals are educated in a specific academic discipline, and partly because, as economies and associated regulatory systems have evolved, so has the scale and complexity of the management issues. The tasks must be broken down and clearly assigned. Broadly speaking government in developed economies has found it more satisfactory to allocate responsibility along sectoral lines, rather than to smaller "internally integrated" management units – although this may be changing. Indeed there is an innate tendency of all management systems (in government and in the private sector) to swing between centralised sectoral management, and more integrated regionally devolved management.

Modern economies also find it difficult to increase levels of participation. Issues are complex and perspectives diverse; many stakeholders lack the time or representation to participate effectively; others have the time but may not be representative. Participation – unless extremely well designed and managed - is not always equitable or cost-effective.

In developing countries on the other hand, there is perhaps more potential for integration and participation, but effective management is severely constrained by lack of knowledge and lack of implementing institutions and capacity.

The ecosystem approach implies another step up in terms of complexity and the need for integration. The difficulties associated with implementing ICZM and IWSM will be similar or greater in the case of the ecosystem approach. Institutional development and capacity building are likely to be key factors contributing to the successful implementation of the ecosystem approach. In this review we examine whether or not institutions are in place, or could be put in place, capable of delivering the EAA.

METHODOLOGY

The objective for this review is to

"Produce a synthetic view of the present state of freshwater aquaculture management, regarding its condition or preparedness to contribute to sustainable development by using an ecosystem approach".

This report is based upon a global literature review, ideas generated in the EAA Palma de Mallorca Workshop (Soto, Aguilar-Manjarrez, and Hishamunda, 2008) and analysis of a set of case studies of freshwater aquaculture informed largely by field experience. Most of the latter is based on Asia experiences as Asia dominates global aquaculture, with some few cases from other continents. The extent to which the case studies meet the three EAA principles at the three scales are tabulated in each case study.

A framework for analysis

Drawing on the CBD principles, the evolving FAO EAA definition and principles, and the key issues identified above, we have sought to address the following questions in both our overview and in the case studies:

Aquaculture should be developed in the context of ecosystem functions and services (including biodiversity) with no degradation beyond resilience

1. **Impact on ecosystem services.** To what extent does the activity affect important ecosystem functions or services, and at what scale? Does it affect ecosystem productivity, and is this an issue?
2. **Limits to change, resilience and precaution.** Has environmental change gone beyond "acceptable limits"? Has change significantly reduced resilience? Are there mechanisms in place to define, discuss and agree acceptable limits to environmental change at various scales? Is there any awareness of the need for a precautionary approach (for example to conserve resilience) or any corresponding mechanisms? What are the potential/possible mechanisms for introducing these ideas?
3. **Minimising impact.** What practical mechanisms (design, practice) can be used to ensure that environmental change stays within acceptable limits at different scales? What might the expression "no net loss" mean?
4. **Adaptive management.** Is any form of adaptive management in place or envisaged? How might adaptive management work?

Aquaculture should improve human well-being and equity for all stakeholders

5. **Net benefit and equity.** Are there net benefits associated with this form of aquaculture – taking into account social, economic and environmental costs and benefits? Does aquaculture reduce poverty and contribute to equity?
6. **Stakeholder involvement.** To what extent are stakeholders already involved in managing aquaculture and the wider environment? What is the potential for this?

Aquaculture should be developed in the context of other sectors, policies and goals

7. **Integration**. Is integration (of activities, farms, sectors, policies) already practiced and at what level? What is the potential for greater integration and what would be the benefits? Are institutions in place which could promote appropriate forms and levels of integration
8. **Environmental costs.** Are there/could there be initiatives/mechanisms to account or ensure internalisation of environmental costs?

Other

9. **Constraints and incentives.** What are the main constraints to implementing an "ecosystem approach" and how might they be overcome? What incentives might be used?
10. In what other ways do examples or case studies shed light on the implementation of an EAA?

Scale is an issue which applies to all these questions and is taken as a cross cutting theme.

CONCEPTS, TERMINOLOGY AND TYPOLOGY OF CASE STUDIES

Concepts and terminology used in the study address both aquaculture and its interactions with the environment. These include ecosystems and agroecosystems, traditional versus industrial aquaecosystems, types of traditional aquaculture, types of aquaecosystems, and intensification. A typology of aquaecosystems based on the preceding concepts and terminology is presented.

Ecosystems and agroecosystems/aquaecosystems

An ecosystem is defined by the Convention on Biological Diversity (CBD) and the Millennium Ecosystem Assessment (MEA) as "a dynamic complex of plant, animal, and microorganism communities and the nonliving environment interacting as a functional unit" (CBD, 2003; MEA, 2005). The Earth's surface has been divided up by the MEA into ten ecological systems: five natural terrestrial (dry land, forest, island, mountain and polar); three natural aquatic (coastal, inland water and marine); and two human dominated or domestic (cultivated and urban) systems. These same categories are used within the Convention on Biological Diversity.

Cultivated systems are defined as areas where at least 30 percent of the landscape is in either agriculture, confined livestock production or freshwater aquaculture and they now cover 25 percent of the Earth's terrestrial surface (MEA, 2005). Urban systems (including industrial development and transportation corridors such as roads railways and airports) cover only a small area of the total landscape (Odum, 1997).

Terrestrial cultivated ecosystems are often called agroecosystems although the corresponding term for aquaculture, aquaecosystems is seldom used. An agro(aqua) ecosystem is simply an ecosystem that is used for agricultural (aquacultural) purposes. The term agro(aqua) ecosystem is something of a contradiction in terms as classically ecosystems are considered to be more or less closed whilst farming systems are open to varying degrees in terms of nutrient transportation across their boundaries. The production system or culture facility of aquaculture, be it a cage or pond or other, may be considered as an "aqua-ecosystem", the aquatic farming equivalent of terrestrial farming or agriculture, in contrast to natural ecosystems with much more internal nutrient cycling (Edwards, 1993). Following Odum (1971) it is useful to distinguish natural from human dominated ecosystems, in particular farmed or agro-ecosystems. The latter as human dominated are simplified ecosystems to produce food in contrast to a more classical Tansley view of natural ecosystems without considering human impact. When including humans as part of ecosystems it becomes clear that their influence and development activities change nature. The surrounding or external environment of an aqua-ecosystem may be either a natural ecosystem such as a river, lake, coastal bay, or open sea; or an agro-ecosystem if it is a land-based pond within an existing, larger farmed agro-ecosystem or a cage in a man-made reservoir. In the former case ecological concerns are likely to be of greater concern than in the latter case where aquaculture is within an already changed agro-ecosystem. Ecological approaches need to be increasingly introduced into aquaculture development for the sector to be become more environmentally sustainable as a whole (Bartley, 2002; Costa-Pierce, 2002).

Traditional versus industrial aqua-ecosystems

Traditional aquaculture has been developed by farmers or local communities using on-farm or locally available resources in contrast to industrial aquaculture which is science/industrial-based, and concerning the nutrition-based terminology used here, in particular in the use of agro-industrially manufactured feed or inorganic fertilizers. Industrial aquaculture is analogous to the "Green Revolution" in agriculture in terms of nutritional inputs (Tacon and Barg, 2007).

Traditional aquaculture is integrated with other human activity systems as these provided the only sources of nutritional inputs for farmed aquatic organisms before the relatively recent advent of agroindustrially manufactured feeds and fertilizers.

In the FAO Aquaculture Glossary (FAO, 2008), the definition for integrated farming systems is: "occurs when an output from one subsystem in an integrated farming system, which otherwise may have been wasted, becomes an input to another subsystem resulting in a greater efficiency of output of desired products from the land/water area under a farmer's control".

However, this is a rather narrow definition as it essentially covers on-farm integration but there are other types of broader integration linking aquaculture with other human activity systems such as sanitation and agro-industry in peri-urban areas and fisheries, the latter not necessarily directly linked in the sense of sitting side by side. Such broader integrated systems described above are thus based on linking diverse human activities with aquaculture, whether the links be direct and closely associated spatially or indirect and involve some form of transportation. A broader definition of integration is:

'integrated farming involving aquaculture combines concurrent or sequential linkages between two or more human activity systems which is directly on-site, or indirectly through off-site needs and opportunities, or both (Edwards,1998).

Three major types of traditional integrated aquaculture systems have been recognized (Edwards, 2002):

- integrated agriculture – aquaculture systems (IAAS) with usually limited on-farm or local sources of vegetation, manures and agricultural by-products as nutritional inputs e.g. rice/fish; crop/fish; livestock/fish; sericulture/fish.
- integrated fisheries-aquaculture systems (IFAS) use small freshwater or marine trash/low-valued fish as feed.

The term 'capture-based aquaculture' introduced by Ottolenghi *et al.* (2004) differs from IFAS as the former is based on seed rather than feed; capture-based aquaculture is defined as "the practice of collecting seed material – from early life stages to adults – from the wild, and its subsequent on-growing in captivity to marketable size, using aquaculture techniques". While the feed used in the capture-based aquaculture of most target species is mainly based on trash fish as in IFAS, this is not the defining criterion for the farming practice. As examples, the farming of molluscs such as oysters, mussels and scallops and herbivorous finfish such as milkfish and rabbit fish are included in capture-based aquaculture but do not involve feeding trash fish.

- Integrated peri-urban-aquaculture systems (IPAS) using wastes of cities and industry such as wastewater (human sewage or agro-industrial effluents), waste vegetables from markets, waste food from canteens and restaurants, and factory processing wastes from the food industry, including offal from slaughterhouses and fish processing factories

The principles of traditional aquaculture have been characterized as integration with other human activities systems such as agriculture, animal husbandry, sanitation and local agro-industry; polyculture of fish with complementary spatial and feeding niches in the pond; waste or by-product reuse such as terrestrial or aquatic vegetation, livestock manure, nightsoil, brans and oil cakes, and food and drink manufacturing residues; nutrient and water reuse and multiple use between farm subsystems or enterprises; and pond for the production of high protein natural food *in situ* as well as an aquatic environment for fish (Edwards, 2004).

There is usually no integration in industrial aquaculture with sole use of formulated pelleted feed fed to a single target organism raised in monoculture. However, a few types of integration have been developed relatively recently which incorporate some of the principles of traditional aquaculture in an attempt to reduce adverse environmental impact. Examples of integration of some of the principles of traditional aquaculture to reduce the adverse environmental impact of the effluents of industrial aquaculture are: aerated microbial reuse systems, linking intensive aquaculture with hydroponics, linking intensive with semi-intensive aquaculture, integration of cage and pond culture, the 80:20 system[3], and a partitioned aquaculture system. The recently described integrated multitrophic aquaculture (IMTA) in which species from different trophic or nutritional levels are incorporated into the same system e.g. seaweeds to utilize

[3] A system of stocking fish in a pond in which a high-value pellet-fed target species such as crucian carp comprises 80 percent of the stocked biomass and a low-value fish such as silver carp to improve the water quality the remaining 20 percent.

nutrients released from salmon cage farms, may be considered as a type of integrated aquaculture-aquaculture system (Chopin, these proceedings).

Types of aqua-ecosystems

The rice field may be the oldest type of aqua-ecosystem with recent archaeological evidence indicating possible co-evolution of agriculture and aquaculture in the People's Republic of China 8 000 years ago (Edwards, 2004). Fish are stocked in household rice fields usually modified to improve fish growth. Recently, community-based management of seasonally flooded rice fields for aquaculture has been developed in the People's Republic of Bangladesh and Viet Nam (Dey *et a*l., 2005; Dey and Prein, 2006).

Ponds are artificially constructed waterbodies, usually made of earth, essentially static bodies of water with limited water exchange with the surrounding environment during grow-out. Ponds also have a long history and are the predominant type of aqua-ecosystem.

Cages and pens are aqua-ecosystems in which there is a ready exchange of water with the surrounding environment. Cages (known also as pens or net pens in North America) are mostly floating or suspended enclosures with water exchange through the sides and bottom. Pens are fenced areas of shallow waterbodies with sediments forming the bottom of the pen with water exchange through the sides of the enclosure. Cages and pens are located in natural aquatic systems such as lakes (more or less static water on lentic) and rivers (flowing water or lotic) or in artificial waterbodies such as reservoirs and irrigation canals. Site requirements are more demanding than for ponds because of competitive uses of aquatic environments and adverse effects of water pollution from other sectors as well as from the aquaculture practice itself.

Raceways or running water ponds have brick or concrete sides and bottom as they have relatively fast flowing water which also provides dissolved oxygen and removes metabolites of fish stocked at high density and fed complete diets. They commonly occur in hilly or mountainous areas where streams or springs provide a continuous flow of water. Examples are trout farming in Europe and North America and common carp in Indonesia.

Recirculating aqua-ecosystems comprise tanks with water recycling and water treatment through various biological, chemical and/or mechanical filtration devices. They have minimal effluents compared to other systems. Capital and operating costs are high so they can only be justified where the water supply is limited or must be heated to make aquaculture independent of the cool season in temperate climates, and the fish has a high market value. Health management and environmental concerns are also important forcing factors, especially for salmon farming. They may be the most environmentally friendly aqua-ecosystem in terms of waste disposal although they have a high carbon footprint as their construction and operation usually require large amounts of fossil fuel.

Intensity of culture

Commonly used terms for the degree of intensification of production in aqua-ecosystems are extensive, semi-intensive and intensive. As these terms are used in widely varying ways and often without precise definition, for the purpose of this study they are defined as follows (Edwards, 1993):

- extensive systems depend on natural food for the cultured organisms produced within the system without intentional nutritional inputs e.g., traditional rice/fish culture, cage and pen culture in eutrophic waterbodies, and community-based fisheries in rice field floodplains, and in lakes and reservoirs.
- semi-intensive systems depend on fertilization to produce natural food *in situ* and/or on the addition of supplementary feed such as energy-rich brans and oil cakes to complement the high-protein natural food. Natural food provides a

significant amount of nutrition for the fish in semi-intensive systems. Examples are most IAAS and some IPAS (e.g. wastewater-fed aquaculture).

- intensive systems depend on nutritionally complete feeds and there is little or no use of natural in situ productivity. Traditional intensive systems are IFAS in which trash or low-value fish is fed to carnivorous fish and some IPAS in which slaughterhouse waste is fed to fish. However, most intensive aqua-ecosystems are fed with formulated diets, in moist or more commonly in dried pelleted form which are products of agro and fish industries. Most cage, raceway and recirculation systems depend for almost all their nutrition on agro, fisheries industrially manufactured formulated feed.

There is a distinct boundary in terms of nutrition between extensive and semi-intensive systems as defined here; natural food is important in both but in the former, in contrast to the latter, there are no intentional nutritional inputs, which has economic as well as ecological relevance. There may be an overlap between semi-intensive and intensive production; if increasing amounts of feed (as supplementary feed or nutritionally complete feed) are provided to fish in a semi-intensive pond as they grow, the proportion of nutrition derived from natural food declines markedly relative to that of added feed so that the system more resembles an intensive one in the later stages of the culture cycle.

Typology

The typology for the case studies used in this study is based on the preceding discussion. It characterizes aquasystems as traditional or modern. It specifies whether a particular aquasystem is located in a natural or human dominated ecosystem. It also indicates whether the cultured organism is raised in monoculture or polyculture and whether the intensity of culture is extensive, semi-intensive or intensive. Eighteen case studies mostly involving farmer practice from various countries are presented (Table 1). The

TABLE 1
Case studies of aquasystems

Case study	Aqua eco-system	Natural or human dominated system	Intensity	Monoculture or polyculture	Country
1	Rice field	Cultivated	Extensive to semi-intensive	Common carp monoculture	China
2	Pond	Mostly cultivated	Semi-intensive	Polyculture	Viet Nam
3	Pond	Mostly cultivated	Semi-intensive to intensive	Polyculture	China
4	Pond	Cultivated	Extensive to semi-intensive	Polyculture	Bangladesh
5	Pond	Cultivated, wetland	Semi-intensive	Polyculture	Hungary
6	Pond	Cultivated, wetland	Semi-intensive	Polyculture	Malawi
7	Pond	Cultivated	Semi-intensive	Polyculture	Viet Nam
8	Cage	Lake, river	Intensive	Snakehead monoculture	Cambodia
9	Pen, cage	Lake	Extensive to semi-intensive	Milkfish, tilapia monoculture	Philippines
10	Open rice field flood-plain	Cultivated	Extensive to semi-intensive	Polyculture	Bangladesh
11	Open Reservoir	Reservoir	Extensive to semi-intensive	Polyculture	Viet Nam
12	Pond	Cultivated	Intensive	Tiger shrimp monoculture	Thailand
13	Pond	Cultivated	Intensive	Channel catfish monoculture	United States of America
14	Pond	Cultivated	Intensive	Pangasius monoculture	Viet Nam
15	Cage	Lake	Intensive	Tilapia monoculture	Philippines
16	Cage	River	Intensive	Tilapia monoculture	Thailand
17	Raceway	River, cultivated	Intensive	Trout monoculture	Denmark
18	Recirculation	Cultivated or human dominated	Intensive	Eel, Tilapia monoculture	Denmark, United States of America

TABLE 2
Approximate relationship between yield (tonnes/ha/year) and intensity of culture.

Intensity of culture	Yield (tonnes/ha/year)					
	0-1	1-5	5-10	10-20	20-100	100-1,000
Extensive						
• no nutritional inputs						
Semi-intensive						
• low quality manure, macrophytes, supplementary feed		+				
• high quality manure, supplementary feed			+			
• inorganic fertilization, pelleted feed						
Intensive			+	+		
• pelleted feed, static water						
• pelleted feed, aeration			+	+		
• pelleted feed, recirculation					+	
• pelleted feed, raceway					+	
						+

Source: modified from Edwards (1993)

first six are traditional IAAS (one rice/fish and five pond culture, although in case study 4 from Bangladesh and case study 6 from the Republic of Malawi the technology was introduced through development projects), one traditional IPAS, and one traditional IFAS. Three case studies are on modern extensive to semi-intensive aquaculture which was introduced through projects (case studies 8-10) and the remaining eight case studies are modern intensive culture in various types of aqua-ecosytem.

OVERVIEW OF THE CASE STUDIES

In this section we examine the meaning of the three draft principles, and associated ideas derived from the Convention on Biological Diversity, in relation to freshwater aquaculture drawing on our case studies as appropriate.

Aquaculture should be developed in the context of ecosystem functions and services

In this section we explore the various impacts of freshwater aquaculture on ecosystem functions and services, acceptable standards or limits to change in relation to these effects, and mechanisms – at both farm and higher levels – by which impacts can be reduced, or maintained within acceptable limits.

Impacts on ecosystem functions and services

The impacts of aquaculture on the environment have been revised extensively (Pullin, Rosenthal and Maclean, 1993; Phillips, 1994; Beveridge *et al.*, 1997). Especially note worthy is FAO/NACA (1995), a regional Asian study and an environmental assessment of aquaculture. The environment may have an impact on aquaculture as well as aquaculture having an impact on the environment so possible interactions are two-way. Environmental impacts of aquaculture may be neutral, positive or negative.

Many aquaculture systems are seen as having a negative effect on biodiversity, although our cases do not reveal any quantitative assessments of this. This is related to:

- loss of biodiversity through habitat conversion and intensification, and inappropriate sitting of farms leading to negative impacts on sensitive habitats;
- organic sediment discharge leading to benthic change. The rate of accumulation will determine whether this leads to increases or decreases in biodiversity and productivity.
- eutrophication of waterbodies;
- impact of released chemicals and drugs on biodiversity;
- genetic, ecological and disease impacts on wild stocks through the presence or release of farmed stock;
- indirect impacts on supply fisheries and other sources of fish feed;

- impact of wild seed collection on wild stocks; and
- introduction of invasive species/alien species.

Habitat conversion

All forms of agriculture and aquaculture have a major impact on biodiversity. Even the more traditional and extensive systems (such as traditional rice-fish culture in Zhejiang Province – case study 1, Annex 1) represent a massive change in habitat and biodiversity relative to the pre-agricultural era. An "agro-ecosystem" has been created characterised by increased productivity of specific elements in the system – that is rice and fish – and reduced production of less valued habitats and species. These systems are also characterised by huge changes to the physical system – in terms of topography, soils and hydrodynamics.

Despite these impacts, such systems are widely regarded as sustainable for three main reasons:

- They are *stable*. Some have generated a stream of valued products for more than a thousand years (case 1).
- They no longer have significant impact on surrounding habitat or aquatic systems.
- They are often characterised by moderate or high biodiversity (although their original development involved a significant *change* in biodiversity).

Regarding this last point it is notable that some fish farming systems are now being designated as nature reserves. A traditional fish pond system in the Republic of Hungary has now been designated as a nature reserve, and boasts 220 species of bird (case 5, Annex 1). Seven fish farms in Hungary and the Czech Republic are now protected under the Ramsar convention. (Chytil *et al.,* 2006). In Hong Kong abandoned shrimp pond systems have been designated as nature reserves. They have also become important for migrating cormorant, herons, and otters. Managing these reserves as fish ponds may be the only way to keep control of siltation, prevent vegetational succession and preserve deeper open water suitable for wildlife.

Most ponds have probably been constructed in cultivated rather than natural terrestrial systems. Ponds are widespread in floodplains in Asia where they were dug initially as borrow pits to provide earth to raise the level of the ground to reduce flooding of the farm homestead. Borrow pits along transportation corridors such as roads and railways are often converted into fish ponds. In many cases, fish ponds have however, been constructed in natural wetlands. The best known and largest area is the dike-pond system South China which occupied 800 km^2 at its peak in the 1980s (Ruddle and Zhong, 1988). Starting about 600 years ago, the coastal and riverine wetlands of the Pearl River Delta were gradually reclaimed by conversion to fish ponds separated by wide cultivable ridges. Fish ponds in Central Europe were built on wetlands and water logged fields or on marginal land where agriculture was not economically feasible (Matena and Berka, 1987).

More intensive systems are typically associated with less biodiversity, at least within the farming system itself. This arises because:

- nutrients are sometimes at higher levels than natural systems;
- a larger proportion of natural productivity is "captured" in the target crop; and
- chemicals may be used to eliminate "weed species", predators, pests and disease carriers.

Limits to change

We allow conversion of land, intensification of production, and parallel reduction in biodiversity because it has been the foundation of civilisation, and historically has lifted us out of poverty. In most cases we have no choice: we cannot support the world's population by reverting to natural ecosystems or even to highly extensive agro-ecosystems. The question is rather, have we gone too far?

The reduction in biodiversity – normally to the benefit of the target crop – may threaten the resilience and stability of the system, thereby making it less "sustainable". The case studies offer few insights into this issue. Many of the semi-intensive pond systems have been going for hundreds of years, although grass carp has been subject to periodic disease problems, especially with increased feed inputs. Only the inland shrimp farming (and of course shrimp farming more generally) is characterised by instability and periodic collapse, though in many cases farmers accept regular crop failure as a necessary cost, or a temporary set-back.

Nor is there clear evidence that other ecosystem services (to aquaculture or to other users) have failed as a result of biodiversity losses associated with aquaculture development. Wild capture fisheries of larger valuable floodplain species have declined in countries like Bangladesh and the Kingdom of Cambodia, related probably to infrastructure development. Some of this may be related specifically to aquaculture, but flood prevention, roads, land reclamation and so on are undoubtedly the major factors (Bangladesh Fisheries Sector Review, 2003). Hunting opportunities have probably declined in many instances, though case 5 (traditional carp farming in Hungary) offers an example of aquaculture enhancing hunting of especially bred and stocked semi-wild ducks.

Land use and habitat change has been subject to public scrutiny in all parts of the world. In the past many countries had specific policies which prevented the conversion of rice fields to other uses – though as the price of rice has fallen, so have such policies weakened. Indeed, in the Red River Delta for example (case study 2, Annex 1) the Government now encourages conversion of rice fields to fish ponds in those areas where only one rice crop per year is achievable.

Recently the local government in Andhra Pradesh in India (which is regarded as the 'fish bowl' of the country) has demolished manually and using explosives, almost 3,000 hectares of fish ponds covering almost 30 000 ha in a wild life sanctuary in Kolleru lake (Ramakrishna, 2007). The sanctuary supports about 188 species of birds. A devastating flood in 2005 was exacerbated by fish ponds blocking the natural drainage through the lake and ultimately into the sea.

Defining limits to land-use change is typically part of the planning process, influenced by local and national political and economic interests. The Andhra Pradesh example, and the Thai Government's ban on shrimp farming in freshwater areas (see below) both show that when impacts on land use and biodiversity are such as to significantly affect delivery of a key valued service such as flood mitigation or water suitable for traditional agricultural production, government will act to prevent further problems. A similar case can be cited for Chile where cage aquaculture has been banned in lakes after some impacts from salmon and trout farming have become evident (Leon-Munoz *et al.,* 2007).

These examples are unfortunately representative of a crisis management approach rather than a strategic or precautionary approach, and cause great disruption to local economies.

Unfortunately it is tough to predict these problems in most cases, and institutions capable of implementing a more strategic approach are lacking. One way round this may be to implement some general principles which will reduce the chances of ecosystem service failure. Any agro-ecosystem is likely to be *more stable, more resilient, and more productive* if we retain corridors and patches of uncultivated land (for example as a reserve of pest predators, pollinators etc). This is discussed in more detail in "Green infrastructure – safeguarding ecosystem services in the wider environment" section.

Nutrients

Almost all aquaculture – whether traditional or modern, in developed or developing countries – involves the import of nutrients in the form of feed or fertilizer. This is normally the case irrespective of whether or not it is "integrated" (Edwards, 1993). A proportion of these nutrients are harvested, but much remains in the system – in water, sediment and soils.

In intensive systems only 20-30 percent of nitrogen and phosphorus contained in feed fed to fish is incorporated into fish and removed at harvest with the rest being discharged into the culture environment (Edwards, 1993; Avnimelech, 1998). In pond culture most of the nutrients are accumulated in the sediments (Avnimelech and Lacher, 1979) whereas in cage and running water pond/raceway culture they are discharged into the external environment.

Aquaculture effluents may not be a problem as natural breakdown processes or dilution in the receiving waters can assimilate them, provided that they are not overloaded (FAO, 2006). Under most circumstances biodiversity increases with modest increases in nutrients, and then declines as levels increase further. In spatial terms this typically means that biodiversity will be reduced within the aquaculture system itself and at points of discharge, but may increase (along with productivity) as nutrients are diluted in the wider environment. Tett *et al.*, (2007) define an "optimum" level of organic enrichment likely to enhance biodiversity and ecosystem "vigour". Moderate nutrient enrichment of some ecosystems may lead to increased production of commercial fisheries (ESA, 2000). It has been suggested for example that the nutrient enrichment from *Pangasius* culture in the Mekong Delta may enhance fisheries in the S. China Sea (case study 14, Annex 1). Nutrient enrichment to concentrations slightly above natural levels may have a positive effect on lakes and rivers through increased fish production, but hyper-eutrophication leads to fish kills at all scales from rivers and lakes to watersheds such as the Chesapeake Bay and Mississippi river watersheds and the Gulf of Mexico in the United States of America and the Baltic, Black and North seas in Europe (Novotny, 2007).

Raised nutrient levels may therefore impact other activities positively or negatively dependent upon the local context. In agricultural systems the impact is likely to be positive. In more natural and oligotrophic systems the impacts are often regarded as negative, though this is not always so (Soto and Jara, 2007).

The relative contribution of various human activities such as the various types of farming (agriculture, animal, and husbandry), industry and urbanization as well as aquaculture to environmental degradation needs to be considered also. In most cases these remain to be quantified, although aquaculture is often the lowest contributor except in "hot spots" where aquaculture farms are clustered in high density such as Lake Taal (case study 15, Annex 1). The major changes in the agricultural sector in the last 50 years have been a major shift from family farming which causes less diffuse pollution to large-scale commercial and mostly monoculture agri-businesses (Novotny, 2007). A similar change is occurring in aquaculture. These changes have led to excessive diffuse pollution and unsustainable adverse impacts on the environment.

A material flow analysis model (MFA) has been developed for the Tha Chin river basin, the Kingdom of Thailand to assess the entire path of pollution generation from its origin through different transformations and diversions to its final discharge into the river (Schaffner *et al.*, 2006). The relative contribution of aquaculture to the other major sources of nutrients to the river basin (rice, fruit and vegetable farms; feedlot pig and poultry farms; factories; urban areas) remains to be assessed although nutrient and water flows from different types of aquaculture farms have been modelled (Wittmer, 2005).

Acceptable nutrient levels

These are difficult to define, since desirable levels depend on who you are and where you are. High nutrient levels only compromise "ecosystem function" in extreme and typically localised situations, but they do cause change which may bring costs to some and benefits to others. *Defining appropriate limits should therefore be informed by local as well as national aspirations and scientific interest*. This is very rarely the case. Standards for freshwater are commonly set and used by national government and their agencies throughout the world. In many cases these levels are already set at what might be termed "precautionary" levels. Some of these apply specifically to aquaculture, as in Viet Nam for example – although implementation remains limited.

The standards used by government usually relate, very loosely, to nutrient levels which may cause algal blooms and de-oxygenation, or compromise drinking water quality. These issues however need to be examined in relation to a waterbody or system, and the needs and aspirations of those people who depend on it. The Water Framework Directive[4] (promoting a form of integrated watershed management) in Europe seeks to move in this direction, but remains very technocratic and conservative: good water quality is closely associated with what is known as good ecological status – essentially corresponding to a "natural" (typically very low nutrient) baseline. This may not be the most desirable status for the various users, may not be appropriate for a developing country, and it may not be that which maximises biodiversity.

This highly precautionary approach is also adopted in particular European countries. Thus in the Denmark nutrient discharge is highly restricted, amounting in some cases to near "zero discharge" – irrespective of other interests.

An ecosystem approach would examine more carefully the desirability of different nutrient levels in different parts of an agro-ecosystem from the perspectives of the various users, and in terms of the stability of the system as a whole. In other words *there needs to be a more flexible and participatory approach to the setting of water quality standards.*

Chemicals

The more intensive aquaculture systems now often use substantial quantities of chemicals – mainly pesticides and antibiotics – which directly reduce biodiversity both within the system and outside, and whose use may in addition have direct and indirect impacts on human health. There are also resilience issues here: chemicals may suppress immune systems, or seriously affect particular trophic groups, making the ecosystem more vulnerable to pressures and shocks.

In terms of source, the worst examples are perhaps the newly intensive or semi-intensive systems, in which biosecurity is poor, the impacts of disease serious, and protocols for the use of chemicals limited in development and implementation. Some very intensive recirculation systems have been able to greatly increase biosecurity by isolating the production system from surrounding waterbodies, and thereby reduce chemical use. The development of vaccines and other preventative measures also allows for a reduction in the use of chemicals as the Norwegian experience shows.

Aquaculture itself has often been the victim of chemicals discharged from other sectors. Many of the more traditional forms of rice-fish culture (case study 1) are compromised by the widespread use of pesticides, in some cases detrimental to fish. Case study 16 illustrates an example of red tilapia cage culture in Thailand which recently suffered major losses due to a sudden drop in dissolved oxygen in the river due to agro-industrial pollution.

Acceptable levels

No one wants noxious chemicals, and especially persistent chemicals in the wider environment. They are allowed only because of the benefits they generate in terms of reduced losses from disease. Ultimately then, acceptable levels should depend on a cost-benefit calculation to society as a whole, taking full account of all the risks

[4] Foundation for Water Research. 2008. [online]. United Kingdom.[Cited 2 June 2008]. www.euwfd.com/

and uncertainties involved. This is rarely done explicitly, and the decision is usually left to scientists rather than stakeholders. Given the wider interests and uncertainties involved, it is arguable that more transparent and participatory procedures should be introduced.

It is also arguable that governments should be more "precautionary" with respect to chemicals, given their insidious nature, the potential for serious consequences, and the uncertainties surrounding their effects. However, there is a fundamental dilemma here: if chemicals are not readily available for use, disease may spread rapidly, and ultimately there may be either – or both – massive costs to the sector, and widespread large-scale use of the chemicals in an attempt to stamp out an epidemic. The meaning of a precautionary approach is far from clear in such circumstances, but thorough risk assessment (GESAMP, 2008) undertaken by national or local government is vital to inform both practice and regulation.

Impacts on water supply

Irrigation accounts for 70 percent of the water withdrawn from freshwater systems for human use with only 30-60 percent of that amount returned for downstream use (Wood, Sebastian and Scherr, 2000). Irrigation for agriculture is the largest net user of freshwater globally and dwarfs that used by aquaculture although the latter is rising significantly with expansion of aquaculture. Water is especially important for aquaculture as it is the medium in which aquatic organisms are produced. Water-based aquaecosystems such as cages and pens do not use or consume water as the culture facility is placed in a natural or artificial aquatic waterbody. In contrast, land-based aquaecosystems consume water to varying degrees depending on the type of facility and the rate of water exchange with the external environment, although raceways associated with springs or streams only "borrow" the water as the water flows through the culture facility so quickly (Boyd, 2000). Pond aquaculture is a water-intensive practice because large amounts of water are needed to fill up the pond and maintain the water level throughout grow-out due to losses from evaporation and seepage. Water reuse is expected to become increasingly important to conserve water as well as to reduce the volume of pond effluents and associated pollution (Boyd, 2000). Water use in aquaculture therefore includes both consumptive use in which there are losses in ponds and non-consumptive use in which water passes through the aquaecosystem such as raceways and cages and is returned to the lake or river.

The water requirement for various aquaecosystems ranges from 0.1-0.2 m^3/kg of fish production for recycling systems through 2.0-6.0 for intensive fish ponds up to 500-900 kg/m^3 for flow-through systems (Varadi, 2002). Water reuse efficiency can be greatly improved through reducing the water exchange rate, either by microbiological processes or by recirculating the water between production and water treatment units, as well as by integrating aquaculture with other water users (Varadi, 2002).

Israel provides good examples of the development of water efficient aquaculture because of the limited water resources of the country because of its arid climate. The national water reserves are fully exploited because of intense development of agricultural, industrial and urban areas during the last 20 years (Mires, 2000). As aquaculture depends on the availability of water, aquaculturists have been developing water saving strategies for many years which include harvesting run-off and sharing water from reservoirs with agriculture. In Israel most inland aquaculture is carried out in dual-purpose reservoirs used for irrigation as well as aquaculture. Highly water efficient intensive closed-water systems have been developed but their economic viability remains to be demonstrated. Super-intensive aquaculture recirculation systems are the most water efficient of all animal production systems, aquatic and terrestrial livestock (Verdegem *et al*., 2006) but are capital and energy-intensive to construct and operate.

One predicted effect of climate change associated with global warming is on rainfall. Tropical regions north of the equator where a significant amount of global aquaculture is located such as south and Southeast Asia are expected to receive less rainfall. Some of these countries are already exhibiting lowered water tables as a result of agricultural abstraction, and expanding aquaculture is likely to exacerbate this.

Some modern aquaculture has had significant impact on the level and salinity of the water table. Pumping of water from boreholes is increasingly common for both agriculture and aquaculture, and consequent lowering of water table has become a significant issue in South and Southeast Asia. Pumping of freshwater from boreholes near the sea may in addition cause saline intrusion underground. The deliberate introduction of seawater also occurs in some countries where shrimp culture has been extended inland (case 12).

Salinization is perhaps a less critical issue from an ecosystem perspective: the system and its ecology may change, but still "functions"; the effects are easily monitored and regulated, and are usually limited in geographic extent. This is more a question of choice, and again a cost benefit calculation is required. This is more easily done than that for chemicals because there are both fewer uncertainties and fewer stakeholders. However, it is notable that the decision by the Thai Government to ban shrimp farming in freshwater areas was not informed by any comprehensive cost benefit analysis. The "limit to change" was determined by a *precautionary policy principle:* we do not want to compromise long term rice production in favour of high but risky (and probably short term) returns from shrimp farming.

Intensive pond fish culture (for example inland shrimp farming, *Pangasius* farming) generates substantial organic sediment which can lead to sediment build up and anaerobic conditions in small waterways and canals. In some cases these canals simply become settling and waste treatment systems in their own right; in other cases the build up compromises their functioning and value for other users.

Introductions, escapes and genetic impacts

Aquaculture, like agriculture, is characterised by the introduction of alien species and by genetic modification of both indigenous and alien species. The use of alien species and genotypes (genetically improved species) is a valid means to increase production in aquaculture (Bartley, 2007). Unfortunately aquaculture organisms escape – however good the bio-security measures – and there is always the possibility that they will become established and change the nature of the ecosystem – either directly through predation or competition with indigenous organisms, as a result of genetic modifications through interbreeding, or as a result of disease introductions. There are examples of these impacts from throughout the world.

Many of our cases (Annex 1) reveal the widespread introduction of alien species: tilapia in many Asian countries; Chinese carps in south Asia and eastern Europe; Indian major carps in southeast Asia; and more recently American white shrimp in east and southeast Asia. Government policies are typically weak and inconsistent. Some countries have sought to exclude tilapia in the past, but now tacitly accept the introductions. Although Viet Nam is seeking to restrict introduction of American white shrimp to particular Provinces this will be extremely difficult to control, and more widespread release is likely. Common carp, Indian major carps and Chinese carps have been moved around the world for decades and in some cases for centuries, and it would be impossible to control this effectively now.

Grass carp has been stocked in traditional fish ponds in Europe (the Federal Republic of Germany, the Czech Republic, Hungary) for many years, but the changing priorities of the public are leading to some conflicts, with strong pressure on fish farmers to cease stocking this alien species, and to make the fish ponds more "natural". This is despite the fact that grass carp help to reduce the excessive growth of aquatic macrophytes which if unchecked would lead to natural ecological succession of vegetation through wetland to terrestrial ecosystems, with the eventual disappearance of the waterbody.

Despite the ecological risks most governments are understandably reluctant to prevent introduction of species that may enhance or stabilize aquaculture production. The very history of civilization can be traced to the introduction and genetic modification of alien species.

There is very little documentation on the impact of many introductions, with most involving disease transmission that have mostly impacted the aquaculture industry itself. According to the records in the FAO Database on Introductions of Aquatic Species[5], the majority of introductions in aquaculture have led to positive social and economic benefits. A large number of exotic species have been introduced to Southeast Asia, some of which play a significant role in national economics e.g., exotic species account for about 49, 100, 26 and 73 percent of the total aquaculture production in Cambodia, the Lao People's Democratic Republic, Thailand and Viet Nam, respectively (Yakupitiyage and Bhujel, 2003). Current evidence in the Asia-Pacific region indicates that widely farmed tilapias which are already present in most of the watersheds of the region have had no major negative impact on biodiversity (De Silva,Amarasinghe and Nguyen, 2006). Furthermore, tilapias are an important group of cultured species in most countries of the region providing an important role in food security and poverty alleviation as well in local, and in some countries, in international. Nevertheless, it would be wise to prevent the spread of tilapia to environmentally sensitive areas. In conservation areas there should be no introduction of alien species and possibly no aquaculture (Mattson, Bartley and Funge-Smith, 2005).

The way forward has to be simply one of more openness and – again – thorough risk assessment. A naïve "precautionary approach" would ban all introductions and modifications, because there is always the risk of ecosystem impact and the associated science is always highly speculative. A pragmatic precautionary approach is one which weighs the severity and likelihood of negative impact on the wider ecosystem, and balances this against potential social and economic gain[6].

The motivation to introduce alien species should be reduced as far as possible through development work with native species – again an area being promoted by many governments and international organisations. However, it is unrealistic to expect that the development of the farming of indigenous species will be able to replace the farming of well established exotic species that have become local food fish in many countries as well as internationally traded commodities.

Fisheries

A large number of species are farmed using marine or freshwater low value and trash fish, either exclusively or in part, in cages or ponds in coastal and inland areas although the main issue is with marine trash fish globally. However, use of freshwater trash fish for feed in aquaculture is not common as preservation of small freshwater fish for sale as human food is usually more profitable than using them as feed for carnivorous fish (FAO, 2005). Case study 9 concerning farming giant snakehead (*Channa micropeltes*) in cages in Cambodia is rather a special exception and the practice has recently been banned by the Government.

In inland aquaculture, a traditional feed for eel (*Anguilla japonica*) was marine trash fish but almost all forms of intensive eel farming in a range of systems now rely on artificial commercial feed. This is a moist paste for larval glass eels and steam pressed or extruded pellets for later stages (Ottolenghi *et al*., 2004). Several freshwater species are cultured in Asia using mainly marine trash fish, e.g. in Thailand, striped snakehead

[5] FAO. 2008. Database on Introductions of Aquatic Species [online]. Rome, FAO. [Cited 2 June 2008] www.fao.org/fishery/introsp/search/en

[6] FAO is currently developing guidance on such risk assessment approaches.

(*Channa striata*) is raised in ponds, and marble goby (*Oxyeleotris marmoratus*) is raised in cages. Soft shelled turtle (*Trionyx sinensis*) is raised in earthen ponds in China, Thailand and Viet Nam using a marine trash fish based diet. *Pangasius hypophthalmus* is partly raised in Viet Nam on a diet of marine trash fish and rice bran in cages, pens and ponds in the Mekong delta in southern Viet Nam. There is limited production of two species of snakehead (*C. micropeltes* and *C. striata*) in Nam Ngum reservoir in the Lao People's Democratic Republic using small freshwater pelagics.

Direct use of trash fish to feed carnivorous fish is unlikely to be sustainable in the long term (FAO,2005). The challenges for aquaculture are to make better use of the existing low value fish and trash fish resources, but in particular to seek alternatives to direct feeding of trash fish in aquaculture. The challenges have social, economic and political as well as technical and environmental dimensions. Stakeholders include small and large-scale fishers and farmers as well as fish processors and feed companies, traders and government. There is a need to recognize that change will have significant implications for the people involved, especially for the poor involved in harvest, and use of trash fish.

An action plan was developed at the Regional Workshop on" Low Value and Trash Fish in the Asia-Pacific Region" in Hanoi, 2005 (FAO, 2005). This was based on a diagrammatic understanding of the supply and demand cycle for low value/trash fish with three possible points identified for intervention: better utilization; reduced use in aquaculture and livestock feeds; and fishery interventions. It was further recognized that there is a need for consistent policy between aquaculture development and fishery management which usually proceed independently of each other, based on a common understanding and information base for decision-making.

Most modern forms of aquaculture are dependent upon the input of compound feed, with fishmeal as a significant ingredient. The sustainability of fishmeal supply has been the subject of much study and debate (Tacon, Hasan and Subasinghe, 2006; Deutsch *et al.*, 2006; SEAfeeds 2003, New and Wijkström, 2002). Given demand and limited resources, it is inevitable that the price of fishmeal will rise, and feed producers will turn increasingly to alternatives. Much research has been undertaken on substitutes and it is well established that a high degree of replacement is possible for most species and in particular for omnivorous freshwater fish, including crucian carp, grass carp, catfish and Tilapia (Cremer, 2006a). In the mean time there are initiatives underway to ensure the sustainability of supply fisheries through certification under the Marine Stewardship Council.

The guidance here is simple and clear: try to reduce dependence on trash fish and fish meal (the price will go up!) and *use only fishmeal/trash fish from sustainably managed fisheries.*

Overall

The case studies tell us rather little about the impact of fish farming on ecosystems or the wider environment. In a sense it is self evident – aquaculture, like agriculture results in huge changes to natural systems, and the creation of "agro-ecosystems" and "aqua-ecosystems" designed to enhance delivery of specific valued ecosystem services (i.e. food and materials production). So long as delivery is sustained, this is widely regarded as a good thing. This may result in loss of biodiversity – a sacrifice most developing economies are quite willing to make - so long as this does not, in turn, undermine the delivery of the valued services themselves. There are now signs that some of these services are being compromised (instability in production; pollution events; increased flooding; erosion; dwindling or poor quality water supplies), and increasing appreciation that changes to current practices are required

In the next section we examine how these pressures can be reduced and ecosystem service delivery maintained or enhanced.

MECHANISMS TO MINIMIZE IMPACT

Nutrients

Managing sediments

Pond mud is a major sink for nitrogen and phosphorus in fertilized and supplementary-fed semi-intensive ponds and in pellet-fed intensive ponds and is traditionally removed in China and Viet Nam for use as a crop fertilizer. However, removing pond mud is labour intensive and the practice is not common in the tropics. Rotation of fish culture and agriculture by cultivating plant crops in nutrient-rich sediments in drained fish ponds was a traditional practice in Hungary but has been discontinued (L. Varadi, personal communication, 2008). Shrimp and *Macrobrachium* are currently grown in rotation with rice in Bangladesh and Viet Nam. Research recently demonstrated the feasibility of cultivating lotus (*Nelumbo nucifera*) to recover nutrients from pond mud, either cultivated alone in the ponds in rotation or in polyculture with tilapia (Yi, Lin and Diana, 2002).

Following the successful use of wetland-type ecosystems to treat domestic wastewater in Europe and the United States of America, these systems are currently being researched for the treatment of intensive aquaculture effluents. Research is being carried out in Hungary on various ways to treat effluents from intensive fish farms, especially African walking catfish (*Clarias gariepinus*). Catfish and Nile tilapia were stocked at high density and fed pelleted feed in monoculture in five 1 ha ponds and the effluent was recirculated within a single 20 ha semi-intensive pond stocked with common carp, bighead carp and silver carp which resulted in a significant reduction of nutrient discharge to the surrounding aquatic environment as 55 percent of the nitrogen and 72 percent of the phosphorus were retained by the system (Gal *et al.*, 2003). A pilot-scale pond-wetland system was also constructed to treat the effluent of an intensive catfish farm (Kerepeczki *et al.*, 2003; Kerepeczki and Pekar, 2005). Nitrogen and phosphorus were primarily removed by the food webs of the ponds stocked with filter-feeding fish while suspended solids were mainly retained by the wetlands which were partially covered by emergent aquatic macrophytes such as cattails and reeds. Research on the treatment of intensive fish farm effluents in a combined fishpond-wetland system is continuing in Hungary with funding through an EU funded research initiative "SustainAqua"– an Integrated Approach for a Sustainable and Healthy Freshwater Aquaculture[7].

Research has also demonstrated that appropriate management to harvest fish could minimize the environmental impacts of pond effluents. The commonly used practice in Thailand to harvest fish is to drain the pond from 1.0 m water depth to 0.5 m, seine twice, and then completely drain the pond to collect the remaining fish. This however leads to a large amount of waste being discharged to the environment. Research has demonstrated that tilapia can be harvested by seining without draining the pond following anaesthetization with tea seed cake (Lin *et al.*, 2001). Channel catfish ponds in the United States of America are not drained for up to 20 years as natural processes remove nutrients and organic matter from pond water.

Integrated aquaculture systems

There are several examples of research to use one or more of the principles of traditional aquaculture to reduce the adverse environmental impact of the effluents of intensive aquaculture.

Aerated microbial reuse (AMR) systems

In the aerated microbial reuse (AMR) system in Israel, low-value carbohydrate-rich supplementary feed is added to intensive culture of pellet-fed tilapia to stimulate

[7] SustainAqua.2008. [online]. Germany. [Cited 2 June 2008]. www.sustainaqua.org

nitrogen uptake by heterotrophic bacteria (Avnimelech, Kochva and Diab, 1994). The bacterial flocs created by constant aeration provide nutrition for the fish, thereby reducing feed costs and also reduce the excess nitrogen in the system. Microbial flocs bioconvert most wastes into natural food organisms which can be consumed by filter-feeding freshwater fish such as tilapia as well as by marine shrimp, in contrast to conventional biofilter systems which aim to treat water in recirculation systems by removing particulate waste (Serfling, 2006). Microbial flocs consists of bacteria, fungi and microalgae suspended with organic detritus in the culture system water. Microbial flocs treat most wastes by converting them into natural food, thereby reducing both waste disposal costs and feed costs. A large commercial-scale tilapia farm was developed in California, the United States of America in the 1980s which used microbial flocs. A similar tilapia farm was developed during the 1990s in Jordan and still operates (Serfling, 2006). AMR appears to have limited commercial application to date in either intensive culture of inland fish or coastal shrimps. Such systems may suffer from consumer resistance: the idea of animals grown in a bacterial soup is not immediately appealing, and undermines the fresh clear image of most seafood.

Intensive aquaculture and hydroponics

These systems have been run on a pilot scale since the mid '70s but few have been fully commercialised. A recent example is a commercial-*scale* integrated aquaculture aquaponic recirculation system being run as a prototype at the University of the Virgin Islands (Rakocy, Masser and Losordo, 2006; Rakocy *et al*., 2007). Tilapia are reared in tanks and are fed with pelleted feed and the effluents are used to fertilize vegetables such as basil, lettuce and okra on floating sheets of polystyrene in hydroponic tanks. The system occupies 500 m^2 of land and can produce annually 4.2-4.8 tonnes of tilapia and 5 tonnes of basil, 2.9 tonnes of okra or 1 400 cases (24-30 heads per case) of leaf lettuce. The immediate potential is for niche markets in which consumers are willing to pay a higher price for high-quality fish and vegetables. Aquaponic systems based on the UVI design have been constructed and perform well at temperate sites in New Jersey and Illinois, the United States of America and Alberta, Canada, in the tropics in Guadalajara, Mexico and economic studies are in progress (Rakocy and Baily, 2003;Hutchings, 2007; Savidov, Hutchings and Nichols, 2007) and initiatives are underway also in Australia, India and Thailand (Lennard, 2007a,b). These approaches are similar to the "Integrated Multitrophic aquaculture systems" (IMTA) being developed in both freshwater and marine systems. IMTA systems combine fed aquaculture of fish with extractive inorganic aquaculture of seaweed and extractive organic aquaculture of shellfish (Ridler *et al*., 2007). These are specifically designed to minimise both import and export of nutrients at the farm level, or within a closely associated group of enterprises. So far this approach has been driven mainly by environmental concerns rather than profitability.

Intensive and semi-intensive aquaculture

Walking catfish (*Clarias macrocephalus* and *C. gariepinus*) in Central Thailand is raised intensively at high density on agro-industrial by-products such as slaughterhouse waste and rice bran and/or pelleted feed which produces nutrient-rich effluents. Some farms discharge the effluent into ponds stocked with Chinese and Indian major carps and tilapia (Little and Griffiths, 1992). Research has also been carried out on discharging or recirculating nutrient-rich effluents of intensive aquaculture ponds into, or through, semi-intensive ponds as a fertilizer where they are treated and converted into plankton and grazed by filter-feeding fish. In Israel water from intensive 1 000 m^2 fish ponds on a farm was reported to be exchanged five times per day with that in larger ponds which function as treatment reservoirs as well as semi-intensive fish ponds (Avnimelech, 1998). While the water quality in the intensive pond was usually high, the combined system required a large area of land as the ratio of semi-intensive to intensive ponds was reported to be at least 10:1. Research on the use of intensive aquaculture effluents to fertilize fish ponds has also been carried out in Hungary (Gal *et al*., 2003)

Pellet-fed caged fish fertilizing surrounding fish pond

Research has developed an integrated system in which the wastes from pellet-fed tilapia raised in cages are treated and recycled in a static water pond in which the cage is floated (Yi, Lin and Diana, 1996; Yi, 1999). Tilapia fingerlings were nursed until they were about 100 g in semi-intensive culture in the pond feeding solely on natural food produced by fertilization of the pond with caged fish wastes. They were subsequently stocked in the cages and raised on pellets until they reached a marketable size of at least 500 g. Caged tilapia and open-pond tilapia incorporated about 36 percent nitrogen and 45 percent phosphorus and 21 percent nitrogen and 28 percent phosphorus in body tissue, respectively, with pond mud acting as a sink for 20-29 percent nitrogen and 27-45 percent phosphorus. Previous research had shown that it takes 5 months or more to raise large tilapia of relatively high-market value in semi-intensive pond culture but this could be achieved in 3 months in the cage/pond integrated system while simultaneously nursing fingerlings to stock in the next culture cycle and treating the wastes of intensive tilapia cage culture. The more intensive production in the cage/pond system is unlikely to carry a health management risk as the integrated system is a 'green water' system with high pH caused by intense photosysnthesis during the daytime probably leading to rapid attenuation of any fish pathogens.

80:20 Chinese system

A feed-based system which combines intensive production of high-value fish with traditional Chinese polyculture has been developed by the American Soybean Association (Ye, 2002). The system is called "80:20 pond fish culture" because about 80 percent of the harvest weight comes from one high-value species such as grass carp, crucian carp or tilapia fed with pelleted feed, and the other 20 percent comes from a "service species" such as the filter feeding silver carp which helps to clean the water and the carnivorous mandarin fish (*Siniperca chuatsi*) which controls wild fish and other competitors. Feeding the major high-value species with a nutritionally complete and high physical quality extruded feed results in better feed conversion, faster growth much higher production, and higher profits than in traditional polyculture technology while having much less impact on the environment. Based on 17 years experience through trials and demonstrations in China of the American Soybean Association International Marketing (ASA-IM) Program in conjunction with the Chinese Extension Service, the ASA-IM has recently expanded its effort to promote the 80:20 system in several countries in India, Indonesia, Philippines and Viet Nam (Manomaitis and Cremer, 2007).

A "partitioned aquaculture system" (PAS) has been researched which adopts high-rate microalgal culture to fish culture (Brune *et al.*, 2003). Low-speed paddle wheels move large volumes of water at low velocities uniformly throughout the pond with filter feeding tilapia reducing algal biomass in water produced by fertilization from pellet-fed channel catfish raised in adjacent raceways

Waste treatment, assimilation, recycling, integration – a comparison of systems

The case studies, and the examples above, reveal 6 different approaches or types of system in terms of nutrient balance with the wider environment. Almost all systems involve the import of nutrients from outside the system, although some use mainly relatively local sources (e.g. manure), others use regional resources (such as food processing wastes, fresh trash fish) while others use global sources (commodity feedstuffs and fertilizers).

The first "integrated" type in its traditional form (case studies 1-6) involves relatively little waste discharge to the wider environment (the waterbody or watershed). Internal or relatively local recycling serves the dual purpose of enhanced production and waste assimilation. It has been suggested that such systems might offer a model for ecologically sustainable aquaculture (Ruddle and Zhong 1988; Korn, 1996). However, many of these systems depend on the import of feed for livestock, whose wastes in turn serve as the inputs to aquaculture (Edwards,1993). Furthermore there is a general tendency to intensify these systems which may lead to environmental problems for the fish themselves and the wider environment (FAO/NACA, 1995; Ye, 2002). The examples discussed in the previous section represent attempts to combine intensification with some form of integration/recycling – either to exploit an opportunity (cheap input or secondary product) or to reduce waste.

The second type (case study 7) actually serves as a waste treatment system in its own right, using domestic wastewater as an input. These systems actually extract nutrients from the environment, so effluents are "cleaner" than influent[8]. Although these systems represent a classic form of integration and recycling, they are in decline. They are usually seen as backward and threatening to human health, and are being replaced by modern wastewater treatment facilities. The quality and productivity of the fish is not only compromised by the possibility of bacterial and viral contamination, but increasingly also by toxic industrial effluents. They are typically located in peri-urban areas where the value of land is rising rapidly and conversion for urban development is probably inevitable.

The third type, represented by cases studies 12, 13 and 14 involves more intensive input of nutrients in the form of feed with only a small proportion of the nutrients actually converted into the target product, although this proportion is 2-3 times higher for high quality feeds compared with fertilizer. The rest accumulates in the system (case 13), is discharged in waste water, or is removed as pond sludge, and applied to pond dykes where it may fertilise fruit trees, or to waste ground or agricultural land. The discharge as wastewater to canals, rivers or lakes may in some situations be sufficient to cause problems of eutrophication (i.e. significant and undesirable ecosystem change). In other cases (depending on dilution rates) it may be seen as a beneficial addition of nutrients which boosts natural or agricultural productivity.

There are numerous variations on this type. Many rice growing areas in China are characterised by trenches and ponds associated with rice fields in which a range of fish and shellfish are grown fairly intensively, releasing nutrients into the rice fields. In Viet Nam shrimp or *Macrobrachium* may be stocked in alternation or rotation with a rice crop – what might be called "serial integration". This again allows for recycling excess nutrients and also has the potential to "break" disease cycles.

The fourth type (case studies 17 and 18) has arisen where problems of potential eutrophication resulting from intensive specialist farming is seen as undesirable, and operations are required to reduce waste discharge in water to a minimum. This may be done through settling wastes and/or through biological waste-treatment. The economics of waste treatment are such that pressures to deliver near "zero" nutrient discharge may favour full recycling systems. In all cases nutrient rich sludge is generated which must be disposed of, usually on agricultural land. Since the nutrients will contribute to agricultural production this effectively amounts to *cross sectoral integration*.

The fifth type, represented by case studies 8, 10, 11, 15 and 16 involves significant input of nutrients and significant discharge to the wider environment. However, because the farms are established in rivers or lakes, there is substantial natural

[8] Many extensive aquaculture systems are extractive in this sense - for example the low input pen and cage systems in Laguna de Bay (case 9) and some of the shrimp farming systems in Bangladesh (Hambrey *et al.*, 2005).

assimilative capacity, and a certain number of farms can operate without the need for waste treatment. Unfortunately the tendency has always been to allow unlimited aquaculture, resulting eventually in serious eutrophication problems, sometimes associated with the collapse of fish farming itself, and major loss of natural resources and ecosystem services to others.

In theory the problem can be addressed: the carrying capacity can be estimated and measures set in place to ensure that levels of activity do not exceed it. Clearly, if farms use any form of waste treatment or increase their efficiency of nutrient utilization, the carrying capacity (in terms of acceptable production levels to maintain water quality within acceptable standards) may increase. Unfortunately there are as yet few examples of effective management structures being set in place to limit overall levels of activity and nutrient discharge. This is likely to be politically and institutionally difficult, and may be associated with issues of equity (see below). Despite these problems, attempts to estimate environmental capacity and carrying capacity[9] are now increasingly widespread, and represent serious attempts to implement a genuine "ecosystem approach" (Santos-Borja and Nepomuceno, 2006; Carino, 2005; Palerud *et al.,* 2007; Hambrey *et al.,* 2005).

Scale of integration

It is apparent from the above review that the idea of integrated aquaculture is rather hard to pin down. Those farms commonly referred to as "integrated", typically recycle a significant proportion of nutrients internally or locally, but usually bring in some nutrients from outside. Others bring substantial nutrients from outside and recycle a proportion to the natural environment or to other enterprises at a range of scales from local to global. Indeed at a global scale all farming systems may be considered to be "integrated".

For all of these systems a "nutrient neutral" circle might be drawn around the farm or farm group representing an "isobar" of zero impact, at which distance nutrient discharge from the system is balanced by nutrient inputs. The size of this circle will depend on the distance from which inputs are drawn (from local to global), and the extent to which excess nutrients (such as pond water and sediments) are distributed (e.g. as fertilizer for crops). The traditional integrated systems are likely to have a smaller circle than the modern intensive systems, although the circle is likely to be large in most cases. The question then arises as to whether a smaller "nutrient neutral" circle is a desirable objective for the EAA – especially where, as is usually the case, this would seriously constrain productivity and profitability.

The reality is that we shift nutrients around a farm, a village, a region, and indeed the globe according to our needs and desires. There is no obvious "ecosystem" based reason to balance the flow of nutrients at some arbitrary scale. The globe has always been characterised by massive natural nutrient flows – and these are often associated with economically important ecosystem services – such as the production of anchovy off Peru. *The objective should rather be that nutrient build up (or extraction) at any one place should not be such as to threaten the delivery of ecosystem services.* This may be achieved through one or more of the following:

1. Local recycling and integration.
2. On farm or higher level infrastructure for wastewater and sediment treatment, coupled with recycling of nutrient rich residues at whatever scale is cost effective.

[9] **Environmental capacity**: A property of the environment, defined as its ability to accommodate an activity or rate of activity without unacceptable impact. Carrying capacity: The amount of a given activity that can be accommodated within the environmental capacity of a defined area. In aquaculture: usually considered to be the maximum quantity of fish that any particular body of water can support over a long period without negative effects to the fish and to the environment. FAO. 2008. Glossary of Aquaculture. [online]. Rome, FAO. [Cited 2 June 2008]. <www.fao.org/fi/glossary/aquaculture>

3. More efficient use of input resources (e.g. higher quality feed and better feed management practices).
4. Limits to entry based on estimated environmental capacity.
5. Increased environmental capacity through development/enhancement of natural treatment systems or "green infrastructure" (see below).

The case studies (especially 1 and 7) suggest that while local recycling and integration may be efficient according to some criteria, it has lower production than intensive aquaculture and is often associated with significant labour and management costs. Furthermore, since the ratio of products is relatively fixed such systems cannot respond to market demand. It should not therefore be promoted as the "solution to pollution" without very careful economic analysis.

A "cost effective" scale for recycling will depend in part on these issues, but is also likely to be increasingly influenced by carbon footprint, and it may be - though this is by no means necessarily the case - that more local recycling will be more carbon efficient.

Unfortunately the shift from integration to more specialist enterprise using formulated feed (see case studies 2 and 3) has not – as yet – been accompanied by the development of wastewater treatment systems, and this is undermining the sustainability of many intensive systems. A reversion to the more traditional forms of integration is highly unlikely; wastewater treatment – at farm or local system level – must therefore be introduced if the industry is not to collapse.

There is also a global question about nutrients. Nutrients and organic matter tend to accumulate in natural ecosystems. This is the basis of soil and aquatic sediment formation – generally regarded as a good thing. However, human activity is leading to a global increase in dissolved nutrients. Whether this will become a global problem (or perhaps benefit), or whether – as suggested above – it is simply a matter of managing nutrients and moving them around as appropriate to the ecosystem services we demand, remains to be seen.

Other impacts

Chemicals

We have noted above the cost benefit calculations that are required to manage the impacts of chemicals on ecosystem functions and services. None of the case studies reveal examples where this has been done, and management of chemicals in most countries remains *ad hoc*. Some chemicals considered particularly noxious are banned, and the extent of this varies from country to country. Codes of good practice are commonly used to ensure that chemical use is minimised. *An ecosystem approach might however emphasise the bigger picture: the need to tackle the causes of disease in the wider environment which commonly lie behind the excessive use of chemicals*. This approach is already being pursued strongly by FAO, NACA and similar organisations.

Escapes

With regard to escapes, introductions and their effects on the wider environment – these are less closely related to the type of system, and more to national policy. We have discussed above the need to limit introductions based on risk assessment and "trade-off" (cost benefit) analyses.

In using risk assessment, it is necessary to consider ecological as well as social and economic impacts to balance the environmental risks and the economic benefits (Bartley, 2007). To achieve this information will be required on the species to be introduced, the habitat into which it is to be introduced and the views of the associated stakeholders.

There are over 40 binding international agreements referring either directly or indirectly to alien species although not all are yet in force and less than a dozen specifically relate to aquatic environments (Moore, 2003). None of these agreements covers all aspects of alien species regulation. Global trade agreements have the greatest potential impact on how alien species can be managed in the future as efforts to control trans-boundary movement of alien species will inevitably become entangled in the trade/development/environment triangle. According to the FAO Code of Conduct for Responsible Fisheries (FAO,1995), "States should conserve genetic diversity and maintain integrity of aquatic communities and ecosystems by appropriate management…in order to minimize risks of disease transfer and other adverse effects on wild and cultured stocks, encourage adoption of appropriate practices in the … introduction of non-native species".

As a number of alien species used in aquaculture have established themselves successfully within the Asia-Pacific region over the last four to five decades, without apparent negative environmental and or biodiversity impacts, it was agreed that it is best to consider such species not as alien species but as "naturalized species" although this is a controversial issue and needs further consideration (NACA, 2007). In the agricultural sector and terrestrial animal husbandry sectors, most farmed plants and animals in most areas are not native but are no longer considered as alien as these have become a part and parcel of existing agroecosystems. The NACA Workshop group noted the following:

1. Terms such as "introduced endemic" or "established exotic" which are often used to refer to species that are now part of the present landscape and therefore no longer seen as alien may be more suitable.
2. However, there should be continuous monitoring of the impacts of such "naturalized species" in time and space.
3. The views on the extent of adverse impacts of aquatic alien species in China remain diverse and controversial and there is need to evaluate the impacts of alien aquatic species. In general in China the adverse impacts of alien species from hatchery-produced stocks that have been translocated and released into the environment, such as large lakes, reservoirs and river systems, leading to mixing and homogenization of stocks, and impacting on the genetic diversity is relatively well documented.
4. There have been very few studies in the Asia-Pacific region on the impacts of alien species or hatchery reared seed on biodiversity and genetic diversity of wild populations; for example impacts such as introgression or dilution of wild gene pools due to intermingling with hatchery reared stocks brought about by cultured, hatchery reared stocks is little known and needs to be studied in detail.
5. There have been substantial and demonstrable social and economic benefits from alien species with some species groups contributing a major share to aquaculture production in the region although acceptable levels of adverse biodiversity impacts relative to societal remain to be established.
6. The impact of alien ornamental fish on biodiversity is not well studied and is an emerging issue.

Research is also underway to develop the culture of nine indigenous species in the Mekong river basin trade by the Mekong River Commission Programme project "Aquaculture of Indigenous Mekong Fish Species" (AIMS) as it is believed that it may be possible to develop indigenous alternative species to reduce the need to farm alien species (Mattson, Bartley and Funge-Smith, 2005). Although all species being studied under AIMS that are not yet farmed can be bred and cultured in captivity, the newly cultured species are difficult to breed and grow slower than exotic species but this may be compensated for by higher local market demand and price (Yakupitiyage and Bhujel, 2003). AIMS involves a network of researchers from Cambodia , the Lao People's Democratic Republic, Thailand and Viet Nam to breed to develop aquaculture systems for indigenous Mekong river basin species. Initially 19 priority indigenous species were identified but this was subsequently reduced to focus on 9 species. As well as on-station research, dissemination involves on-farm demonstrations with farmers, production and distribution of extension materials and training. AIMS has led to a marked increase in interest in farming indigenous fish species in the four countries in the network if not yet their actual farming practice.

Biodiversity

Biodiversity again presents us with a dilemma. Extensive systems (exemplified in case study 1) are relatively rich in biodiversity, but the area required to generate a tonne of rice or fish is high. To feed the existing and future world population using such systems is unrealistic – there is simply not enough land – and there would certainly be no space left for natural habitat if such systems were to be developed on a more widespread scale. More intensive systems are characterised by lesser biodiversity, but at least offer the opportunity of leaving more land aside as natural habitat and “green infrastructure” (see below).

There may also be opportunities to combine intensive systems with biodiversity enhancement. For example, it has been proposed to enhance the incorporation of excess nutrients into native-species food webs by using filter feeders, enhancing bottom habitat heterogeneity, and managing free-living fish around salmon cages in a freshwater lake in Chile (Soto and Jara, 2007). Artificial reef structures made of PVC tubes were placed on the bottom of a freshwater lake where the early stages of salmon are grown in floating cages. The constant bioturbation of the native bivalve *Diplodon chilensis* on the sediments reduced the impact of nutrient accumulation due to salmon farming. Furthermore, the artificial structures enhanced the recruitment of an endemic freshwater crab (*Aegla* sp.) and crayfish (*Samastacus spinifrons*), the latter with market potential, through deposition of excess salmon feed. Excess feed around salmon cages is also utilized by both native fish and escaped salmon which could benefit sport fishing if managed appropriately. Such integrated ecosystem management, providing for ecosystem and biodiversity conservation as well as social and economic benefits, is desirable to allow salmon farming and fisheries to co-exist in Chile.

As for the other environmental impacts we cannot, and should not, point to a particular technology as being “best for biodiversity” . The selection must be informed by local understanding – of both farming systems and biodiversity values. And in many cases it may be possible for farmers or local government to enhance biodiversity in and around farms through a variety of methods.

Green infrastructure – safeguarding ecosystem services in the wider environment

Most countries have policies relating to designation of nature reserves or “protected areas”. Increasingly however, the focus on ecosystem services is encouraging a more holistic approach to biodiversity conservation. Ecosystems and their associated biodiversity are part of the “green infrastructure” (Benedict and MacMahon, 2002) which sustains ecosystem service delivery. Isolated patches of rich biodiversity are inadequate: we need corridors and networks, a web of biodiversity encompassing and supporting all our activities; a buffer and a resource.

In most cases this “green infrastructure” will be off-farm, although as the Hungarian example shows, where there is strong demand for nature conservation, angling and hunting, it may be possible to combine this economically with fish farming. The Hungarian case also illustrates the link between the idea of “green infrastructure” and landscape conservation. There are 600 000 ha of fish ponds in Central and Eastern Europe ranging in size from less than 1 to 500 ha which are now an integral part of the landscape, and might be considered as a key element of “green infrastructure” offering a wide range of services from nutrient assimilation to recreation.

The decision by Governments in several parts of the world to protect belts of coastal and estuarine mangrove is an example of green infrastructure conservation. Mangrove is recognised as delivering a range of services including fishery nursery areas, nutrient assimilation, coastal protection and wood production. The "ecosystem approach" should see such policies extended to the strategic conservation of freshwater wetlands, riparian vegetation, woodland corridors and so on. This should be supplemented by encouraging farmers themselves to reinforce these "landscape level" initiatives. In the Red River delta for example wide pond dykes are developed from the soil excavated from converting rice fields to fish ponds and these are planted with fruit trees which also help to prevent flooding (Edwards, 2005a)

The nature, amount and pattern or distribution of this green infrastructure should be a matter of national policy, informed by science and local needs and perspectives. The decision will be more or less precautionary depending upon the commercial value of land, the wealth of the Government and/or the people using that land, and the level of experience and awareness of problems associated with environmental degradation.

Science cannot as yet tell us how much land should be set aside for such purposes, but it can contribute to the debate and associated decisions – for example by identifying and highlighting the services associated with particular habitat types in different locations. In the mean time, the guidance should always be *to keep as much as possible.*

Institutions and management

Governance

The track record of aquaculture development indicates the poor governance of some of the sector, with boom-and-bust development due to adverse environmental impacts (Pullin and Sumalia, 2005). The technology and profit-driven nature of aquaculture tends to lead farmers towards giving little consideration to environmental issues (FAO/NACA, 1995) even though it is undesirable for aquaculture farms to exceed the capacity of the environment in which they are located. There are numerous cases of aquaculture severely affecting its own culture environment through self-pollution as well as the surrounding aquatic environment (FAO/NACA, 1995).

While the above criticism of the poor track record of aquaculture may be unfair given the adverse environmental impacts of other sectors such as agriculture, capture fisheries and forestry, industrial-based aquaculture in particular has caused severe environmental damage in some areas. Promotion of aquaculture has been successful in most countries but if a certain aquaculture venture is profitable governments have often found it difficult to control "runaway development" with often catastrophic adverse environmental impact (FAO, 2006). So far the growth of aquaculture has been self-limiting although governments have introduced aquaculture legislation often addressing the issue of effluents, and attempts are being made to promote best management practices (BMPs).

In practice freshwater aquaculture has been less prone to the boom and bust cycles typical of much coastal and marine aquaculture, related mainly to the generally lower value and less well developed international marketing opportunities for freshwater fishery products. However, the recent growth in *Pangasius* farming in both Viet Nam (case study 14) and to a lesser extent in Bangladesh suggests that this may be changing as inland infrastructure develops.

Few case studies reveal well developed management institutions and associated management systems, although those from developed countries tend to be most highly developed.

Adaptive and strategic management

The older agriculture and aquaculture systems have evolved and adapted over centuries. Society has adapted to the systems and the systems have adapted to the needs of society.

Integration has been refined according to both need and opportunity. Change has been slow and limited and therefore no monitoring is required.

More modern systems are different: they are expanding and changing rapidly. If we are to have any form of adaptive management, we need monitoring and analytical information to inform this adaptation – whether this be changes in technology, practice, or environmental management. In developing countries this is rarely available, and the nature of the enterprises – typically small-scale and widely spread – often makes monitoring prohibitively expensive. In developed countries monitoring is well established (see Denmark trout case study) and linked through to management systems.

However, the existing monitoring and adaptation tends to be focused at farm level. Ideally, an ecosystem approach would see monitoring at a higher "ecosystem" level. The Water Framework Directive in Europe seeks to achieve this through monitoring defined "waterbodies" and watersheds, and identification of the various pressures on water quality, including fish farming. Some may be defined as contributing to "at risk" status in which case action must be taken to reduce the risk. This approach is therefore both precautionary and adaptive.

Unfortunately, a monitoring-based "adaptive" management system tends to suffer from "overshoot". By the time an environmental problem is picked up by a monitoring system, the underlying cause (such as too many farms) is usually well entrenched and difficult to address. Ideally we need a "strategic" management system (GESAMP, 2001; Hambrey *et al.,* 2005), which can assess environmental carrying capacity and put in place planning and management measures to prevent development exceeding capacity. This approach is exemplified in case studies 9 and 15. In the case of Laguna de Bay a "Zoning and Management Plan" is used to allocate areas and limit production based on an analysis of the lake's carrying capacity for aquaculture. Such an approach is usually based on imperfect information and very rough models, and should therefore be supplemented with monitoring and adaptive management. In Lake Taal (case study 15), the carrying capacity has been estimated, and appears to have been exceeded by a factor of 2.8 (Palerud *et al.,* 2007). That capacity has indeed been exceeded is confirmed by the regularity of fish kills related to deep water turnover and de-oxygenation. Unfortunately the carrying capacity estimation was not "strategic" – it was made after the development took place - and it will now be extremely difficult to get total nutrient and organic matter discharges back down to an acceptable level.

"Adaptive management" typically means something very different for farmers. In a market economy they are encouraged to "adapt" to market demand and opportunities. This is problematic for more integrated systems, since the ratio of different (trophic) products is largely governed by trophic relationships. If the farmer begins to specialise in a particular product in response to market demand, then the product ratio will change, as will the efficiency of nutrient recycling. This is one of the major reasons for a decline in traditional integrated systems in Southeast and East Asia.

Aquaculture should improve human well-being and equity for all stakeholders

This is a huge subject in its own right and we have therefore prepared a separate working paper/literature review on these issues (Belton, 2007), the key points of which are summarized below. In the following we also review more specific insights arising from the case studies.

Summary of the literature review

The evidence presented in Belton (2007) suggests that, perhaps contrary to what might be expected, the major contributions of aquaculture toward the improvement of human well-being and equity are to be found not in income and food security for producers (although these may be important), but in upstream and downstream employment in ancillary service provision, and (where aquaculture is strongly commercially oriented and produces small, low value species) in the enhanced provision of high quality animal protein at low cost to consumers.

Although historically there has been a tendency for better resourced and powerful individuals or groups to capture benefits from the promotion of aquaculture, there is also now evidence that in some areas where aquaculture infrastructure is well developed even poorer marginal or functionally landless households have the ability to engage in the activity on a small-scale and for commercial purposes (e.g. Haque *et al*., 2006).

However, it should be noted that even where commercial, aquaculture often plays a relatively small part in the total household livelihood portfolio and is utilised strategically to achieve specific ends, which may make outputs appear technically sub-optimal. Furthermore, the image of fish production aimed solely at providing household food security or income is over simplistic. The benefits that people gain from waterbodies that contain fish may be of far greater complexity than simple assumptions about the nature of 'food' or 'income' might suggest. Although, ´clearly, households culturing fish tend to consume more fish, food security is typically achieved through more complex strategies in which producer households continue to source fish for consumption elsewhere and their own farmed fish may be sold, gifted or consumed strategically to meet household needs for cash, social benefits and food security (Little *et al.*, 2007).

Finally, although production standards, eco-oriented or otherwise, may benefit some groups of producers with the economic and social capital to mobilise effectively in response, other smaller producers operating sustainable production systems may potentially lose out, making such measures potentially counterproductive.

In the following section we review some of the main findings from the case studies.

Poverty

Many of our cases appear to show a strong contribution of aquaculture to poverty alleviation (see for example case studies 1-4, 7, 10, 11, 15). The very rapid increase in freshwater aquaculture production in Bangladesh over the last decade for example has undoubtedly contributed to income, employment and high quality food supply across the country (ADB 2005). Relatively cheap and locally available inputs such as cattle manure, rice bran and mustard oil cake can be used to generate fish yields of 3-5 tonnes/ha. Freshwater fish accounts for 60-80 percent of animal protein consumed by the population. It has been estimated that as many as 800 000 full-time equivalent jobs may have been created.

Case study 7 (wastewater aquaculture around Hanoi) reveals a system which tends to be operated by the poor and which generates relatively low cost fish (Bunting 2004; Little and Bunting 2005), and might therefore be seen as contributing strongly to poverty alleviation. These systems are however in decline for wider social and economic reasons, although they may have more potential as a low cost water treatment system in arid and semi-arid climates where there is increasing necessity to recycle water (WHO, 2006)

This example highlights another fundamental dilemma in assessing the contribution of any activity to poverty alleviation. If large numbers of poor people are engaged in a particular form of aquaculture, does this mean that they are trapped in poverty, and the returns from aquaculture are so poor that they cannot escape? Or does it mean that this is an activity that even the poorest people can gain access too, and which might offer a rung on the ladder to increased wealth? The statistics rarely cast any light on this issue, although Bangladesh case study (4) does suggest significant economic benefits from aquaculture. It also shows that even where aquaculture households are poor, they have relatively greater access to a highly nutritious food.

Intensification and specialization

The nature of aquaculture also mirrors that of many other enterprises and poses a second dilemma of particular concern in relation to the ecosystem approach. If people involved in aquaculture are poor, they typically have two options in terms of improving their livelihood: to move to another enterprise or employment which offers higher returns; or to generate higher returns from their aquaculture enterprise. Since few poor people are able to generate more income through expansion – i.e. purchase or rental of additional land/water resources – they can only increase returns through ***intensification, and/or specialization*** on those products generating the greatest return – such as higher value (often carnivorous) fish species.

Many of the case studies – especially those from South and Southeast Asia – reveal this dominant trend of intensification on the one hand, and specialisation in response to market opportunities on the other. There is very little doubt that they have usually benefited in the process. The more traditional integrated systems do not usually allow people to escape poverty; intensification and specialisation sometimes does – although risks may be higher (Hambrey, 2002). Case study 1 is a classic example of a traditional extensive integrated system which is environmentally sustainable, but which is not economically sustainable. Case study 2 illustrates the tendency to increase the quantity of off-farm inputs in order to increase production from an integrated system. Case study 3 illustrates the inevitable shift from highly locally integrated systems to more specialist systems drawing in more external inputs.

This raises a question as to the wisdom of promoting farm level integration as a means to tackling the issue of excessive nutrient discharges from farms of all kinds as discussed above. Farm level integration may contribute to the objective of minimising the externalities from fish farms; but it may also compromise the opportunities for small-scale producers to escape poverty.

Support for extensive and/or integrated production

There are various possible solutions to this dilemma. Traditional rice/fish culture in Zhejiang province in China has been listed by FAO, UNDP and GEF as a "globally important indigenous agriculture heritage system"[10], and this may lead to levels of support for the activity, or its products, such that a better living can be made. More generally, products from such systems may be able to command a premium associated with organic or other forms of certification. However, any such premium is likely to be less than 20 percent and more usually closer to 5 percent, which may be trivial compared with the alternative of major increases in production and income through intensification and specialisation, or even leaving the farm for off-farm employment.

Aquaculture as food and supplementary income

Case study 2 (traditional small-scale integrated farming system known locally as VAC in the in Viet Nam) reveals perhaps an alternative development trajectory which might allow for the maintenance of small-scale integrated systems and its on-going contribution to well-being. Rather than increasing inputs, household income may be increased primarily through off farm employment in the developing economy. The small-scale integrated farm may then serve as the nucleus or anchor for the family, while at the same time providing nutritious food primarily for home consumption. This was in part the motivation for support and promotion of VAC under a UNICEF Household Food Security project. To some degree this mirrors the development process in Taiwan, where small family farms remain a key part of the social economy.

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[10] FAO. 2008. Globally Important Agricultural Heritage Systems [online]. Rome, FAO. [Cited 2 June 2008]. www.fao.org/sd/giahs

Unfortunately, as development takes place, the opportunity cost of labour increases, and since small integrated systems are typically labour intensive, the likelihood is that they will be simplified, and anything which can reduce labour input – such as formulated feed – is likely to be used. Simplification and intensification seem almost inevitable.

The nature of the development trajectory is closely related to both cultural traditions (particular the attachment to land and family household) and the nature of the land market. Where the former is weak and the latter unregulated, and where there are significant opportunities for off-farm employment, the emergence of larger specialist profit driven farming enterprises is almost inevitable, with large scale migration of small-scale farming households out of farming and into rural or urban industry and service.

Tough trade-offs

The VAC case also illustrates another "ecosystem" related issue. Grass carp was traditionally a key element in the VAC system. However, these require very high inputs of grass to achieve good rates of production, requiring much labour, and if used to excess causing low pond oxygen levels and associated mortality of the grass carp. Further intensification of the VAC system can be achieved by growing tilapia which are highly productive in fertilised ponds. The combination of market price and production costs for alternative species will be the ultimate determinant as to which species has the greatest potential for poverty alleviation. The use of tilapia however illustrates the potential conflict between different "dimensions" of the ecosystem approach, and the significance of some form of trade-off analysis. Although potentially contributing to poverty alleviation, the introduction of alien species may be associated with significant ecological risk. There is no easy answer to this beyond recourse to CBD EA Principle 1: *The objectives of management of land, water and living resources are a matter of societal choice.*

Ecologically sustainable aquaculture

Case study 6 (integrated agriculture and aquaculture in Malawi) reveals some of the difficulties associated with promoting a more integrated approach, especially as a tool for poverty reduction. This initiative, supported by the WorldFish Center for more than 15 years, sought to promote sustainable development, as measured using three ecological indicators: diversity; nutrient cycling and natural resource systems capacity. This represents a commendable early attempt to introduce an "ecosystem approach" to aquaculture. Unfortunately the low productivity of these systems – or rather the low value of that production – has severely constrained its contribution to rural development (NASP 2005) and despite the support national production from fish ponds has increased to only around 1 000 tonnes. One of the mistakes that has often been made in assessing these approaches has been to use profit margin (profit/cost, or benefit cost ratio) as a measure of economic viability or sustainability. While this is one measure of economic efficiency, it is of little concern to a farm enterprise constrained by available land and resources. For such an enterprise *profit per unit area of land* is the key factor determining the allocation of resources (land, labour etc) to different activities – and well-being in terms of increased income (Hambrey, 2002). If production is sufficiently high it is quite possible to have a very high profit/ha coupled with a low profit margin.

Related to this point, it is now being more widely recognised that the motivation of "non-commercial farmers" is similar to that of commercial farmers – i.e. profit – and that commercial, rather than subsistence farming is likely to make a greater contribution to national fish supply in Africa for example (FAO 2006, Moehl *et al.*, 2006). Aid projects using aquaculture as a tool for poverty alleviation and improved nutrition are now being taken forward building on the concept of "clusters" which should allow the achievement of skill, production, economic and marketing thresholds. Cluster promotion locations should be determined by assessment of comparative advantage – in terms of resources and markets.

Multifunctional ponds in Europe

Opportunities are different in more developed economies. Case study 5 (an example traditional pond aquaculture in Hungary) reveals the opportunities for enhancing income from a relatively low input semi-intensive system by tapping into the nature conservation, science, and recreational markets. While this is an excellent example of the "ecosystem approach" it must be remembered that not everyone can go down this route. This is a classic example of exploiting a particular "niche", and there will be limited space for other entrants.

Equity

Equity is a complex political issue and difficult to address on a sectoral basis. However, two questions can be posed:

- Is the nature of aquaculture such that it contributes to increased equity?; and
- are there specific mechanisms by which equity within the fish farming sector can be promoted?

To answer these questions requires in depth social research, and rather little has been done. However, some general points can be made and some of the case studies do illustrate equity issues.

Access rights and economies of scale

To farm fish requires access to resources, and specifically to land and water. As for almost all forms of enterprise, there are therefore barriers to entry for the poorest. Cage and pen culture in ponds, rivers and lakes requires relatively modest start up investment and in this sense is "pro-poor". However, there are always economies of scale, and small scale producers usually start at a disadvantage. The DFID/CARE cages project in Bangladesh specifically sought to exploit these opportunities by working with the poorest members of society and encouraging them to get started using extremely small cages and readily available inputs in open access and privately owned waterbodies. Although superficially financially viable, these small enterprises have generally faded away. The reasons are unclear, but it may well be that both the level of investment and return were inadequate – even for the poorest – to encourage the required level of commitment and husbandry. Furthermore, few poor farmers had tenure or even secure access to a waterbody. Larger cages – belonging to rather richer members of society with clear access rights – are on the other hand increasing in numbers. The disparities between rich and poor remain.

There are however some positive examples. Rearing fry or fingerlings can be done in relatively small waterbodies, cages or trenches around rice fields. In Bangladesh this is done for carp, tilapia and *Macrobrachium*. Where water and harvesting regimes are suitable some growout may also be possible. In this case, the returns (especially for *Macrobrachium*) from even small scale activity can be significant.

Culture based (stocked) fisheries

Case study 10 (similar examples may also be found in Cambodia) illustrates the potential for poverty alleviation through cooperative organisation to enhance production from a common resource – i.e. a seasonally flooded floodplain – with relatively little in the way of inputs. Stocking of fish in areas amenable to fencing (i.e. those already partially enclosed by embankments and dykes) can result in yields significantly greater than that from wild fisheries. There appears to be great potential for developing these systems across huge areas in both Asia and Africa.

The key to success is likely to hinge on institutional arrangements (Dey *et al*., 2005; Dey and Prein 2006). The entry costs to this activity may be low where cooperative organisation is effective.

Case study 11 also illustrates the great potential for community based aquaculture in small reservoirs (De Silva, Amarasinghe and Nguyen, 2006). If only 5 percent of the available 62 million ha of small waterbodies in Asia were used in future for culture-based fisheries, with a feasible average yield of 750 kg/ha, Asian rural fish production could be increased by 2.5 million tonnes/year (De Silva, Amarasinghe and Nguyen, 2006). As for floodplain stocking, success will depend on institutional arrangements and relations between the various stakeholders. Such initiatives have a tendency to fail either through lack of leadership, or as a result of "inappropriate" leadership from the point of view of poverty alleviation. There is always the danger of those with greatest capital effectively making the greatest investment and taking the greatest share. This reinforces the general point that while aquaculture has enormous potential for poverty alleviation, this will only be realised in a favourable socio-political context.

The difficulties of targeting

The Laguna de Bay case study (9) illustrates some of the difficulties of targeting the poorest members of society. The Laguna de Bay Fish Pen Development Project aimed to provide marginal fishers with an opportunity to farm fish through organization into cooperatives and other forms of support. In practice nearly all the fish farming activity was taken over by businessmen, and the expansion of aquaculture further undermined the livelihoods of the poorest fisherfolk. However more recent planning and management initiatives place limits on ownership, thus ensuring wider distribution of benefit.

The effects of limited entry

We have already discussed the need to limit entry into fish farming in a bounded system with finite environmental capacity such as Laguna de Bay and Lake Taal. This has possible implications for both equity and poverty. If limits to entry are established, then those already operating become a privileged elite. If on the other hand a "market" is created, and user rights sold or auctioned, then the poor are immediately at a disadvantage. Any kind of limit therefore becomes disadvantageous to the poor, and government is again faced with a dilemma.

Land value

Successful aquaculture, like any other business tends to have both positive and negative knock on effects. Fish farming usually leads to an increase in income per unit area of land, and therefore drives up the price or rental value of land. This benefits the landed and further excludes the landless. On the other hand, it may lead to an increase in employment per unit area of land – providing a livelihood for the landless.

Use of trash fish

Cage culture of snakehead in Cambodia , case study 8, illustrates a particular dilemma with many forms of aquaculture, which may have indirect negative impacts on poverty at local or global level. The use of wild low value fish as feed for higher value snakehead grown in cages may result in both a reduction in supply and a higher price (through increased demand) for traditionally low priced species – a key source of high quality nutrition (directly, or as fish paste or fish sauce) for poor people. There was also a view that the capture of large volumes of small fish was threatening stocks. In recognition of these likely impacts, the Government of Cambodia has banned the practice. This argument may be "scaled up" to global level: the use of trash fish and fishmeal in fish production is effectively reducing rather than increasing fish supply globally and the impacts will be greater for poorer people.

While there is much behind the argument, each case needs to be examined carefully. This is a distributional issue. Adding value to low value fish by conversion into high value fish makes economic sense and may contribute to local, national and global economies; but if this has an indirect negative impact on others, then this cost must be taken into account. This issue is already high on the FAO agenda.

Rationalization

Case studies 2 and 8 also illustrate a near universal economic development dilemma. If something makes significant money, investment will flow in, large farms will be created (assuming there is an open land market) , and smaller operators will find it hard to compete because of dis-economies of scale and lack of marketing capacity. They may go out of business, or sell to larger concerns. They themselves may become labourers on larger farms, or find employment elsewhere, which may be to their ultimate benefit if off-farm employment is able to provide a better livelihood than that of their often small and resource poor farm.The impacts of these dynamic changes on poverty are highly complex and situation specific, but rationalisation of this kind is inevitable in liberal market economies, and has been a feature of all rapidly developing countries. In Viet Nam at least this trend in recent years has been correlated with a significant overall reduction in poverty. It is unclear how the EAA principle relating to poverty and equity can be implemented given these development processes.

Net benefit and strategic planning

The key question in respect of all these issues is net benefit – and perhaps more importantly the distribution of costs and benefit. There may be social and environmental costs, and social, economic and environmental benefits associated with aquaculture. To promote an ecosystem approach we need to assess, strategically, all these costs and benefits and make choices for the benefit of society as a whole. There are examples in developed and developing countries of aquaculture strategies, frameworks, and plans which seek precisely to achieve this. In Viet Nam for example aquaculture Master Plans are now produced by each Province, and there is an umbrella national Master Plan which serves as the framework for these. The Philippines has just completed an ADB funded exercise - 'Strategy for sustainable aquaculture development for poverty reduction". Europe has its own Aquaculture strategy, and individual countries such as Scotland have more detailed strategies. Malawi (case study 6) has recently developed a national Aquaculture Strategic Plan, and so have many other countries. These typically seek to promote sustainable development of the industry, which in practical terms comes down to seeking to ensure net benefit in the long term for the country as a whole – and interpreting at appropriate scales the implications of the ecosystem approach.

In Viet Nam the development of best practice models for reservoir based fisheries specifically seeks to maximise net benefit through a recognition of the multiple uses of the resource (case study 11).

Stakeholder involvement

Our cases reveal very little stakeholder involvement relating to the wider impacts of aquaculture on the environment. Danish trout farms are now operating within the requirements of the European Water Framework Directive, which requires stakeholder input into setting objectives and standards for waterbodies (though to date this remains very technocratic).

Many countries, and especially those dependent on irrigation infrastructure, already have stakeholder involvement in water management committees, though these typically focus on the amount, distribution and timing of water flows, rather than issues of water quality. However, as more intensive aquaculture increases, it is likely that issues will arise, and these committees will be well placed to address them, in collaboration with national environment protection agencies.

In areas where there has been widespread construction of ponds, the interests of others are necessarily affected. It is therefore likely that representative institutions will evolve to deal with these issues at a practical "aquatic system" level. The experience with Tropeca (Hambrey *et al.*, 2005) suggests that groups of farmers and other stakeholders are interested in developing and enhancing management structures to deal with the wider issues of land-use change, water quality and fertility, disease, chemical use and so on. However, significant efforts will be required to *facilitate* the development of these systems to deal with the range of issues implied by the ecosystem approach.

The World Wildlife Fund (WWF) has initiated six aquaculture dialogues to develop standards to certify river catfish, tilapia and trout from inland aquaculture (as well as molluscs, salmon and shrimp from coastal aquaculture). Each dialogue is a network of various stakeholders (producers, feed manufactures, processors, members of the market chain, researchers non-profit organizations, government officials and investors) who use a transparent, multi stakeholder process to develop the standards (www.worldlife.org/aquadialogues).

Best management practices (BMPs) reflect the most technically practical and economically feasible methods to reduce adverse environmental impacts of aquaculture (Ozbay and Jackson, 2006). A main aim of BMPs is to develop simple effluent treatment systems that reduce the amount of nutrients, organic matter and suspended solids in effluents to prevent pollution of receiving waters. Effluents as well as production costs can be reduced by using properly formulated stock-specific feeds distributed in small amounts several times a day. Maintaining moderate fish densities and feeding rates can improve water quality and reduce stress on stocked organisms, and also reduce the need to exchange water. Use of water retention ponds allows excess solids to settle out and greater water management flexibility by conserving and treating effluents for reuse. However, it is more difficult to treat effluents from pens and cages (case studies 9, 15, 16).

Aquaculture should be developed in the context of other sectors, policies and goals

We have necessarily touched on policy level integration in relation to the issues discussed above.

Freshwater aquaculture development necessarily affects, and is affected by human activities such as agriculture, fisheries, irrigation and urban development.

Water shortages are an increasing global concern which is leading to wastewater reuse (Stediman, 2007). Treated wastewater needs to be seen as an integral part of water management, with fresh water reserved for cities and treated wastewater becoming the major source of irrigation water. Currently wastewater irrigates about 10 percent of the worlds crops which is mostly unregulated in developing countries leading to adverse effects on human health. Arid countries are increasingly using treated wastewater for irrigating parks, non-potable household uses such as toilet flushing and for industrial process water (Stedman, 2007). However, there are little excreta and wastewater reuse in aquaculture, and as shown in case study 7, current traditional reuse is declining.

There may also be interactions with industry. Case study 16 illustrates the vulnerability of cage culture in rivers to pollution from other sources. About 8 000 tonnes of mainly tilapia, worth more than US$1million, were lost along a 20 km stretch of the Chao Phraya River in Central Thailand. The culture of *Pangasius* in Viet Nam (case 14) has recently shifted from cage culture in rivers to pond culture, in part because of the vulnerability of caged fish to increasing riverine pollution.

These considerations reinforce the need for integrated watershed management. History suggests that exhorting sectoral agencies to take account of the interests of other sectors is inadequate. They are necessarily driven by sectoral interests, and "take account of" is rarely strong enough to ensure genuine collaborative planning and management. There is a growing consensus that new evaluation techniques, investment approaches and governance reforms could improve the contribution of aquaculture to water productivity (Dugan, 2007). We have already referred to the implementation of the water Framework Directive in Europe, which seems to be forcing a more integrated approach to river basin planning and management. The challenge in developing countries is far greater. The pace of development tends to outstrip the rate of institutional capacity building; and the priority placed on development by each sectoral agency tends to work against anything which may constrain growth.

Nonetheless there are clear examples of cross sector integration. The Vietnamese Government's policy to encourage conversion of rice fields to aquaculture in areas which are marginal in terms of suitability for rice cultivation is an example of rational allocation of resources between sectors, by central government (also illustrated in case study 3). However, such an approach does not always sit well with more liberal market orientated economies, where the allocation of resources according to market demand and comparative advantage is considered to be more efficient and responsive.

On a more negative note, the Thai Government decision to ban "freshwater shrimp farming" in the main rice producing areas of Thailand for fear of salinization and obstruction of irrigation canals (case study 12) illustrates a precautionary approach to the conservation of a national resource, and the protection of a well established traditional sector, in the face of a threat from a lucrative but risky, and possibly short term activity.

Laguna de Bay (case study 9) represents an example of a more formal and strategic move toward sectoral integration. The Laguna Lake Development Authority (LLDA) represents a cross sectoral management and development authority with responsibility for a large (2 300km^2) aquatic system (or ecosystem)[11]. It has introduced some forward looking initiatives designed to minimise conflict between users and reduce "externalities". These include the introduction of an environmental user fee designed to motivate users to comply with effluent standards, and a "zoning and management plan" for fish pens and cages.

Despite the complexities and difficulties, it appears that the LLDA has met with some success. Laguna de bay was accepted as the 18th member of the Living Lakes Network in 2001, which was considered to be a "break through for Laguna de Bay and a milestone for the Philippines environmental history" (Santos-Borja and Nepomuceno, 2006). The turn around in the condition of Laguna de Bay from being regarded as a "dying lake" to one of the "living lakes" of the world has been attributed to stricter implementation of environmental legislation, proper valuation of ecosystem resources through market-based instruments, forging partnerships with communities of ecosystem users, and development of a watershed and basin approach for management of the lake (Guerrero, 2005). However, according to a recent newspaper article, Laguna de Bay continues to deteriorate (Anon, 2008). It could become biologically dead in a few years if about 100 000 illegal lakeside dwellers continue to dump their waste in the lake and local government officials do not adopt measures to mitigate the pollution and establish effective waste disposal systems for impoverished squatter families, factories and leaking municipal garbage dumps along the 238 km shoreline.

The use of reservoirs (case study 11) is also a good example of the need for sectoral integration. All the various uses of reservoir water (such as drinking water, irrigation etc) must be taken into account when considering, for example, fertilisation in order to increase fish yields. In Viet Nam a best practice model is being developed to address these issues.

[11] LLDA mandate: "to promote and accelerate the development and balanced growth of the Laguna Lake area and its surrounding provinces, cities and towns…with due regard and adequate provisions for environmental management and control, preservation of the quality of human life and ecological systems, and the prevention of undue ecological disturbances, deterioration and pollution".

DISCUSSION AND CONCLUSIONS

Our overview of freshwater aquaculture systems and the case studies we have selected reveal a huge range of systems set within a tremendous diversity of social, economic and environmental contexts. *Our first conclusion is that detailed prescriptive guidance on how to implement the ecosystem approach is inappropriate. The principles can and should be interpreted and applied according to context.*

Principle 1: Aquaculture development and management should take account of the full range of ecosystem functions and services, and should not threaten the sustained delivery of these services to society at large

Our review and many other studies reveal a wide range of interactions between aquaculture systems and the wider aquatic system or ecosystem. In most cases these are relatively benign, in so far as they have not led to significant loss of ecosystem services – either to the aquaculture sector itself, or to wider society. In some cases they may even be seen as positive – where for example nutrients generated enhance the productivity of other activities such as agriculture and fisheries.

There are, however, some examples where aquaculture activities appear to have compromised "ecosystem functions and services" in freshwater environments. These include:

- loss of biodiversity through habitat conversion, local accumulation of organic sediments, or impacts of chemicals;
- creation of unsuitable or unstable water quality in canals and rivers, lakes and reservoirs;
- disruption of natural flood relief and buffering systems;
- genetic, ecological and disease impacts on wild fish stocks through the presence or release of farmed fish; and
- impact on wild capture fisheries through unsustainable capture of wild fish for aquaculture seed or feed.

Improved decision-making

An ecosystem approach would address these issues through a participatory process involving stakeholders to eliminate or reduce these effects to an acceptable level using the most cost effective and socially acceptable mechanisms.

The definition of "*acceptable*" will depend on local social and economic conditions and perspectives, and should be informed as far as possible by good science and economic analysis. In Europe the Water Framework Directive goes some way to delivering such an approach, but our review reveals few other practical examples, although some research pilots which have sought to develop such an approach in Asia (Hambrey *et al*., 2005; Palerud *et al.,* 2007).

To implement the ecosystem approach will require the development of institutions which can deliver such an approach, taking full account of the needs and impacts of other sectors. The scale at which these institutions operate will depend on the nature of the impact: issues related to introduction of alien species must be tackled at national and regional level; impacts on biodiversity also at national level; impacts on (say) irrigation systems, rivers, lakes, or reservoirs at a more local level.

In setting limits to change it is essential that some *resilience* is retained in terms of service provision. This implies two things: firstly that acceptable limits include a "safety margin"; and secondly that those factors which strengthen system resilience – such as biodiversity and enterprise diversity – should be promoted as much as possible.

Management of alien species, impacts on wild stocks and fishery resources is a matter for national and international policy and regulation and has been widely discussed elsewhere.

Infrastructure, technology and practice

There are many specific mechanisms which can serve to eliminate or reduce negative effects on ecosystem function and service.

Loss of biodiversity can be addressed through on-farm incentives to diversify and minimise the use of chemicals, and through off-farm development of "green infrastructure". Green infrastructure refers to the strategic allocation of significant patches or swathes of undeveloped land or waterbodies of different types which will increase biodiversity, underpin many other ecosystem services, and increase the "resilience" of the whole system.

Where excessive nutrients are a problem it may be feasible to use the following:

- local recycling and integration;
- on-farm or higher level infrastructure for wastewater and sediment treatment, coupled with recycling of nutrient rich residues at whatever scale is cost effective;
- more efficient use of input resources (e.g. higher quality feed and better feed management practices);
- limits to entry based on estimated environmental capacity;
- increased environmental capacity through development/enhancement of natural treatment systems or "green infrastructure"; and
- better sitting to ensure that any excess nutrients have a neutral or positive effect on wider ecosystem services.

With regard to the first of these there are two main approaches. Modern recirculation systems which incorporate waste treatment may be employed, although they currently are only economically viable for high-value niche markets due to high construction and operating costs.

On the other hand attempts are being made to introduce some of the principles of traditional aquaculture to reduce the adverse environmental impact of intensive aquaecosystem effluents such as aerated microbial reuse, aquaponics, linking intensive and semi-intensive systems, pellet-fed caged fish fertilizing a surrounding pond, the 80:20 Chinese fish stocking system, and partitioned aquaculture systems.

Great care is required in promoting any specific mechanisms to implement the ecosystem approach. Optimal solutions depend on context. Guidance must be flexible and adaptable. In this sense the *principles* are far more important than any specific *mechanisms*. The latter are a matter for local ingenuity and choice.

Flood or erosion mitigation can be enhanced mainly through specific infrastructure design, and/or retention of adequate "green infrastructure".

Intensity of production

There is a major trend in aquaculture of delinking integrated farming enterprises, which have generally been considered as an environmentally friendly way to produce fish and other commodities, and independent intensification of crop, livestock and fish farming subsystems or enterprises. While traditional integrated aquaculture systems continue to play an important role for small-scale farmers and local communities, highly productive and profitable aquaculture requires considerably increased nutrient flows than can be provided from other on-farm or local sources. Formulated pelleted feed is becoming the most significant source of nutrients for farmed fish.

From an EAA point of view, pelleted feed is more nutrient efficient in terms of incorporation into fish biomass than pond fertilizer. Furthermore, considerable improvements are being made by the feed industry to manufacture more environmentally friendly pellets which have increased digestibility, reduced fish meal and fish oil, improved water stability, and float rather than sink.

There is therefore nothing fundamentally wrong with intensification from an EAA point of view – indeed it has some advantages - *so long as the extraction of nutrients for feed manufacture (agriculture, industrial fisheries) does not threaten ecosystem services or have negative socioeconomic impacts elsewhere; and the discharge of nutrients does* *not threaten ecosystem services or have negative socioeconomic impacts in the vicinity of the fish farm.*

Better management practices

Most of these issues have already been well rehearsed, and the solutions require action from both governments – in the form of better policy, regulation, and planning and management procedures (see 6.3 below), and industry – through better management practices.

A recently published review (Tucker, Hargreaves and Boyd, 2008) on better management practices (BMPs) for freshwater pond culture presents the BMPs under various categories: site selection, pond construction, pond renovation, overflow effluents, pond draining effluents, water conservation, fertilization, feeds and feeding, fish escape, predator control, aquatic plant control, mortality removal and disposal, and facility operation and maintenance (Table 3). Implementation of these BMPs would lead to much more environmentally sustainable freshwater aquaculture.

Principle 2: Aquaculture should improve human well-being and equity for all stakeholders

The evidence from the case studies and literature is generally positive: aquaculture is a rapidly expanding and dynamic economic sector and is making a significant contribution to the growth of many economies in the world. Economic development is widely regarded as increasing human well-being. The scale of the positive impact of aquaculture varies tremendously. However, it is notable that it is making a particular contribution in poor countries such as Bangladesh as well as rapidly developing countries such as China and Viet Nam. This general economic impact is supplemented by the substantial contribution which most freshwater aquaculture is making to the availability of nutritious food to both farming households and wider society.

The contribution of aquaculture to equity is far more difficult to assess. The poorest often lack access to water resources, either to a waterbody or to sufficient land to develop a pond, or the capital to develop efficient fish farming systems. But in this sense aquaculture is no worse, and in some cases may be better, than alternative enterprise opportunities (Hambrey, Tuan and Thuong, 2001). Even if the poorest are unable to develop their own aquaculture farm, they benefit from considerable employment opportunities on large fish farms and in input supply, marketing and processing (ADB, 2005).

The ecosystem approach implies something more pro-active in terms of facilitating or maximising the potentially positive impact of aquaculture. *This is a policy issue and will therefore be dealt with under Principle 3.*

Principle 3: Aquaculture should be developed in the context of other sectors, policies, and goals

This principle amounts to an exhortation to develop multi-sectoral or integrated planning and management systems – not only to account for "other sectors, policies and goals" but also to provide a framework, and consistent cross-sectoral standards (a "level playing field"), for the delivery of the management and development initiatives required to meet Principles 1 and 2.

A great deal of guidance is already available relating to Integrated Watershed Management, Integrated Coastal (Zone) Management, and more specifically Planning and Management for Sustainable Coastal Aquaculture Development (GESAMP, 2001). In terms of implementation, the Water Framework Directive in Europe is probably the most advanced legislative system in the world which seeks to advance such an approach.

TABLE 3

Better management practices to reduce the adverse environmental impact of pond aquaculture

Better management practice
Site selection : • do not site ponds in wetlands or protected areas • do not site ponds in areas prone to regular flooding • do not site ponds near urban areas, near industrial pollution sources, or in sites with contaminated soils • do not site ponds where regulatory or other restrictions apply • select sites with suitable topography for pond aquaculture • select sites with consideration of the downstream impacts of pond construction • select sites where water supplies are free from contamination • select sites where soils are suitable for pond construction
Pond construction : • prepare the site prior to pond construction • construct ponds according to specific design criteria • compact pond embankments and bottoms properly • control erosion during and after pond construction • protect pond embankments from erosion • construct drainage ditches to minimize erosion • eliminate steep slopes on farm roads and cover roads with gravel • avoid leaving ponds drained in winter and close valves once ponds are drained
Pond renovation : • use sediments from within the pond to repair embankments rather than disposal outside the pond • reduce discharge of sediments during renovation • excavate to increase operational depth • properly dispose of solids removed from settling basins
Overflow effluents : • reduce or eliminate intentional water exchange • manage ponds to capture rainfall • optimize the ratio of watershed : pond area • use drains with surface water intakes • control erosion on pond watersheds and pond embankments • divert excess runoff from large watersheds away from ponds • prevent water discharge from ponds during fish kills • use effluents to irrigate crops
Pond draining effluents : • reuse water for multiple fish crops without draining • reuse or recirculate water drained from ponds • drain water from pond surface • allow solids to settle before discharging water • treat pond effluents in constructed wetlands prior to discharge • treat pond effluents in settling basins prior to discharge • release pond effluents in low-gradient drainage ditches
Water conservation : • select sites with soils suitable for pond construction • construct ponds properly • reduce or eliminate intentional water exchange • manage ponds to capture rainfall • reduce water loss during pond drainage • reuse or recirculate drained pond water • use water efficiently by increasing production intensity
Fertilization : • fertilize only as needed • fertilize efficiently • lime when total alkalinity is <20 mg/l as $CaCO_3$ • do not use livestock manure • do not exchange water after fertilization • do not fertilize ponds 1-2 days before heavy rainfall is forecast • store fertilizers properly
Feeds and feeding : • use feeding practices that maximize feed use efficiency • feed according to pond waste nutrient and organic matter assimilation capacity • use high-quality feeds • use feeds with the least amount of fishmeal and other animal protein as possible • handle and store feeds to maintain feed quality

TABLE 3 (Continued)

Fish escape : • consider flood risk in site selection • construct and maintain pond embankments to prevent failure • include barriers to escaped fish in drainage structures and ditches • prevent escape during fish transfers • deter nuisance wildlife • do not farm invasive species without rigid safeguards
Predator control : • assess predator impact • identify predator responsible for losses • check with appropriate regulatory authorities • design facilities to reduce predator losses • use frightening or harassment techniques • discourage birds from areas near the farm • use exclusions, impediments or barriers • prevent introduction of predatory fish
Aquatic plant control : • prevent weed problems whenever possible • identify the weed problem • make management decisions based on site-specific conditions • use herbicides labelled for aquaculture • carefully follow herbicide label instructions • handle herbicides safely • be aware of consequences of herbicide use • dispose of herbicide containers properly • use sterile grass carp for weed control
Mortality removal and disposal : • follow recommended aquatic animal health management practices • ensure dead animals are not discharged with overflow • remote dead animals from ponds for sanitary disposal if practical
Facility operation and maintenance : • maintain all equipment in good working condition • inspect pond water supply and drainage structures frequently and repair when needed • use and store petroleum products to prevent environmental contamination • use and store chemicals to prevent environmental contamination • develop a response plan for spills of hazardous materials • collect and dispose solid waste regularly and responsibly according to regulations • develop a record keeping system

Source : Tucker, Hargreaves and Boyd (2008).

As stressed repeatedly in this report, the mechanisms and procedures for such approaches are now well rehearsed. The weakness in both developed and developing countries lies with the institutions – or lack of them. In most cases institutions with sufficient power to oversee integrated planning and management do not exist; where they do they tend to be sectorally anchored, or inefficient and ineffective.

Any government which wishes to adhere to and promote the ecosystem approach to aquaculture must create or strengthen appropriate institutions. Such institutions must be capable at least of the following:

- engaging and involving the full range of sectoral agencies and stakeholders;
- strategic thinking and planning – including the ability to define limits to change which secure adequate levels of system resilience;
- capacity to conserve or enhance ecosystem service delivery, and associated resilience, through conservation or enhancement of "green infrastructure";
- capacity to set in place a suite of incentives and constraints which will encourage the implementation of appropriate management measures for aquaculture (as discussed under Principle 1) and other interacting sectors;
- capacity to monitor ecosystem service delivery, and the cumulative multi-sectoral pressures upon the health of the ecosystem; and to respond as required, including adaptation of existing management regimes.

This is a tall order indeed. It will require significant changes in national and local government and regulatory structures. Requisite institutions are likely to evolve slowly as the greater adverse impact of not having developed multi-sectoral planning and management is realized by specific stakeholders as well as society in general.

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

A summary of the key points made above and elsewhere in the text is provided in the executive summary at the beginning of this document.

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ANNEX 1
Case studies

The selection of case studies was based on the need to represent a range of different types and intensity of aquaculture within a range of ecological and economic contexts, as discussed in "concepts, terminology, and typology of case studies" section. The selection is biased in favour of East and Southeast Asia, since this is where most freshwater aquaculture takes place, and also where the full range of types is best represented.

Eighteen case studies from various countries are presented (Table A1). The first six are traditional integrated agriculture – aquaculture systems (IAAS) (one rice/fish and five pond culture, although in case study 4 from Bangladesh and case study 6 from the Republic of Malawi the technology was introduced through projects), one traditional Integrated peri-urban-aquaculture systems (IPAS), and one traditional integrated fisheries-aquaculture system (IFAS). Three case studies are on modern extensive to semi-intensive aquaculture which was introduced through projects (case studies 8-10) and the remaining eight case studies are modern intensive culture in various types of aquaecosytem.

Each case study comprises a short description and discussion based upon review of relevant documents and discussions with persons closely involved. This is followed by a tabulated summary analysis/assessment against the three proposed principles for the ecosystem approach to aquaculture. Where cells have been left blank in the tables this is either because inadequate information was available to comment, or because the case provides little generic insight.

TABLE A1
Case studies of aquasystems

Case study	Aqua eco-system	Natural or human dominated system	Intensity	Monoculture or polyculture	Country
1	Rice field	Cultivated	Extensive to semi-intensive	Common carp monoculture	China
2	Pond	Mostly cultivated	Semi-intensive	Polyculture	Viet Nam
3	Pond	Mostly cultivated	Semi-intensive to intensive	Polyculture	China
4	Pond	Cultivated	Extensive to semi-intensive	Polyculture	Bangladesh
5	Pond	Cultivated, wetland	Semi-intensive	Polyculture	Hungary
6	Pond	Cultivated, wetland	Semi-intensive	Polyculture	Malawi
7	Pond	Cultivated	Semi-intensive	Polyculture	Viet Nam
8	Cage	Lake, river	Intensive	Snakehead monoculture	Cambodia
9	Pen, cage	Lake	Extensive to semi-intensive	Milkfish, tilapia monoculture	Philippines
10	Open rice field flood-plain	Cultivated	Extensive to semi-intensive	Polyculture	Bangladesh
11	Open Reservoir	Reservoir	Extensive to semi-intensive	Polyculture	Viet Nam
12	Pond	Cultivated	Intensive	Tiger shrimp monoculture	Thailand
13	Pond	Cultivated	Intensive	Channel catfish monoculture	United States of America
14	Pond	Cultivated	Intensive	Pangasius monoculture	Viet Nam
15	Cage	Lake	Intensive	Tilapia monoculture	Philippines
16	Cage	River	Intensive	Tilapia monoculture	Thailand
17	Raceway	River, cultivated	Intensive	Trout monoculture	Denmark
18	Recirculation	Cultivated or human dominated	Intensive	Eel, Tilapia monoculture	Denmark, United States of America

CASE STUDY 1 – TRADITIONAL RICE FIELD-BASED IAAS IN ZHEJIANG PROVINCE, CHINA

The culture of a red coloured variety of common carp (*Cyprinus carpio*) in terraced rice fields fed by streams in mountainous Qingtian County in Zhejiang Province, China has a documented 1 200 year tradition (Edwards, 2006). About 80 percent of the rice fields in the County, almost 7,000 ha, are stocked with the carp. Rice cultivated on the small farms averaging only 1 300 – 1 700 m^2 is for household consumption but fish are more likely to be sold today as the red carp is considered to be a delicacy and has a farm gate price of US$ 4-5 /kg, some even being exported abroad.

In the traditional system the fish are bred in a trench with direct release of fry into the rice field. Livestock manure is provided as a basal fertilizer for the rice, but the fry are otherwise raised extensively without further addition of fertilizer or feed for 2-3 years until they reach table size of 350-400 g. Fish production is low, 600-1 200 kg/ha. The Zhejiang Freshwater Aquaculture Institute is working with farmers and local officials to increase fish yields and therefore benefits to farmers while maintaining a balanced ecological system. Breeding sites have been set up and fry nursed before being stocked in rice fields and fed formulated feed, increasing yields to 4 500 kg/ha of still tasty fish. Unfortunately some farmers have intensified their systems beyond the recommended level, stressing fish which has caused disease as well as fish with a lower flesh quality which command a much lower price.

Local people, farmers and government are concerned about the sustainability of the traditional rice/fish system with recent developments. In addition to concerns about adverse environmental effects of intensification such as eutrophication and increased water demand, there is a declining farming population. Up to 50 percent of the population of the densely populated mountainous County have emigrated abroad and most young people continue to leave the area to seek better paid opportunities. In recognition of the long history of the traditional Chinese rice/fish farming system in Qingtian County, it has been listed by FAO, UNDP and the GEF as a Globally-important Indigenous Agriculture Heritage System (GIAHS) in 2005 (Lu and Li, 2006). The purpose of the GIAHS is to develop appropriate policy, institutional support and technology to protect and promote important agricultural heritage such as this traditional Chinese mountain rice/fish system in Zhejiang Province. Other demonstration sites are also being set up in a wide range of other agro-ecologies so that farmers may learn to live with the new opportunities and challenges brought about by globalization.

Discussion of Case study 1

Integrated rice/aquaculture is an environmentally friendly practice as the animals are stocked in rice fields and raised extensively without addition nutritional inputs or are fed a limited amount of supplementary feed. Capture of wild animals in flooded rice fields is a traditional and widespread practice but the Green Revolution with increased pesticide use led to a marked decline of wild aquatic animals in rice fields and short stemmed high yielding rice varieties that require shallow water reduced the feasibility of developing an integrated aquaculture system. Furthermore, intentional stocking of animals in rice fields i.e. traditional rice/fish culture as opposed to trapping wild fish in rice fields, is much less common than generally appreciated. Inspite of numerous projects to promote rice field–based aquaculture, it has been estimated in a recent review of the practice that only about 1 percent of the world's rice fields are stocked with fish (Halwart and Gupta, 2004). There are constraints to adopting rice field-based aquaculture e.g. it is labour intensive to modify fields for better water management; water management may be difficult, keeping sufficient water in the rice field for fish during the dry season and avoiding flooding and loss of fish during the rainy season; and there is a relatively low return on producing small fish in such shallow water systems as they have a low market value. However, such small fish harvested from rice fields may provide an important source of animal protein, healthy fats, vitamins and minerals for poor farming households (Halwart, 2006).

Rice field aquaculture appears to have most relevance for poorer rural people in marginal rice growing areas. In addition to producing low value but nutritious fish for household consumption, rice fields may produce higher value produce such as fingerlings and high-value crustaceans. Common carp (*Cyprinus carpio*) fertilized eggs are stocked in irrigated rice fields and nursed to produce fingerlings in some areas of Northwest Bangladesh and participatory research carried out with farmers has also indicated the feasibility of producing Nile tilapia (*Oreochromis niloticus*) fingerlings in irrigated rice fields (Barman and Little, 2006). Farmers culture high value river prawns (*Macrobrachium rosenbergii*) in rice fields in southwest Bangladesh, post-larvae initially being nursed in trenches in the rice field, and then raised concurrently with rice as rains flood the field (Nandeesha, 2003). Some farmers in the Mekong River Delta in southern Viet Nam culture low-value fish such as common carp, kissing gourami, rohu, silver carp and tilapia concurrently with rice but there is a trend to culture higher value river prawn in rice fields for sale in rotation with rice; the prawns are stocked and fed in the flooded rice fields following the harvest of a dry season rice crop. In China where rice fish culture is reported to occur on a massive scale with over 1.5 million ha in 2001, high value species such as prawns (*Macrobrachium nipponensis* and *M. rosenbergii*) and Chinese mitten-handed, crab (*Eriocheir sinensis*) are grown concurrently with rice in trenches connected to the rice field (Fang, 2003). Rice-based aquaculture is considered as a low-cost and low-risk entry point for farmers to carry out aquaculture without jeopardizing the sustainability of rice production in China but farmers have been reported to abandon rice farming and convert their fields to ponds in China (Miao and Xuan 2007; Miao 2007; Miao undated). Conversion of rice fields to fish ponds, either partially or entirely, is a widespread and growing trend in Asia.

Fish culture has been promoted as a component of integrated pest management as stocking fish in rice fields requires a reduction in the use of pesticides, especially in Bangladesh (Nandeesha, 2004), but the extent of sustained adoption by farmers remains unclear due limited impact assessment following cessation of donor funding. A new system of rice cultivation, the System of Rice Intensification (SRI) is likely to have a major impact on the future of rice/fish integration as one of its major features is to avoid flooding the rice plants to enhance plant root growth and the activities of soil organisms (Uphoff, 2007). The soil in the rice field in SRI is kept moist but not continuously saturated to maintain mostly aerobic soil conditions by either daily applications of small amounts of water or alternate wetting and drying of the field. Six years ago SRI was practiced only in Madagascar but its benefits have since been demonstrated in at least 24 countries in Africa, Asia and Latin America and it is being widely adopted by farmers in several countries in which rice field-based aquaculture occurs in some areas. While the novel rice water management practice has led to a doubling to tripling of yields in many areas, it would obviously curtail the possibility of either continuing with or introducing concurrent culture of fish and rice as standing water is eliminated from the field. However, such a marked increase in the production of rice could allow farmers to diversify their rice-based farm by converting part of the field to a fish pond to product higher value fish.

Some Asian countries have policies restricting the conversion of rice fields to fish ponds because of concerns about possibly diminishing the production of the national staple, rice, although these are being relaxed as to allow farmers to diversify their rice-based farms which may not provide a suitable income. It is now government policy in the Red River delta, north Viet Nam for areas subject to flooding and able to produce only one rice crop annually to be converted to fish ponds. In the last few years, thousands of hectares have been converted to either fish ponds, or pond-dike systems with wide dikes constructed with soil used to excavate the pond planted with fruit trees as well as serving to protect the pond from flooding (Edwards, 2005).

TABLE A2
Relevant issues under each principle at different scales in Case study 1

Principles	**1**	**2**	**3**
Scales	**Ecosystem functions and services**	**Improved human well-being and equity for all stakeholders**	**Developed in the context of other sectors, policies and goals**
Farm	• Integrated with rice cultivation in existing rice fields • Extensive so environmentally friendly • Farmers reduce pesticide use	• Low yields of small fish provide some nutritional benefits for poor farming households • Some systems in other areas produce higher value fingerlings or crustaceans which generate household income for poor farming households	• Farmers in other areas convert rice fields to fish ponds, threatening existence of rice/fish culture
Watershed/zone	• Indigenous species farmed	• Constrained by off-farm migration in Qingtian County, Zhejiang Province, China	• System in Qingtian County, Zhejiang Province, China receives RandD support from local government • Rice/fish sometimes promoted as a component of integrated pest management
Global		• Constrained by off-farm migration abroad in Qingtian County, Zhejiang Province, China	• System in Qingtian County, Zhejiang Province, China listed by FAO, GEF and UNDP as a Globally-important Indigenous Agriculture Heritage System • Threatened by promotion of System of Rice Intensification

CASE STUDY 2 – TRADITIONAL POND–BASED INTEGRATED AGRICULTURE AQUACULTURE SYSTEMS (IAAS) IN RED RIVER DELTA, VIET NAM

There is a traditional small-scale integrated farming system known locally as VAC in the Red River Delta (RRD) in which a polyculture of carps is raised in household-level ponds in association with livestock and crops. VAC is an acronym for the Vietnamese words for garden (vuon), pond (ao) and livestock quarters (chuong). Pond-based polyculture of carps in IAAS appears to be an indigenous practice in the RRD and may have a long history as the wild food fish supply would have been constrained by early flood prevention structures in the Delta.

According to a baseline survey carried out in the 1990s, most farming households in the RRD have small ponds, 1.0-1.2 m deep, located near the house (Luu *et al.* 2002). Farmers stocked a polyculture of common carp (*Cyprinus carpio*), Chinese carps (grass carp, *Ctenopharyngodon idella*, and silver carp, *Hypophthalmichthys molitrix*) and Indian major carps (mrigal, *Cirrhinus mrigala*; rohu, *Labeo rohita*). The three main pond nutritional inputs were rice bran, grass and pig manure. Fish yields ranged from <0.1 to 6.7 t ha-1 per season. Many ponds were dug for soil for use as fill to raise the level of the land for the homestead and surrounding garden. Ponds are traditionally multipurpose: water supply for domestic purposes; watering vegetables; and cultivation of floating aquatic plants such as water hyacinth (*Eichhoria crassipes*) and water lettuce (*Pistia stratiotes*) for feeding pigs, and harvesting wild fish. There are diverse linkages between the subsystems comprising VAC. Domestic effluents may drain into the pond and nightsoil may be used to fertilize the pond although it is usually used on crops, especially rice.

There may be a garden and/or an orchard with pond water used to irrigate crops and leaves of vegetables used to feed herbivorous fish or as green manure for the pond. Grass and other wild vegetation and chopped banana trunks are also used to feed grass carp. Pond silt may be removed annually to fertilize fruit trees and/or to provide a nutrient-rich layer of soil to cultivate vegetables. Livestock quarters for pigs and poultry are constructed adjacent to or near the pond so that washings and urine may be flushed or drained into the pond. VAC has long been recognized as important for household food security and increasingly as a source of income as the rice-based economy is diversified. The importance of VAC was emphasized by Ho Chi Minh during the Veitnamese/American War in the late 1960s to increase the nutritional standard of the rural poor. They were promoted in the early 1990s as part of a Household Food Security Project implemented by UNICEF in cooperation with the government-sponsored NGO, VACVINA. As the aquaculture component of the VAC system remained underdeveloped and had considerable potential for intensification and wider dissemination, The Research Institute for Aquaculture No. 1 (RIA No.1) and the Asian Institute of Technology based in Thailand carried out a participatory on-farm research programme with farmers in the 1990s to improve the efficiency of use of on-farm and locally available resources in VAC with average extrapolated fish yields increased to 3-4 t ha-1 in the 700-1 000 m^2 ponds and cost:benefit ratios of 1:2.7-2.8 (Luu *et al.* 2002).

The Luu et al (2002) study also revealed that there were technical as well as social limits to intensification of the current VAC system. There was a limit to pond intensification with vegetation which was used to feed the major species, grass carp, as it has a high oxygen demand in water and occasionally excess input of grass led to anaerobic water and mass fish mortality. Further intensification of the VAC system was recommended through a tilapia-based rather than the traditional carp-based system as increased productivity and profitability could be attained by farming this relatively high-value species in a fertilized and supplementary, green water system. Poorer families, especially women, were spending increasing amounts of time and travelling increasing distances by bicycle, up to 4 hours and 14 km daily, respectively, to collect grass which was in increasing demand for aquaculture.

Discussion of Case study 2

Small-scale pond-based IAAS are considered likely to be environmentally neutral although there may be considerations over the alternative use of land, water, fertilizers and feed, and seed (FAO/NACA, 1995). Aquaculture, however, has a positive environmental impact through treatment of manures as fish ponds function essentially as aerobic waste stabilization ponds. Advantages of traditional aquaculture are it uses local resources rather than globally traded animal and plant meals, and the fish pond is a manure and by-product treatment and disposal system with most excess nutrients not being incorporated into fish being mostly tied up in pond sediments. Furthermore, fertilizer nutrients are cheaper than those in formulated feed even though the former are converted less efficiently to fish. Traditional aquaculture is the best entry point for poor farmers to farm fish because it is relatively low cost and has minimal risk. It can be the “first step on the ladder of intensification” for farmers interested in developing aquaculture as a livelihood. Fish produced by traditional aquaculture are lower in cost than those produced with pelleted feed and can be marketed at a lower price, making them more readily accessible to poor consumers.

The major culture system is the integrated VAC system with Chinese and Indian major carps which is well integrated into the local resource base with little to no adverse environmental impact (case study 2). VAC farmers traditionally fertilize ponds with pig manure, and feed agricultural by-products such as rice bran and green fodder such as grass. However, there are competing alternative uses for manure for crops and agricultural by-products for feeding livestock. As these on-farm resources are limited on relatively small farms, intensification of aquaculture depends on intensification of livestock and/or use of off-farm supplementary or complete feeds, increasingly in pelleted form. The productivity of the carp polyculture system dominated by grass carp has reached its yield ceiling in the RRD. Use of excessive amounts of grass is unsustainable because a high organic matter loading in ponds due to large amounts of grass causes poor water quality, which stresses the fish and may cause red spot disease or mass mortality of fish. Grass has become scarcer as aquaculture has expanded and intensified. Some households use up to 100 kg fresh grass daily and this also places a heavy burden on women who collect the grass.

Aquaculture is changing rapidly through introduction of new or improved species as well as intensification, with possible adverse environmental impact on larger and more intensive aquaculture farms. Many farmers wishing to gain more profit stock higher value species such as hybrid common carp, river catfish and tilapia, usually in polyculture with a limited number of species but sometimes in monoculture. Viet Nam has a policy of agricultural diversification as rice farming does not provide an adequate household income. Two major ways that farmers can improve the profitability of their farms appear to be aquaculture, with or without integration with improved breeds of livestock.

Almost all farmers in the Red River Delta still raise pigs, 1-5 for fattening and 1-2 sows to provide piglets per household, and they have small flocks of scavenging poultry but with limited integration with aquaculture as it is difficult to reuse the manure. The rational and economics of pig rearing remain the same for the majority of farmers: pigs raised with little to no profit because of a relatively low price for local pigs and large price fluctuations; manure mainly used for rice, fruit and vegetables; and pigs fed agricultural products and by-products such as rice bran, maize, cassava and greens. However, there is an economic incentive to raise exotic or cross-bred pigs with lean meat and low fat., to which better-off farmers are responding, for an increasing urban demand, especially in Hanoi, for higher quality pork.

Although poultry is traditionally scavenging in the Red River Delta, with local breeds, some farmers are intensifying poultry with exotic and cross-breeds which require use of formulated feed. Manure can be used for fish production, especially from ducks swimming on the pond. Some farmers with support from the National Institute of Animal Husbandry and provincial agricultural departments have introduced feedlot poultry integrated with fish into the RRD. Large numbers of chickens and ducks fed with off-farm feeds are raised adjacent to or above fishponds, which receive spilled feed and manure.

When the Red River Delta in Viet Nam was formed, the human population density was low and the region was covered by vast forests, flooded forests and brackish water swamps in coastal areas. Dikes have been constructed for more than 1 000 years to control flooding and most of the Delta has been converted into terrestrial farms (Phan, Nguyen and Nguyen,1997). The Red River Delta (RRD) in North Viet Nam has a total area of 1.5 million km^2 and 15 million people; it is one of the most densely populated areas of the world with an average population density of over 1 000 person per km^2. The RRD has minute agricultural holdings of only 0.3-0.5 ha per household. The distribution of land to rural households which started in 1988 was relatively egalitarian and in the Red River Delta is fairly evenly distributed from poor to rich. However, some fish farms are now rather large and cover several hectares which is possible due to the emergence of a land market with rural households leasing land in or out (Viet Nam Development Report 2004; Poverty Task Force, 2005). Land rental markets allow more productive households to gain access to land and increase output; and allow other households to pursue non-farm income opportunities.

Poverty reduction in Viet Nam is one of the greatest success stories in economic development, and a simply remarkable achievement according to the Viet Nam Development Report (2004). Based on a poverty line computed according to international standards, poverty has been halved in less than a decade from 58 percent of the population living in poverty in 1993 compared to 29 percent in 2002 i.e., almost a third of the total population has been lifted out of poverty in less than 10 years. Furthermore, Viet Nam continues to reduce poverty much faster than other countries at a similar developmental level. The initial gains in reduction in poverty had been associated with the distribution of agricultural land through Resolution 10 (April 1988) which re-established the household as the primary economic unit in the rural economy (MARD/UNDP 2003). In more recent years, job creation by the private sector and the increased integration of agriculture in the market economy have been the driving forces (Vietnam Development Report, 2004). The proportion of people who mainly work on their own farm dropped from almost two thirds to slightly less than half. However, increased incomes from farming have also been important in poverty reduction with farm households more oriented towards the market.

While the incidence of poverty (percentage of people below the poverty line) is highest in the Central Highlands followed by the Northern Mountains, the poverty density is highest in the two deltas and the coastal areas because of the high overall population density in these areas. In 2002, 22 percent of the poor in Viet Nam resided in the Red River Delta. The majority of the heads of poor households are employed in the primary sector (agriculture, forestry, fisheries), 60 percent in the Red River Delta (Poverty Task Force, 2005).

There do not appear to be any specific studies on the role of aquaculture in poverty reduction in the Red River Delta although it has surely benefited the poor in general through providing fish for domestic consumption, income from sale of fish from household farms and for the non-farming poor through increased fish supply and employment opportunities on larger farms and input supply and marketing. Leasing out land and taking up non-farm employment may benefit the poor more than farming.

TABLE A3
Relevant issues under each principle at different scales in case study 2

Principles	1	2	3
Scales	**Ecosystem functions and services**	**Improved human-well-being and equity for all stakeholders**	**Context of other sectors, policies and goals**
Farm	• Semi-intensive with use of on-farm and local inputs so environmentally friendly • Limits to intensification in grass carp dominated system due to high oxygen demand of excess grass • Relatively high yields in a fertilized green water system, still environmentally friendly as small-scale • Aquaculture diversifying and intensifying with new or improved species including exotics and development of integrated feedlot livestock and pelleted feed with possible adverse environmental impact • Small ponds constructed on existing farms	• Moderate yields of medium size fish provide significant benefits for poor farming households in terms of nutrition and income	• Integrated with agriculture and animal husbandry and sometimes sanitation
Watershed/ zone	• No evidence that exotic species has had an adverse environmental impact	• Increasing competition for off-farm wild grass to feed grass carp places heavy burden on women • Widespread benefits in Red River Delta • Increasing industrialization, organization and development of land market allows some farmers to specialize in aquaculture with increased benefits to farm and region	• Research and development promoted by national and local governments
Global			• Support of international donors and educational and research institutes in Research and Development

CASE STUDY 3 TRADITIONAL POND BASED IAAS CHINA

China has the longest history of continuous aquaculture practice and is the leading aquaculture producer in the world in terms of total production. The well known traditional Chinese practice of carp polyculture is characterized by integration with other local human activity systems: agriculture, animal husbandry, sanitation and reuse of cottage-level industrial by-products such as from distilleries and soybean processing. There is a polyculture of up to 8-9 species of fish, with various feeding and spatial niches in the pond leading the efficient utilization of resources. The major species are the herbivorous grass carp (*Ctenopharyngodon idella*) the filter feeding bighead carp (*Aristichthys nobills*) and silver carp (*Hypophthalmichthys molitrix*), the omnivorous common carp (*Cyprinus carpio*) and crucian carp (*Carassius auratus*) and the snail eating carnivorous black carp (*Mylopharyngodon piceus*) (NACA (1989; Chen, Hu and Charles, 1995. It reached its most complex stage of development in the 1980s during the era of collective ownership. A survey conducted in 1985/6 indicated two main models : one dominated by filter feeding bighead and silver carp stocked at relative low densities in poorer areas and a model dominated by "feeding fish" (black carp, grass carp and omnivorous carps) stocked at high densities dominated in better-off provinces(Chen, Hu and Charles, 1995). Fish harvests ranged from about 4 to 10 tonnes/ha. Grasses were the major feed by weight in both groups, being used by 90 percent of farms surveyed but grains and oil cakes dominated feed costs. Most farms used manure either from cattle, pigs or poultry raised on the form or purchased from off-farm.

There has been a surge in production of the traditional Chinese polyculture system since the Government introduced a market-driven economy in the mid 1980s as pond polyculture of carps was relatively profitable compared to rice cultivation and animal husbandry, leading to greater production of major carps leading to falling prices and a decline in profitability (Ye, 2002). The inland fish pond area in China expanded by almost 150 percent from 1983-2003, mainly from conversion of agricultural land, facilitated by both government policy and economic benefit (Miao, 2007) although according to Leung and Shang (1993) most fish ponds have been constructed on low-lying land subjected to flooding and not suitable for agriculture.

Furthermore, the more recent increasing demand for fish has been primarily for higher value species in contrast to the lower value filter feeding species that dominate the traditional system. However, pond-based IAAS is still the major fish production system in China and continues to dominate national production (Mias, 2007). Grass carp is still the major cultured species and formulated pelleted feed is fed to the fish in addition to grass. There has been a de-linking of the crop and livestock from the pond subsystem on many IAAS farms in the major fish farming areas in China. As fish culture has been intensified, there is no need for manuring from livestock as there are more than enough nutrients from the residual fertilization of uneaten feed and fish faeces. Increasing diversification of species farmed in intensive monoculture has greater potential adverse environmental impact. Recent changes in Chinese inland aquaculture (increased IAAS intensity, reduced integration, monoculture of high-value species) have adverse environmental impact as there is no treatment of pond effluents (Miao *et al.,* not dated).

Discussion of Case study 3

Chinese integrated pond culture is considered to be sustainable as it reduces adverse environmental impacts considerably by farming various fish species within a mutual foodweb with recycling and other feedbacks between species and depends on inputs from economic activities outside the farm as it integrated with agriculture, animal husbandry and agroindustry (Folke and Kautsky, 1992). Thus, it produces food from wastes thereby changing environmental damage into benefits. IAAS are widely believed to be environmentally friendly because the most basic traditional system involved the recycling of nutrients mainly within the farm between crop, livestock and fish components subsystems or enterprises. The fish pond functions essentially as a sump, treating nutrients that would otherwise leak into the external environment, and converts them into fish.

It has been often been claimed that the Chinese carp polyculture system is a relatively closed ecological cycle and could therefore provide a model for ecologically sustainable aquaculture development elsewhere (Ruddle and Zhong, 1988; Korn, 1996) but productive IAAS, while producing fish on recycled nutrients, are driven by a large import of nutrients from outside the system (Edwards, 1993). The large flow of nutrients required to produce relatively high yields of marketable fish are mainly provided by the import of feed for integrated livestock. Intensification of IAAS also leads to environmental problems both for the pond and the fish, as well as surrounding environment (FAO/NACA, 2005; Ye, 2002). The pond water quality may deteriorate because of the large amount of organic matter input in fertilizer and feed. There may also be a build up of sediments on the pond bottom from organic matter inputs as well as erosion of pond dikes, leading to reduction in pond depth which may further reduce pond water quality. Eutrophic pond water can also have an adverse environmental impact on natural waterbodies when ponds are drained. There has also been indiscriminate dumping of pond sediments in canals and rivers in the Pearl and Yangtse river deltas. The traditional Chinese pond IAAS is a sustainable aquaculture system with moderate intensity as it is integrated with other agricultural activities but recent intensification of production has increased its adverse impact on the environment.

To improve fish feeding efficiency in China, farmers are moving increasingly to a feed-based production system with high quality agro-industrially manufactured pelleted feeds (Ye, 2002). Fed aquaculture is two to three times more nutrient efficient than fertilized aquaculture as there is a higher retention of N and P by the fish in feed than fertilizer; while fertilizers are cheaper than feed, pellets are formulated for optimal fish performance and are directly consumed by fish rather than indirectly through fertilizers stimulating the production of natural food *in situ* in the pond (Edwards, 1993). As intensive production of fish such as common carp in monoculture may yield up to 30-40 tonnes/ha compared to 12-15 tonnes/ha for traditional polyculture, the former "becomes the choice of farmers for higher production and profit" (Miao, 2007).

The intensification of IAAS and the development of monoculture are relatively recent changes in Chinese aquaculture which have not attracted enough attention from administration and science (Miao, 2007). Research and development is required on feed and feeding and water management technologies for intensive monoculture so that good management practices can be developed (Ye, 2007). Poor water quality is also caused by nutritionally incomplete pelleted feed with unsatisfactory physical properties (Ye, 2002). It has been predicted that the commercial viability as well as the sustainability of aquaculture will need to be based on efficient feeds and that future freshwater fish production will be entirely feed-based (Cremer, 2006b). Sustainability of aquaculture will also require increased adoption of plant-based feeds because of the finite supply and escalating price of fishmeal. Field trials carried out with several species of omnivorous freshwater fish (crucian carp, grass carp, catfish and tilapia) by the American Soybean Association (ASA) in China have demonstrated that soybean can effectively replace the majority of fishmeal in fry and fingerling rations and as the primary protein source in all-plant protein grow-out diets as no fishmeal is needed to feed fish larger than 50g (Cremer, 2006a).

It has been proposed that a water treatment system for both water supply and drainage canals of fish farms be developed involving biological and mechanical filters to remove suspended solids and provide a large surface area for bacteria to remove dissolved nitrogenous wastes (Ye, 2007). The Chinese Government is in the process of establishing effluent standards for aquaculture (Miao, Yuan and Yuan, not dated).

TABLE A4
Relevant issues under each principle at different scales in case study 3

Principles	1	2	3
Scales	**Ecosystem functions and services**	**Improved human well-being and equity for all stakeholders**	**Context of other sectors, policies and goals**
Farm	• Small ponds constructed on existing farms or low-lying areas subjected to flooding • Semi-intensive with use of on-farm and local inputs so environmentally friendly • Aquaculture diversifying and intensifying with new or improved species including exotics and development of integrated feedlot livestock and pelleted feed with possible adverse environmental impact	• Relatively high fish yields in optimized IAAS systems provide significant benefits for farmers in terms of nutrition and income	• Integrated with agriculture animal husbandry, local agro industry and sanitation • Expansion of farms during collectivization and subsequent privatization
Watershed/zone	• Indigenous species farmed in traditional IAAS • Diversification and intensification, accompanied by reduced integration, causing eutrophication in some areas where farms are large and/or concentrated	• IAAS still dominate Chinese inland aquaculture, about 60% of total production • Market-driven economy led to rapid expansion of IAAS but market saturation and economic development led to increasing diversification and intensification with major benefits to farmers in terms of higher profits and wider choice for consumers	• RandD promoted by national and local governments • Chinese Government in process of developing effluent standards
Global	• Increasing pressure on small pelagics for fish meal for pelleted feed		• RandD by American Soybean Association and Government shown that soybean can replace most of fish meal

CASE STUDY 4: POND BASED IAAS IN BANGLADESH

A survey of 100 fish farming households in Kishoreganj District which owned individually managed ponds was conducted as part of a study to assess the role of small-scale inland aquaculture in poverty reduction (ADB, 2004). There was an abundant carp seed supply in the area, as is the case in many parts of Bangladesh, from a large number of hatcheries. Among the fish farming household respondents, 98 percent farmed a carp polyculture of up to nine fish species, comprising mainly Indian major carps and Chinese carps. Among respondents, 98 percent used pond fertilizers (mainly cow manure and urea but some used poultry manure and triple superphosphate) and 99 percent used supplementary feed (mainly rice bran and oil cake but some used banana leaves and grass). The productivity of the fishponds was high because of the relatively sophisticated, semi-intensive aquaculture practice with an average extrapolated annual fish pond yield of 3.1 tonnes/ha.

All of the surveyed households used their fishponds for several purposes. Several other uses of the pond water were reported by the respondents: washing clothes (94 percent), bathing (87 percent), washing dishes (62 percent), livestock (21 percent), cooking (18 percent) and drinking water (1 percent) after filtering. No respondents used pond water for irrigating or watering crops. In spite of the multiple water use, there were relatively few water use conflicts. Fish farmers relied on both ground water and rainfall. Although most of the surveyed farmers did not report significant constraints related to water quality or supply, 40 percent of the respondents confirmed that seasonality had influenced the availability of water for fish farming. A majority of respondents reported that they had caught wild fish from either their own ponds (69 percent) or elsewhere near their farm (79 percent), although they believed that the wild fish catch had decreased significantly.

Small-scale farming households benefited from both sales and consumption of fish, most respondents consuming an average of 56 kg of fish and selling an average of 244 kg of fish, making a highly significant contribution to their income. The marketing chain for fish was short with most farmers selling their fish locally to market intermediaries, further generating employment. Fishpond owners may be generally categorized as relatively better-off among rural households in the context of rural Bangladesh but they do not necessarily escape from poverty; among small landowners in Bangladesh with moderate access to land of 0.5-1 ha, including fish ponds, 34 percent live below the poverty line. They do not produce much surplus from farming and are vulnerable to crises. Even some fishpond owners who may be categorized as medium-size landowners with 1-2 ha of land are also vulnerable; 25 percent of them live below the poverty line with the rest precariously above it and they can easily slide into poverty when faced with an unexpected crisis. A large majority of the respondents in the study were exposed to several crises, the most serious being illness of household members, shortage of food and damage due to floods, erosion, heavy rain and cyclones.

The respondents were optimistic about the benefits of fish farming. Compared to 5 years ago, the surveyed households overwhelmingly confirmed that their food and fish consumption had increased and they had benefited from employment and cash income. Furthermore, they reported that conditions of natural resources for fish farming had not declined. The respondents were also optimistic about their future in fish farming and a large majority (90 percent) of respondents would continue to farm fish.

Discussion of Case study 4

Freshwater aquaculture provides more than a third of the total fisheries production in the country. Over the last decade there has been a dramatic increase in freshwater aquaculture production, from 124 000 tonnes in 1986 to 561 000 tonnes in 2000, with average yields increasing from 0.84 to 2.44 tonnes/ha (ADB, 2005). Traditionally much farmed fish came from ponds constructed as borrow pits, dug to raise the level of land for village homesteads and roads on the flood plain. With the growing importance of freshwater aquaculture, ditches that were formerly only flooded seasonally have been converted into perennial ponds through deepening and expansion in area.

Semi-intensive fish culture is a relatively recent introduction into Bangladesh as traditional aquaculture practice involved only stocking wild seed in ponds without any intentional nutritional inputs. Fertilization of fishponds with cattle manure produces natural feed organisms for hatchery produced stocked fish: phytoplankton and zooplankton in the pond water column and invertebrates animals on the bottom of the pond. These plankton and benthic organisms serve as food for filter feeding carps and bottom feeding carps, respectively. Although manure has alternative uses as a fuel and a crop fertilizer, many villagers use it as a pond fertilizer because of the attractive profitability of fish farming. Households generally own livestock that are fed on wayside vegetation, rice straw obtained from sharecropping, and other agricultural wastes. The most common supplementary feeds for use in fishponds are rice bran and mustard oil cake, which are readily available on-farm or in local markets. Important introductions of exotic fish to the traditional polyculture of indigenous Indian major carps are the grass carp (*Ctenopharyngodon idella*), which is fed with on-farm vegetation such as grass, banana leaves and duckweed, and the filter-feeding silver carp (*Hypophthalmichthys molitrix*) which grows rapidly in green water ponds and comprises a major part of the harvest. Such semi-intensive aquaculture practice fits well into the predominantly agricultural landscape with minimal adverse environmental impact.

Through many research and developments projects over the last three decades farmers now get fish yields of 3 -5 tonnes/ha in well-managed semi-intensive ponds using mainly resources from on-farm or obtained off-farm locally such as manures, brans and oil cakes.

The pond IAAS that has been developed in Bangladesh over the last two decades is relatively simple compared to the traditional pond IAAS of China and Viet Nam. Livestock are not commonly raised on or near the pond to facilitate the use of manure as a pond; nor are vegetables commonly raised on the pond dikes. Pond inputs are primarily on-farm sources of cattle manure and rice bran, with bran increasing being purchased off-farm as well as oil cakes and inorganic fertilizers with intensification of the semi-intensive system. However, cultivation of dike crops has developed rapidly in recent years in some areas (Ahmed, Wahab and Thilsted, 2007; Edwards, 2007).

Freshwater aquaculture, primarily carp polyculture in IAAS plays an important role in rural livelihoods in Bangladesh (ADB, 2005). It provides employment and income as well as accounting for 60-80 percent of the animal protein consumed by the population and is a major source of essential vitamins, minerals and fatty acids. Considerable employment is generated in diverse ways through inland aquaculture in Bangladesh (ADB, 2005). Employment is generated through employment in hatcheries and seed trading, pond construction and repair and harvesting and marketing fish as well as in direct self-employment on the farm. With about 400 000 ha of farmed water surface area, direct full-time employment may be about 800 000 people assuming a requirement of 2 persons/ha. As most work is part-time the number of people with a livelihood associated with inland aquaculture may be at least 2 million.

While integrated carp polyculture has great potential for further expansion and intensification in Bangladesh, there is a recent development in the country of intensive pond culture of river catfish (*Pangasius hypophthalmus*) and Nile tilapia (*Oreochromis niloticus*) (Edwards and Karim, 2007; Ahmed and Hassan, 2007). River catfish are commonly farmed in monoculture with formulated pelleted feed and high rates of feeding cause pond surfaces to froth with green bubbles from intense photosynthesis. Some farmers have developed a polyculture with 5-10 percent Indian major carps and tilapia in the 80-90 percent catfish-dominated pond to reduce phytoplankton blooms

(Edwards and Karim, 2007). Earlier attempts to use the more rapidly growing silver carp to filter phytoplankton failed as this species is less resistant to low dissolved oxygen, a good example of farmer experimentation.

TABLE A5
Relevant issues under each principle at different scales in case study 4

Principles	1	2	3
Scales	**Ecosystem functions and services**	**Improved human well- being and equity for all stakeholders**	**Context of other sectors, policies and goals**
Farm	• Semi-intensive with use of on-farm and local inputs so environmentally friendly • Aquaculture diversifying and intensifying with new or improved species including exotics and use of pelleted feed with possible adverse environmental impact	• Low to moderate fish yields provide significant benefits for farmers in terms of nutrition and income in some areas	• Integrated with agriculture animal husbandry and local agro-industry • Small ponds constructed in settled areas initially as borrow pits in floodplains but increasing in rice fields
Watershed/zone	• Diversification and intensification causing eutrophication in some areas where farms are large and/or concentrated and where there is demand from urban areas for new species	• Part and full-time employment in input supply and marketing • Considerable potential for intensification and more widespread dissemination of IAAS with increase of benefits to local populations	• R and D promoted by national and local governments and in cooperation with international donors and R and D institutes
Global			

CASE STUDY 5: TRADITIONAL POND BASED IAAS IN HUNGARY AND THE CZECH REPUBLIC

Aranyponty Fish Farm in Hungary was built by a nobleman more than 100 years ago in 1896 on poor quality agricultural land prone to water logging. It was originally a wetland but was drained in 1825 for agriculture. More recently it was a state farm and was purchased by its present owner from the State in 1994 who began to diversify activities in 2000 so that the farm is now the core of the Rétimajor – Ponds Nature Reserve established in 1996 and covering about 1 500 ha. (Szücs *et al*., 2007). The core of the reserve is a fish pond system with 12 large ponds (10-70 ha), 16 small ponds (1-5 ha) and 21 wintering ponds, with a total farm water surface area of 739 ha. More than 220 species of birds are registered on the farm, almost 60 percent of those found in Hungary, the majority of which have protection status. The reserve was designated as a Wetland of International Importance under the Ramsar Convention on Wetlands in 1997. The farm is one of only seven organic fish farms in Hungary currently certified by Bio-Kontrol Hungaria. There are various tourist and recreational facilities such as a hotel and a restaurant, angling, bird watching and nature trails. A former stable houses the Hungary's only fishing museum. A field laboratory has been established in cooperation with the Institute for Fisheries Aquaculture and Irrigation (HAKI) to monitor the environment, develop innovative aquaculture technologies and study multifunctionality of fish farms. The farm revenues of the multifunctional pond farm are 20-50 percent higher than that of a conventional pond farm, and in addition the former has a more diversified income which increases its economic sustainability and social acceptance.

Discussion of Case study 5

The dominant aquaculture technology in Central and Eastern Europe (CEE) is a traditional system of carp culture in ponds with almost a 1,000 year old history (Berka, 2007, Szücs *et al*., 2007; Zdenek, Berka and Huda, In press). There are over 600 000 ha of large fish ponds ranging in size from 1-500 ha in the CEE region with an average production of carps of 190 000 tonnes between 1999-2003 (Szucs, Stundl and Varadi, 2007). Today there are 50 000 ha of fish ponds in the Czech Republic and 25 000 ha of ponds in Hungary, two of the major carp producing countries in the CEE.

Ponds are considered as an integral part of the landscape as well as being fish farms. Ponds were built in low lying wetlands or areas with soil conditions too poor to support productive agriculture. In some areas e.g. in parts of Southern Bohemia in the Czech Republic,centuries old fish ponds are the major feature of the landscape. Although they are all artificial and are drained annually, they look like lakes because of their large size. There has also been a continuos programme through the centuries of draining wetlands in Hungary to develop agricultural land as well as fish ponds.

Carp culture comprises three sequential pond stages which have remained more or less unchanged since it was developed in the 14th century, nearly 700 years ago. The three groups of ponds which are drained annually are: nursing ponds are up to 1 ha; summering ponds up to 10 ha in area are used to raise 1- 2 year old fish; and marketing ponds at least 50-100 ha in area stocked with 2 year old fish which are raised until they are 3-4 years old and have attained a marketable size of 1.5-3 kg. The typical polyculture is dominated by common carp (*Cyprinus carpio*) stocked at 50-90 percent of the total, followed by Chinese carps (bighead carp, grass carp and silver carp) at 10-30 percent with a few percent of predators (pike, *Esox lucius*; pikeperch, *Stizostedion lucioperca*; European catfish, *Siluris glanis*) and other species such as tench (*Tinca tinca*). About 70-75 percent of the nutrition for the fish is from protein-rich natural food (plankton and benthos) with 25-30 percent from supplementary feeding with energy-rich grain (barley, maize, wheat). Cattle manure is mainly used to fertilize ponds but pig and poultry manure is used in areas where these livestock are raised in feedlots. However, ponds in many areas are eutrophic from agricultural, industrial or urban effluents or run-off so fertilization may not be required. Pond yields are relatively low, ranging from 600-1 500 kg/ha.

Due to their large size, the ponds are part of the rural economy as well as the landscape. Although aquaculture's contribution to employment is relatively small, in some areas it is one of the few livelihood options and helps to sustain rural populations. Until recently, fish farms were state owned but they have now been privatized with some companies owned by worker stakeholders. A large majority of common carp production is sold live at Christmas for the traditional Christmas Eve dinner.

Many ponds are multipurpose. Besides producing fish they may serve for recreation and tourism such as bird watching, angling and hunting especially bred, semi-wild ducks; water storage and flood protection of surrounding areas; irrigation; as nature reserves; and to preserve the local cultural heritage of aquaculture and carp consumption. The major flood experienced by the Czech Republic in 2002 would have been much worse without fish ponds which held more water than storage reservoirs, even though their water holding capacity has declined by 25 percent due to silting in recent years (R. Berka, personal communication, 2008). The current low yields of carp ponds in the CEE is partly due to their multiple use, especially strong pressure from nature conservancy and environmental groups. Aquaculture may take second or even third place behind biological treatment of water, water retention and nature conservation (Berka, 2007). Aquaculture in the Czech Republic is "fighting for existence" with environmental groups who would be "happy without fish in the ponds" even though all fish ponds in the country are artificial (R.Berka, personal communication, 2008). Fish ponds have been taken over by environmentalists in Germany with a 50 percent decline in carp production (R.Berka, personal communication,2008). Environmental groups have also prevented the stocking of grass carp in ponds in the Czech Republic as it is not a native fish even though it would help to reduce excessive growth of aquatic macrophytes in the shallow ponds. In Hungary grass carp can still be stocked in fish ponds but not in reservoirs or natural waters.

The main point of conflict is the desire of environment groups to consider a fish pond only as a natural wetland which is hardly feasible. Building fish ponds made the landscape more useful for humans as well as for nature: without aquaculture, there would be no waterbodies; had wetlands not been converted into fish ponds, they would have been developed into agricultural land (R.Berka, personal communication, 2008). The majority of ponds function as wetlands because of their large size and vegetated margins and three fish farms in the Czech Republic and four in Hungary have protected fauna, flora and habitats under the Ramsar Convention on Wetlands (Chytil *et al*., 2006; Ramsar, 2007). Under the European project Natura 2000, it is predicted that further additional protected fish pond areas will be designated in the Czech Republic in which fish production will be decreased in many ponds to almost an extensive level (Zdenek *et al*., in press). The Czech Government has set a limit of a ratio of 50:50 fertilizers to feed to produce carps in ponds (R.Berka, personal communication, 2008). It is prohibited by law in the Czech Republic to add inputs to a fish pond but permission may be granted based on analysis of pond water quality and pond history.

Fish predators such as cormorants, herons and otters cause high economic losses to fish farmers although in the Czech Republic they are compensated under law for losses caused by protected animal species (Z. Adamek, personal communication, 2008). The number of cormorants has increased dramatically in recent years in the Czech Republic as migrating flocks of tens of thousands of birds spend a few weeks on the ponds in spring and autumn as they pass through the region. Farmers are not concerned about a few hundred locally nesting cormorants but huge migrating populations from Northern Europe consume huge amounts of fish as a cormorant eats 0.5 kg fish/day according to Dr. Adamek (personal communication, 2008) who is involved in assessing fish loses due to animal predation.

At present the most important concern in Czech aquaculture is shallow ponds caused by siltation (R. Berka, personal communication, 2008). This has always been a problem and ponds in the past have been desilted when the mud layer exceeded 40cm in depth. However, in recent years the silt load of water has increased as greater overall management of water has slowed down the flow rate and therefore the flushing rate and increased the siltation rate in rivers as well as in ponds. In the Czech Republic the average pond depth is now only 0.6-0.9m compared to 0.8-1.1m previously. Ponds are currently being desilted to increase their depth but it is expensive and requires government subsidy. It was easier to desilt ponds in the 1950s and 1960s, and even through the 1970's and 1980's, as there was a large demand for nutrient-rich sediments to put on agricultural land. Today there is no demand for fish pond sediments for agriculture and sometimes they have to be treated like hazardous wastes because of a high pesticide content from improper agricultural practices during the previous socialist era.

However, carp farming is increasingly being seen as part of the solution to nature conservation and not as a problem, at least by aquaculturists (Berka, 2007). As well as producing more fish, deeper fish ponds can store more water as well as provide a more suitable habitat for water birds. Shallow carp ponds left idle in Hungary for a few years became infested with dense stands of emergent macrophytes and therefore unsuitable for water birds attracted to open water (P. Edwards, personal communication, 2008). In fact, fish farming may be the only economic way to manage fish ponds to prevent them from disappearing through vegetational succession so that they can also serve as a suitable habitat for water birds (R.Berka, personal communication, 2008).

A balance needs to be struck between the various multiple functions. It is a major developmental goal of carp farming in the CEE countries to maintain the condition of existing fish ponds so that they may continue to function as wetlands with potential to preserve habitats for diverse fauna and flora as well as rural landscapes and economy. Multiple functioning of fish ponds is now considered to be a strength of pond aquaculture by the aquaculture fraternity (Szücs *et al.,* 2007) as they have been demonstrated to preserve habitats for diverse fauna and flora as well as maintain the rural landscape for aquaculture and the local economy.

There are also marketing issues which threaten the sustainability of carp farming. Carp production is still profitable with farm gate prices of Euro 2.2-2.4/kg for carp of at least 1.5 kg but annual fish consumption is very low in the CEE e.g. only 5 kg/person/year (and only 1.1 kg/person/year of freshwater fish) in 2006 in the Czech Republic (Z. Adamek, personal communication, 2008) and only 3.7 kg/person/year (only 0.7 kg/person/year of freshwater fish) in Hungary (L. Varadi, personal communication, 2008). Carp prices have been stagnant over the last 10 years. Most carp are eaten at the traditional Christmas Eve dinner, over 90 percent of the carp consumed in the Czech Republic although only 30 percent of the total annual sale is now at Christmas in Hungary. Carp are also used to stock ponds for anglers. They are exported for human consumption as well as for stocking ponds for angling. Very little fish is processed as the price of processed fish is much higher than that of processed pork and imported marine fish such as salmon. River catfish (*Pangasius* spp.) is now imported from Viet Nam and is considered to be a major threat to the sustainability of local aquaculture as it is a high quality and cheaper product than locally farmed fish. Advertising campaigns are being carried out to try to increase consumption of carp as a high quality fish with low fat content as natural high-protein food contributes 70-75 percent of the total food for the fish but there is concern that the traditional carp polyculture might not be able to survive the increasing rate of importation of foreign fish.

TABLE A6
Relevant issues under each principle at different scales in case study 5

Principles	1	2	3
Scales	**Ecosystem functions and services**	**Improved human well-being and equity for all stakeholders**	**Context of other sectors, policies and goals**
Farm	• Semi-intensive with use of local inputs rather than on-farm inputs but environmentally friendly as relatively low yields • Aim is to maintain traditional relatively low-input low-output system so that it remains environmentally friendly	• Relatively low yields but large pond sizes provide significant benefits for farmer in terms of employment and income	• Indirectly integrated with agriculture and animal husbandry as grains and manures are sourced off-farm • Constructed on poor agricultural land, occasionally on wetlands
Watershed/zone	• No evidence that exotic Chinese carps adversely affected environment • Most farms have typically large 10 to >100 ha ponds and in some areas are in clusters so that lake-like ponds dominate the landscape	• Aquaculture is well-planned and regulated and is considered as a cultural tradition • Little employment but helps to sustain rural communities as one of a few livelihood options • Provides carp for traditional Christmas dinner	• Increasingly ponds are multipurpose and also serve for recreation and tourism (angling bird watching, hunting ducks), water storage and flood protection, irrigation, and nature reserves • R and D by national local government and institutes in environmentally sustainable and multi functional aquaculture • Three farms in Czech Republic and four farms in Hungary under Ramsai Convention on Wetlands
Global			

CASE STUDY 6 – POND-BASED IAAS IN MALAWI

Concerted efforts have been made to develop small-scale IAAS in Malawi over the past few decades with substantial support from external donors but fish ponds are characterized by low productivity which minimizes their contribution to rural development (NASP, 2005). A typical farm has one or two ponds 200 m^2 or less, usually located in close proximity to a seasonal wetland or "dambo". The most commonly farmed species is the indigenous tilapia *Oreochromis shiranus* although it is usually stocked in polyculture with *Tilapia rendalli*, *O. korongae, Clarias gariepinus* or *Cyprinus carpio* in order of decreasing priority. The majority of farmers use green compost to manure the pond and maize bran as a supplementary feed. Reproduction is not controlled so tilapias breed in the pond. Farmers mainly rely on Government stations to provide fingerlings although they are increasingly being produced and sold by farmers. As Malawi an ponds are "low-input – low-output" operations, estimated yields are only 700-1 200 kg/ha but pond water is also used to cultivate crops on or near the pond dikes.

Research and development involving farmer-participatory experiments in Malawi aimed to transform traditional farming systems and make them more sustainable through integration of aquaculture and agriculture (Brummett and Noble, 1995). Farms which adopted IAA were believed to become more sustainable than non IAA farms as indicated by increases in three ecological indicators: diversity, nutrient cycling and natural resource systems capacity. Diversity was defined as the number of species cultivated, speculated to contribute to sustainability through biocontrol of pests, reduced risk through compensation by one species for possible reduced production in another, and maintenance of a larger range of germplasm. Recycling was defined as the number of IAA linkages or bioresource flows, speculated to contribute to sustainability through reduced pollution, utilization of wastes and more nitrogen and phosphorus in available forms. Capacity was defined as the total farm production in tonnes/ha. IAA farms were demonstrated to have higher economic efficiency than non integrated farms as measured by profit: cost ratio but through this approach after more than 15 years of WorldFish involvement in Malawi , the total national production from fish ponds has increased to only about 1 000 tonnes per year (Dey *et al*., 2006).

An ex-post impact assessment by The WorldFish Center and its national and international partners of the development and dissemination of small-scale IAAS over more than 15 years in Malawi estimated a benefit: cost ratio of 1.4 and an internal rate of return of 15 percent (Dey *et al.* 2006). However, there are fundamental challenges and constraints to the currently operated IAAS in the country (NASP, 2005): relatively few farmers have access to land suitable for aquaculture or with a water source; most farmers either do not have access to pond inputs because of a poor farm resource or cannot afford the risk of purchasing fertilizer, feed and seed.

The National Aquaculture Strategic Plan for Malawi proposes a strategy to ensure that aquaculture activities are environmentally responsible and sustainable (NASP, 2005). The Plan includes the promotion of commercial aquaculture in Malawi which would require high yield technologies involving selection of appropriate species and strains, controlling reproduction in ponds, and adequate fertilization and feed (NASP, 2005). It also recommends that the Fisheries Policy and Act needs to be revised and amended with respect to environmental threats; an early warning system to monitor potential threats caused by aquaculture to biodiversity and the environment needs to be established; and national knowledge of the link between aquaculture practices and environmental issues needs to be increased.

Discussion of Case study 6

Pond-based IAAS are not traditional in Africa but have been introduced mostly through donor-funded projects over the last few decades. However, it is now recognized by

FAO that aquaculture development in sub-Saharan Africa has stalled despite decades of interventions and support programmes from regional and international development agencies (FAO, 2006). Fish consumption in sub-Saharan Africa, currently 6.6 kg/capita/year, is the lowest in all regions and is the only part of the world where it is declining. A major reason for the limited contributed of aquaculture to fish consumption in Africa is undoubtedly the poor resource–base of most small-scale African farms which constrains the development of aquaculture.

In ten countries of sub-Saharan Africa there are believed to be nearly 110 000 "non-commercial" farmers defined as small-scale subsistence, small-scale artisanal or integrated aquaculture normally practiced by resource-poor farmers (FAO, 2006). Non-commercial farmers may purchase inputs such as feed and seed but rely mainly on family labour and on-farm sale of produce. Aquaculture is promoted today in almost all Africa countries under poverty reduction strategies. Rather than promoting aquaculture to essentially improve subsistence as part of a livelihoods diversification strategy to provide greater food security at the family level, it is now recognized that the motivation of "non commercial farmers" is often similar to that of commercial farmers which is profit (FAO, 2006, Moehl *et al*., 2006). It is now believed that non-commercial aquaculture is not likely to make a significant contribution to national fish supply in many sub-Saharan African countries and to increase the supply will require a paradigm shift in the support role of donors and lead agencies. While reliance on on-farm inputs may not be appropriate for many small-scale farms, it is recognized that scaled-up, livestock/fish integration may be economically viable (Moehl *et al*., 2006) although this would depend largely on off-farm feed as livestock are essentially raised intensively in such integrated systems.

The paradigm shift in support required for sub-Saharan African aquaculture is towards entrepreneurship rather than subsistence (Moehl *et al*., 2006). The starting point is the concept of "clusters" of activity in which there are production and economic thresholds (number of farmers, farmed area or tonnes produced) below which public or private support is not worthwhile. Cluster sites would be "high potential zones for a particular aquaculture system based on bio-physical or ecological socio-economic parameters, such as a site well endowed with water and a peri-urban area with good access to markets for inputs and produce, respectively."

TABLE A7
Relevant issues under each principle at different scales in case study 6

Principles	1	2	3
Scales	**Ecosystem functions and services**	**Improved human well- being and equity for all stakeholders**	**Context of other sectors, policies and goals**
Farm	• Ponds mostly constructed on existing farms • Semi-intensive with use of mostly on-farm inputs so environmentally friendly	• Low yields of fish provide significant benefits to poor farming households but relatively few adopters of aquaculture in rural areas	• Integrated with agriculture
Watershed/zone	• Indigenous species farmed • National Aquaculture Strategic Plan for Malawi recommends inclusion of an early warning system to monitor potential threats caused by aquaculture to biodiversity and the environment	• Limited benefits to other than farming households as markets for input supply and produce not well developed	• National Aquaculture Strategic Plan for Malawi includes the promotion of commercial aquaculture with adequate fertilization and feed from mainly off-farm sources
Global			• FAO now recognizes that the poor-resource base of most small-scale African farms constrains the development of aquaculture • FAO recognizes the need for a paradigm shift for sub-Saharan African aquaculture towards entrepreneurship rather than subsistence with well endowed sites and good market access for inputs and produce

CASE STUDY 7 – TRADITIONAL POND-BASED IPAS IN HANOI, VIET NAM

Hanoi has a major system of wastewater reuse involving aquatic vegetables such as water spinach and fish (rohu, silver carp and tilapia) in low lying Tranh Tri district which used to provide a significant part of the diet of the city's people (Vo and Edwards, 2004). The system has been developed by farmers and the local community from a sparsely populated wetland which was previously used to grow rice but production was low due to frequent flooding.

Wastewater in Hanoi is still discharged without treatment into a network of rivers that flows to the south of the city through Thanh Tri district, and eventually into the Red river, although conventional wastewater treatment plants are to be installed. Farmers through experience accumulated over the past four decades have developed wastewater-fed aquaculture involving either a polyculture of finfish (mainly the Indian major carp rohu, the Chinese silver carp and tilapia) with or without rotation with rice, or aquatic vegetables (mainly water mimosa and water spinach). A large number of individuals, especially people of lower socio-economic status, are involved in production and marketing of wastewater-fed produce, either part or full-time. Produce is also consumed by a large number of urban people, especially the poor.

There has been a recent rapid rate of change with the rural landscape of fields and ponds in Than Tri district being converted into an urban one of brick and concrete. Under the first phase of the Hanoi Master Plan for sewerage, drainage and environmental improvement, wide drainage canals, storage reservoirs and a pumping station have been installed in areas recently occupied by wastewater-fed fish ponds. Buildings are sprouting like mushrooms all over the district, right up to the water's edge of fish ponds. Large blocks of buildings co-exist with the remaining fields and ponds.

The old Thanh Tri district has recently been divided into two. The northern half in which most of the wastewater reuse takes place has been renamed as a new district, Hoang Mai, and declared an urban area in November 2003. While the map for 2001 in the Hanoi city Master Plan indicates large areas of fish ponds, none are indicated for Hoang Mai district for 2020. The total area of wastewater-fed aquaculture declined from 751 ha in 1985 to 417 ha in 2002 and will decline further. Most of the government support for aquaculture is to be for high-value aquaculture species such as red tilapia, river catfish and giant freshwater prawn in line with industrialization and modernization.

Change of land use from rural to urban development with an associated marked increase in land value is the main factor in the on-going demise of wastewater-fed aquaculture and agriculture in Hoang Mai district. The increasing content of industrial effluents in the total wastewater stream has an adverse effect on both fish growth and survival. Farmers reported that fish ponds could only safely accommodate 10-30 of the total pond volume with wastewater, with occasional mass mortality of fish due to toxic wastewater. Farmers now have to supplement low volumes of wastewater with other fertilizers such as livestock manure and beer and wine residues as feed. As the price of pelleted feed is high, farmers lose money if they use it to raise relatively low-value wastewater-fed fish.

Furthermore, the quality of fish raised on wastewater is said to be poor, with a bad smell and taste because of industrial chemical effluents in the previously mainly domestic wastewater. As most fish raised in wastewater-fed ponds are also small, they are difficult to market in the increasingly sophisticated Hanoi markets. Wastewater-fed fish supplied as much as 40 percent of Hanoi's daily requirement for freshwater fish in the past but now they are mainly marketed for poor people in remote rural areas in central and north Viet Nam . However, Vietnam has many cities which are at an earlier phase of development than Hanoi and in some wastewater reuse occurs and still may have relevance.

Discussion of Case study 7

Wastewater-fed aquaculture, the use of human excreta such as night-soil, faecal sludge and domestic sewage as fertilizers to produce fish or aquatic plants has a long history in several countries in East, South and South East Asia but particularly in China (Edwards, 2005b; WHO, 2006). Most of these systems are informal having been developed by farmers, with limited introduction of formally designed and engineered systems. Wastewater-fed aquaculture contributes in particular to the livelihoods of the poor through providing employment and income for peri-urban farmers and low-cost fish for urban consumers (Bunting, 2004; Little and Bunting, 2005). Revised guidelines have recently been published for the safe use of wastewater and excreta in aquaculture (WHO, 2006). Wastewater-fed aquaculture can also be considered as a low-cost wastewater treatment option which may have particular relevance in arid and semi-arid climates where there is increasing necessity to recycle water (WHO, 2006).

Most existing systems of wastewater reuse through aquaculture are threatened or in decline as in the Hanoi case study. There has been a major reduction in wastewater-fed aquaculture in China which has the longest tradition and until recently the greatest extent of practice. According to Wang W.M. (personal communication, 2008), use of wastewater in aquaculture was a “last century practice” (Edwards, 2006). The largest single wastewater-fed aquaculture system in the world in Kolkata, India, although reduced from 7 300 ha at its peak in 1945 to 3 500 ha today, continues to provide social benefits to the poor in periurban and urban areas of the city as well as environmental benefits through low-cost wastewater treatment. As it is a haven for wildlife it has been declared a wetland of international importance under the Ramsar Convention (Bunting, Kundu and Mukherjee, 2005).

Wastewater-fed aquaculture appears to be a transient phenomenon of pre-industrial and early industrial societies in which reuse of wastewater is socially acceptable because of high population pressure and scarce resources (Edwards 2005b,c). Once a national economy starts to expand, a series of factors constrains wastewater-fed aquaculture : increasing shortage and value of peri-urban land; declining quality of wastewater as a nutrient source due to increasing contamination with industrial effluents and associated declining quality of produce; increasing demands of more affluent consumers for large and often carnivorous species even though these are higher priced than wastewater-fed fish; and ability of farmers to meet the demand for alternative farmed species because of availability of seed through R and D and pelleted feed from agro-industry.

According to the World Health Organization at least 2.4 billion people lack access to basic sanitation and 1.1 billion lack access to safe water which are linked directly to the deaths of almost 4 000 children/day (Sandino, 2007). The Millennium Development Goal (MDG) for sanitation is to half the number of people without adequate sanitation in 1990 by the end of 2015 (Mara *et al*., 2007). During this period there will be increasingly severe global scarcities of water, nutrients and energy, especially in developing countries. According to Mara *et al*. (2007) human waste will become an increasingly important resource, especially for small-scale farmers in developing countries and sanitation planning will have to change to reflect the growing economic importance of using waste-derived nutrients for food production, including aquaculture. A sanitation selection algorithm has been designed which considers all the available sanitation arrangements including reuse as well as treatment (Mara *et al.,* 2007).

Lagoon-based treatment solutions which it is possible to link with reuse through aquaculture are generally only feasible in relatively small urban locations (Sandino, 2007). Relatively simple and inexpensive mechanically based wastewater treatment options are needed for medium to large urban areas in developing countries and/or in the absence of large areas of available land where conventional mechanical technologies such as activated sludge commonly used in developed countries are expensive to build and operate and require a high level of expertise to run and maintain. These would preclude reuse through aquaculture so that it is unlikely that new wastewater reuse schemes through aquaculture will be implemented on a large scale.

TABLE A8

Relevant issues under each principle at different scales in case study 7

Principles	**1**	**2**	**3**
Scales	**Ecosystem functions and services**	**Improved human well-being and equity for all stakeholders**	**Context of other sectors, policies and goals**
Farm	• Ponds constructed in cultivated land • Semi-intensive cultivation of aquatic vegetables and culture of fish in wastewater-fed ponds is environmentally friendly	• Sale of aquatic vegetables and fish provides a livelihood for poor farming households	• Aquaculture integrated with wastewater as low-cost treatment
Watershed/zone	• No evidence that exotic species have adverse environmental impact	• Aquatic vegetables a major source of vegetables for Hanoi • Poor quality fish mainly consumed by the poor in remote rural areas	• Domestic wastewater is increasingly contaminated with industrial effluents • Wastewater-fed aquaculture not included in Hanoi City Master plan
Global			• WHO policy to promote well managed wastewater-fed aquaculture where appropriate and guidelines issued • General global aversion to recycling wastewater is aquaculture, especially in more developed economies

CASE STUDY 8 –TRADITIONAL IFAS, SNAKEHEAD IN CAGES IN CAMBODIA

Giant snakehead (*Channa micropeltes*) used to be raised in floating cages in the Mekong river and the Great Lake in Cambodia using wild seed and wild small-sized fish as feed but the practice has been banned by the Ministry of Agriculture, Forestry and Fisheries (MAFF). Cages were rectangular in shape, 5-200 m^3 in volume, with the wooden frame and wooden slats of the cage floated with bundles of bamboo (Interim Committee for Coordination of Investigations of the Lower Mekong Basin, 1992). Stocking densities were about 50 kg/m^3 with a net production of about 100 kg/m^3. Wild snakehead seed were abundant but the practice required the harvest of a large amount of small wild fish to feed the carnivorous snakehead fish, with a food conversion ration of 4-6 : 1 on a fresh weight basis. Snakehead cage culture was initially a secondary occupation of small-scale artisanal fishers who caught wild seed and feed but the practice became dominated by large-scale fish farms. Cage culture was constrained by the seasonal availability of fish for feed, the capture of which is prohibited during the closed fishing season from June to September so culture encouraged poaching during this season as well as use of fine- meshed illegal fishing gear such as mosquito netting.

The ban was announced by MAFF on 3 August, 2004. It was introduced according to senior officials in the Cambodian Fisheries Administration following complaints from some fishers about excessive harvesting of small fish which they perceived to be a cause of declining catches of larger fish. The major concern was the catch comprised important commercial species before they have had time to grow large, as well as the naturally small fish called 'trey riel' in Cambodian (*Cirrhinus lobatus* and *C. siamensis*) used to make fermented fish paste, a national dietary staple.

A translation of the ban is: "MAFF would like to announce to fish farmers that snakehead fish farming was very active recently, leading to illegal fishing of small wild fish to feed to snakehead, especially in the closed fishing season which severely affected natural aquatic resources. In order to eliminate this negative impact, all fish farmers must stop farming these species immediately, and temporarily to allow Government technical fisheries staff to study the negative impact on aquatic resources and to find alternative feeds for snakehead. MAFF would also like to recommend that farmers culture species other than snakehead to increase the fish supply, the second staple food after rice. MAFF strongly hopes that fish farmers, local authorities, and concerned officials at all levels will cooperate to prevent the farming of these species in an effective way and find alternative species for the long term conservation of aquatic resources".

The ban did not come into effect until 2005 as farmers were allowed to complete the snakehead culture cycle already underway at the time of the ban and market harvested fish. A visit to major cage farming sites in the Tonle Sap River and in the Great Lake in September 2007 revealed that the ban is being effectively enforced and several cage farmers who had previously cultured snakehead had stocked river catfish, *Pangasius hypophthalmus* (P. Edwards, personal communication, 2008). No cage farmers interviewed knew of any farmers raising snakehead in the neighbourhood but reported that it may still occur to a limited extent in remote areas deep inside the flooded forest as it is highly profitable. Forty farmers were caught illegally farming snakehead in 2006 by the provincial Fisheries Administration. The farmers were ordered to market the fish and 50 percent of the sale was taken by the government as a fine (Fishery Inspector, personal communication, 2008).

Research is planned to assess the impacts of the ban on the livelihoods of fishers, fish farmers and poor people, and on aquatic biodiversity. The Cambodian Fisheries Administration of MAFF would also like to carry out research on alternative diets for snakehead to fresh small fish so that the temporary nature of the ban may be lifted.

Discussion of Case study 8

Direct use of trash fish to feed carnivorous fish is unlikely to be sustainable in the long term (FAO,2006). The challenges for aquaculture are to make better use of the existing low value fish and trash fish resources but in particular to seek alternatives to direct feeding of trash fish in aquaculture . The challenges have social, economic and political as well as technical and environmental dimensions.

TABLE A9

Relevant issues under each principle at different scales in case study 8

Principles	1	2	3
Scales	**Ecosystem functions and services**	**Improved human well-being and equity for all stakeholders**	**Context of other sectors, policies and goals**
Farm	• Cage culture of snakehead based on wild seed and wild small-sized fish as feed	• Farmers mainly better-off and large-scale as considerable capital was involved • A few small-scale fishers were involved who caught wild seed and wild fish as feed but constrained by inability to catch sufficient feed	• Integrated with inland capture fisheries but unsustainable use of small wild fish as feed, including fingerlings of large commercial species
Watershed/ zone	• Indigenous farmed species		• Cambodian Government banned snakehead farming in 2004 • Research planned to assess impacts of ban on livelihoods of farmers, fishers, poor people and aquatic biodiversity
Global			• Global level and regional concern on use of low value and trash fish in aquaculture

CASE STUDY 9 – MODERN EXTENSIVE TO SEMI-INTENSIVE AQUACULTURE IN LAGUNA DE BAY, PHILIPPINES

Laguna de Bay is the largest and most important lake in Philippines with a total water surface area of about 90 000 ha (Santos-Borja and Nepomuceno, 2006). Its watershed area excluding the lake itself is 2 300 km^2 and contains 66 local government units (LGUs) including 12 cities and a population of about 6 million. The lake is a multiple use resource providing water for transport, irrigation, power supply, cooling of industrial equipment and more recently a source for domestic water supply. However, its dominant use at present is for capture fisheries and pen and cage aquaculture.

The Laguna Lake Development Authority (LLDA) which manages the lake implemented some projects in the 1970s to the early 1990s to provide alternative livelihoods to fishers and other marginalized users of the lake's water resources. The Laguna de Bay Fishpen Development Project aimed to provide marginal fishers with an opportunity to farm fish in cages and pens through organizing them into cooperatives with provision of credit and supporting services (Santos-Borja and Nepomuceno, 2006). However, aquaculture in the lake was taken over by businessmen because the financial assistance to enable fishers to construct fish pens was implemented slowly and LLDA failed to establish policies to protect the scheme from such speculators. The area of the lake occupied by fish pens and cages reached 30 000-35 000 ha in the 1980s, at least one third of its surface area. The uncontrolled expansion of aquaculture severely affected the livelihoods of open water fishers who it was supposed to benefit.

The lake is eutrophic and natural food plays a significant role in fish nutrition; when aquaculture first began in the lake, culture was extensive as it was based solely on natural food in the lake and today about 50 percent of cage operators and 67percent of pen operators still do not use supplementary feed (Santiago *et al*., 2005). Fish are grown in pens in the shallow lake of average depth of 2.5 m or in suspended cages. Pens range in size from 0.1-50 ha with yields of 4-10 tonnes/ha; and cages from 50-9 000 m^2 but yields are fairly low in these high water volume cages from about 2.5-4.5 $kg/m^{3.}$ Nile tilapia and bighead carp are cultured in cages, and Nile tilapia and bighead carp as well as milkfish are cultured in pens, either in monoculture or polyculture in both systems. The estimated total aquaculture production for 2002 was 60 000 tonnes (Santiago *et al*. 2005).

The lake also serves as a receptacle for floodwaters, and a sink for agricultural, domestic and industrial effluents (Santiago *et al.,* 2005). The domestic wastes of a majority of the watershed's 6 million inhabitants ultimately enter the lake as there are few centralized sewerage systems. It is estimated that 79 percent of the total nitrogen input comes from domestic sources, 16.5 percent from agriculture, 4.5 percent from industry and 0.5 percent from other sources which include aquaculture. It is believed that the lake has not yet reached an extreme level of eutrophication which would adversely affect aquaculture but algal blooms do occur causing fish kills. About 40-50 percent of farmers reported fish kills which they attributed to industrial effluents and poor water quality.

Although management of the Laguna de Bay watershed is complex with conflict among stakeholders, the LLDA has initiated innovative actions following an integrated water resources management approach for the lake and its watershed (Carino, 2005). For example, an Environmental User Fee system motivates polluters to comply with effluent standards which is believed to have led to a decrease in industrial pollution from 35-40 to 20 percent of the total pollution load. There is also a Zoning and Management Plan (ZOMAP) for fish pens and cages with maximum allowable areas of 100 km^2 and 50 km^2, respectively. Limits were also set on the maximum areas to be occupied by corporations, coorperatives and individual owners for pens of 0.05, 0.01 and 0.005 km^2, respectively, and for cages 0.001 km^2. The area allocated is based on an analysis of the lake's carrying capacity for aquaculture, itself based on long-term primary productivity data from the lake. ZOMAP is considered to be the most feasible management system for equitable allocation of the lake's fishery resource.

Discussion of Case study 9

Laguna de Bay is managed by a special agent of the Philippine Government, the Laguna Lake Development Authority, created in 1966 because of perceived threats from the rapidly changing lake region to simultaneously develop the area and manage its environment (Santos-Borja and Nepomuceno, 2006; Carino, 2005). The LLDA became part of the Department of Environment and Natural Resources in 1993. As stated in the law, its mandate is "to promote and accelerate the development and balanced growth of the Laguna Lake area and its surrounding provinces, cities and towns… with due regard and adequate provisions for environmental management and control, preservation of the quality of human life and ecological systems, and the prevention of undue ecological disturbances, deterioration and pollution". However, the existence of many stakeholders (policy-makers and planners; regulators; local government units; research and development institutions; resource user communities such as industries, farmers, fishers and fish pen operators; and NGOs) and no coherent and integrated development or environmental governance system is a liability for the management of the Laguna de Bay Region.

TABLE A10
Relevant issues under each principle at different scales in case study 9

Principles	1	2	3
Scales	**Ecosystem functions and services**	**Improved human well-being and equity for all stakeholders**	**Context of other sectors, policies and goals**
Farm	• Eutrophic lake water provides a significant amount of feed for fish so aquaculture is environmentally friendly	• Pen cage culture dominated by large operators but poor employed in the industry • Small-scale farmers involved in cage culture	
Watershed/zone	• Indigenous milkfish is main species in pens but exotic tilapia in cages although no evidence of adverse environmental impact	• Aquaculture project targeted at marginal fishers but taken over by large businessmen	• Lake receives agricultural, domestic and industrial wastes which stimulate natural food production for fish but occasional algal blooms and fish kills occur • Integrated water resources management approach implemented for lake and watershed • Zoning and Management Plan for cages and pens
Global			• Laguna de Bay a member of the Global Living Lakes Network

CASE STUDY 10: MODERN COMMUNITY BASED FISH CULTURE IN SEASONALLY FLOODED FLOOD PLAINS IN BANGLADESH AND VIET NAM

Farmers in flooded-prone rice-based agro-ecosystems in Bangladesh and Viet Nam grow high yielding varieties of rice in shallow flooded fields during the dry season, followed by either deep water rice or a fallow period during the flood season and capture of wild fish from the flooded fields (Dey *et al.*, 2005; Dey and Prein, 2006). The introduction of irrigation-based 'green revolution' technology has increased the total rice production from about 2 to 6 tonnes/ha/year but the wild fish harvest has declined from about 200 to less than 100 kg/ha/year. Land ownership is based on dry season tenure. During the 4-6 months of flood when the fields are submerged they are community property with all members of the local community allowed to catch wild fish but the rice fields are privately owned and farmed during the dry season.

Groups each with about 20 households comprising landowners, fishers and landless labourers were organized to stock fish fingerlings in fenced areas during the flood season by a WorldFish organized project. Stocked fish were a polyculture of Chinese and Indian major carps which thrive with small indigenous fish species naturally present in the system. The system is largely extensive as the fish benefit from residual nutrients from the proceeding rice crop as well as nutrients brought by the floodwaters. Rice bran may occasionally be fed to the fish for a few weeks after the waters have receded and fish are confined to a smaller area in the enclosed floodplain.

Fish production was increased by about 600 kg/ha in shallow flooded areas and up to 1,500 kg/ha in deep-flooded areas without a reduction in either rice yield or in wild fish catch, with additional income of US$ 135-437/ha. Fish production from fenced and stocked floodplain areas can be increased 2-10 fold over the wild fish catch. The returns from the sale of fish were shared among group members and were especially significant for the landless. Neighbouring communities to trial sites over the 3-year period (1998-2000) of the project widely adopted the technology.

The sites need to be topographically suitable area with as much of the area as possible with partially enclosing existing embankments such as roads to reduce the high cost of fencing open areas. The main technical limitation is the vulnerability of the system during heavy floods which can destroy fences leading to large loss of stocked fish.

Discussion of Case study 10

There is considerable potential for widespread dissemination of community-based fish culture in seasonally flooded floodplains which is essentially an extensive system with fish growth based on naturally occurring food in the flooded rice fields.The technical options tested during the trials in Bangladesh and Viet Nam, and other possible options need to be tested and assessed under varying institutional arrangements in various floodplains in Africa as well as Asia (Dey *et al*., 2005; Dey and Prein, 2006).

In Bangladesh there are 3 million ha of medium and deep flooded areas with about half estimated to be suitable for community-based fish culture. In the Mekong river basin there are 0.8 million ha of medium and deep flooded areas in the Indo-Gangetic basin, 1.2 million ha in Myanmar, 0.7 million ha in Thailand and 0.1 million ha in the Red River delta in Viet Nam. There are almost 0.5 ha of floodplains in West Africa used to grow deep water rice which could possibly be used to stock fish.

TABLE A11
Relevant issues under each principle at different scales in case study 10

Principles	1	2	3
Scales	**Ecosystem functions and services**	**Improved human well-being and equity for all stakeholders**	**Context of other sectors, policies and goals**
Farm	• Community-based floodplain aquaculture		
Watershed/zone	• Mostly extensive fish culture in flooded rice fields in the rainy season so environmentally friendly as fish benefit from residual nutrients from previous rice crop and nutrients brought by floodwaters • Stocked indigenous Indian major carps and exotic Chinese carps although no evidence for adverse environmental impact	• Increased yields of fish above the wild fish catch benefit all members of local community	• Research in partnership with local community
Global		• Considerable un-developed potential in various floodplains in Africa and Asia	• Participatory research initiated and supervised by WorldFish Center

CASE STUDY 11 – MODERN EXTENSIVE TO SEMI-INTENSIVE CULTURE-BASED FISHERIES IN FARMER-MANAGED SMALL RESERVOIRS IN VIET NAM

Most reservoirs in northern Viet Nam were constructed after 1960, primarily for hydroelectric power generation and irrigation but government policy in recent years has encouraged farmers to use them for fish production. Small reservoirs are leased to farmers or farmer groups for aquaculture but fish yields are below optimum due to lack of scientifically determined stocking and harvesting strategies with current fishery management is based on trial and error (Nguyen, Bui and Nguyen 2001; De Silva *et al*., 2006).

Recent surveys of 20 small reservoirs in northern Viet Nam revealed stocking densities of 27-145 kg/ha for small farmer-managed reservoirs of 5-30 ha. Fish species stocked were Chinese carps (bighead, grass and silver carp), Indian major carps (mrigal and rohu), common carp, silver barb and Nile tilapia. Fish are normally harvested from March-May when the water level is the lowest due to irrigating rice, once each year, with average fish yields ranging from 115-429 kg/ha. Stocked fish contributed more than 80 percent of the total harvest. Research also revealed that the water was poor in nutrients with fish yield closely correlated to conductivity and chlorophyll a concentration. The current yield in small reservoirs in Viet Nam averaging 100-500 kg/ha/year is one of the lowest in Asia, indicating that their fishery potential is not fully realized.

Although yields and proceeds from sale of fish are low, the supplementary income is significant in mountainous North Viet Nam , one of the poorest regions of the country. As most small irrigation reservoirs are located mostly in remote areas, culture-based fisheries have the potential to produce a significant amount of cheap animal protein and generate income in poor rural areas in the country.

Participatory research with farmers has determined the most desirable species combination for culture-based fisheries in northern Viet Nam (bighead carp, common carp, grass carp, mrigal and silver carp) and this is being disseminated. As the natural productivity of most farmer-managed reservoirs is relatively low, it may be possible to fertilize them with organic manure, taking into consideration possible alternative uses for manure and possible conflicts of interest among various water users. The development of a best-practice model is expected to significantly increase the net gains from culture-based fisheries (Nguyen, 2006a). The Government of Viet Nam considers reservoir fishery research and development to be a priority, as well as training farmers in appropriate practices.

Discussion of Case study 11

There are about 67 million ha of small waterbodies that have been constructed primarily for irrigation in Asia (De Silva, Amarasinghe and Nguyen, 2006). Some attempts at introducing culture-based fisheries in the past have failed, a major cause being lack of effective community consultations and lack of consultation or cooperation from multiple users of the waterbodies which have often led to conflicts (De Silva, Amarasinghe and Nguyen, 2006). However, some nations have introduced culture-based fisheries development as government policy with the realization that fish production can be integrated as a secondary use with limited demand on existing waterbodies (De Silva , Amarasinghe and Nguyen, 2006) .

Culture-based fisheries are essentially a type of extensive aquaculture carried out in small waterbodies usually less than 100 ha (De Silva, Amarasinghe and Nguyen, 2006). Perennial or seasonal waterbodies are stocked with suitable species to consume natural food in the waterbody. A selected community group has ownership of the stock. Although culture-based fisheries are usually extensive with no intentional nutritional inputs for aquaculture, farmers may use supplementary feeds such as cassava flour and rice which can be purchased cheaply locally. Culture-based fisheries have several advantages over other forms of aquaculture : they utilize existing water resources as a secondary user; they are less resource intensive and utilize natural water productivity; and are relatively easy to extend to farming communities as they are technically less complicated than conventional aquaculture (De Silva, Amarasinghe and Nguyen, 2006).

TABLE A12
Relevant issues under each principle at different scales in case study 11

Principles	**1**	**2**	**3**
Scales	**Ecosystem functions and services**	**Improved human well-being and equity for all stakeholders**	**Context of other sectors, policies and goals**
Farm	• Community-based reservoir aquaculture	• Although yields and proceeds from sale of fish are low, the supplementary income is significant in poor rural areas.	
Watershed/zone	• Mostly extensive fish culture in small reservoirs based on natural food in the waterbody so environmentally friendly • Stocked mainly exotic Chinese carps, Indian major carps, silver barb and tilapia but also indigenous common carp. No evidence of adverse environmental impact by exotic species	• Stocked fish contributed more than 80% of total fish harvest, significantly increasing benefits to local communities	• Research in partnership with local community
Global		• Considerable un-developed potential in Viet Nam and other countries for culture-based reservoir fisheries	• Participatory research initiated and supervised by Australian national university and donor

CASE STUDY 12: INLAND SHRIMP FARMING IN CENTRAL THAILAND

Marine shrimp are traditionally produced in coastal ponds but the shrimp boom of the 1990s resulted in rapid degradation of the coastal environment and widespread disease outbreaks, causing repeated crop failures. Meanwhile, farmers found that shrimp could be cultured in low salinity (<5 ppt) water. Starting in areas subjected to saltwater intrusion, low-salinity shrimp farming quickly spread to more than 10 inland provinces normally uninfluenced by seawater so that thousands of hectares of rice fields in the rice bowl of Central Thailand distant from the sea coast were converted to low-salinity shrimp farms (Lin, 2006). As the economic gain from shrimp production was more than 50-fold that of the rice crop, shrimp culture was regarded as a bonanza for debt-ridden rice farmers (according to Flaherty *et al.,* 1999, the estimated gross income from inland shrimp culture was a more modest but still large, 15 times that of rice).

Large quantities of high-salinity seawater or brine (100-200 ppt) were transported from coastal salt pans by truck from salt pens during the salt making season and the brine was discharged into ponds to make the initial pond salinity about 10 ppt by mixing with freshwater. The water depth was initially less than 0.5 m to acclimate and nurse post larvae, and was increased gradually to reduce the salinity to 4-5 ppt over a period of several weeks by filling with freshwater and the salinity of pond water was reduced to a nearly undetectable level at the end of the grow-out period. To reduce saltwater contamination of the adjacent land farms through seepage, inland shrimp ponds were constructed differently from coastal and regular fish ponds as they had wider dikes (>3 m) with good compaction, an enclosed drainage canal around the ponds with sufficient storage capacity for waste water, and were designed to recycle pond water. Shrimp were stocked at high density (50-100 PLs/m^2) and were cultured intensively with pelleted feed in a so- called 'closed system' without water exchange, with freshwater used to top up water loss from evaporation and seepage. The shrimp production commonly exceeded 10 tonnes/hectare/3-4 month crop. During the peak period, the shrimp production from inland areas accounted for nearly 40 percent of total annual production of 200 000 tonnes in Thailand .

However, inland shrimp farming was short-lived as the rapid increase in shrimp production in inland areas caused strong protests from non governmental agencies about environmental concerns and the Royal Thai Government eventually issued a decree banning the inland shrimp farming in inland provinces in 1998 on the grounds that it led to salination of soil and ground water and may ultimately have jeopardized the national rice bowl.

Low-salinity shrimp farming is still allowed by the Government in areas in coastal provinces where intrusion of natural seawater occurs. With persistent disease problems encountered in culturing the native tiger shrimp, *Penaeus monodon*, the exotic white shrimp (*Litopenaeus vannamei*) has become the major species and adapts to low salinity even better than tiger shrimp. The adverse environmental impact of salinization has not been systematically investigated and remains unknown but a large proportion of the salt was probably retained in clayey soil with a relatively small amount entering ground water (Lin, 2006). Although the Department of Fisheries prohibited draining saltwater into public freshwater systems or farms, a survey showed that less than half of inland shrimp farms treated their effluent and most discharged directly into irrigation canals. Furthermore, shrimp farms described as "closed systems" could not treat the large volumes of effluent at harvest. Pond sludge was also dumped on site which could then be eroded by rain into the canals (Flaherty *et al*., 1999). Large amounts of removed sediments blocked small irrigation canals, denying farmers downstream access to water. Shrimp farming also required almost an order of magnitude more water per hectare than rice which would likely have increased tensions between rice and shrimp farmers over access to water had it been allowed to continue.

The Chao Phraya River plain is the largest and most productive rice growing area in Thailand and the rapid development of marine shrimp farming in converted rice fields caused major concerns about possible adverse environmental impacts of the practice before the practice was banned by the Thai Government.

TABLE A13
Relevant issues under each principle at different scales in case study 12

Principles	**1**	**2**	**3**
Scales	**Ecosystem functions and services**	**Improved human well-being and equity for all stakeholders**	**Context of other sectors, policies and goals**
Farm	• Intensive marine shrimp culture in ponds constructed in inland rice fields	• Farmer income estimated at 15-50 times that of a rice crop so significant short-term benefits to converting farmers but neighbouring farms continuing to grow rice concerned about possible adverse long-term impact of salt build-up	
Watershed/zone	• Concern over adverse environmental impact of brine on neighbouring rice farms • Sediments discharged from shrimp ponds blocked small irrigation canals restricting rice farmer access to water. • Exotic white shrimp (*Litopenaeus vannamei*) became the major species and adapts to low salinity even better than tiger shrimp		• Thai Government banned shrimp farming in inland provinces in 1998 due to concerns over possible salinization of soil and groundwater
Global			• Fishmeal and soybean mainly imported for inclusion in pelleted feed and used also in livestock feed

CASE STUDY 13: INTENSIVE STATIC WATER POND CULTURE OF CHANNEL CATFISH, THE UNITED STATES OF AMERICA

Channel catfish (*Ictalurus punctatus*) is the most important aquaculture industry in the United States of America (Hargreaves and Tucker, 2003). Current optimal practice is in relatively large ponds of 4-5 ha with high stocking densities and feeding rates, limited aeration from floating paddle wheel aerators, and multiple fish stocking and harvesting. Fish feeding rates of commercial pelleted feed are up to 100-185 kg feed/ha/day although short-term rates can exceed 175 kg/ha/day. Faster growing fish are selectively removed from the pond with large-mesh sein nets and are replaced by fingerlings. Multiple-batch cropping was introduced to provide fish year round for market but a significant benefit from an environmental point of view is the ponds need not be drained for many years. This dramatically reduces the pond effluent volume as well as the need for pumped water to refill ponds as in a single-batch cropping system.

The success of channel catfish farming is due in part to lower production from the ability of the static water ponds to treat wastes through microbial degradation of organic matter with low accumulation of sediment organic matter. It is believed that the limit to intensification of channel catfish production has reached a ceiling at 5.6-6.7 tonnes/ha/year with the current technology in static water ponds and with the tolerance limit of the species to lowered water quality

Discussion of Case study 13

Catfish ponds function in a similar way to aerobic waste stabilization lagoons or sewage maturation ponds which are especially built for the purpose of organic waste, either human sewage, livestock or agro-industrial effluent treatment, with photosynthesis providing most of the oxygen used for bacterial degradation of organic matter as a "free" ecological service (Hargreaves and Tucker, 2003). As most of the wastes are treated during the fish culture cycle and there is only an effluent when ponds are drained which is infrequent, there is minimal adverse environmental impact.

The channel catfish case study shows that intensive, pellet-fed aquaculture can be environmentally sustainable providing that the intensity of culture is within the pond treatment capacity for the wastes. There appeared also to be minimal adverse environmental impact in pellet-fed small-scale pond culture of tilapia in Central Luzon in the Philippines (ADB, 2005). Most farmers drained their ponds after each 3 month culture cycle but their farms were usually only one component on a multi-component farm with the effluent serving as a nutrient-rich source of water for irrigating rice and vegetables. However, discharge of pond water during draining from groups of medium to large fish ponds could cause eutrophication of receiving waters. Better management practices have been developed for channel catfish culture (Tucker, Hargreaves and Boyd, 2008) and are generally relevant for freshwater pond culture elsewhere.

TABLE A14
Relevant issues under each principle at different scales in case study 13

Principles	**1**	**2**	**3**
Scales	**Ecosystem functions and services**	**Improved human well-being and equity for all stakeholders**	**Context of other sectors, policies and goals**
Farm	• Minimal adverse environmental impact as static water ponds treat most fish farming wastes and ponds need not be drained frequently	• Largest aquaculture production system in United States of America benefiting numerous farming households and employees	• Good management practices for discharge of pond water
Watershed/zone	• Indigenous species farmed	• Major source of freshwater fish for consumers • Major source of employment for input suppliers and marketing functionaries	
Global	• Better management practices for discharge of pond water have been developed for channel catfish culture and are generally relevant for freshwater pond culture		

CASE STUDY 14 – INTENSIVE POND CULTURE OF RIVER CATFISH IN THE MEKONG DELTA, VIET NAM

Viet Nam expects to produce almost 1 million tonnes of river catfish (mainly *Pangasius hypophthalmus;* and some *P.bocourti*) in 2007, a goal the government had set for 2010, increasing from just 10,000 tonnes in 1995. The explosive development of the industry has taken place without any government guidelines, recommendations or regulations (Nguyen, 2006b,c). The growth of culture is driven to a large extent by the dramatic increase in demand for processed fish, mainly white fillets marketed in more than 80 countries. The United States of America used to be the major market but its share of exported fish has declined from 80 to 100 percent, with European Union countries now dominating the export market with almost a 50 percent market share. Increased output has also been possible because of the recent development and ready availability of relatively cheap hatchery raised seed and agro-industrial pelleted feed.

River catfish have been cultured intensively in cages in the Mekong Delta, Viet Nam for at least 30 years but the rapid recent increase in production is mostly from pond and to a lesser extent from pen culture (Nguyen, 2006b,c; Le and Merican, 2006; Le, 2007). Farmers are changing from cage to pond culture because the latter is more economic with current high price of wood and the farmers increased ability to control water quality in ponds compared to cages installed in the river (Le, 2007). River water is becoming increasingly polluted from factories and fish processing plants discharging effluents into the river as well as agricultural and urban run-off. (MOFI/WB.2006). The airbreathing species is stocked at high densities of 10-20 individual 10-15 cm fingerlings/m^2 in 1.5-6.0 m deep earthen ponds converted from rice fields. Fish are fed either a farm cooked diet of marine trash fish, rice bran and broken rice but increasingly formulated pelleted feed. Pond water is exchanged daily in the second half of the culture cycle at 20-30 percent of pond water volume with the Mekong River. Yields after 8-12 months of culture are 50-300 tonnes of 0.8-1.5 kg fish.

Ninety eight percent of the farmers are independent, not belonging to state enterprises, and most have no academic background in aquaculture and so learn through experience. As a result most farms are poorly managed and lack basic planning and management of their farming operation. Pond construction through flushing excavated earth into the river as well pond flushing during culture operations have caused siltation of small canals in the Delta (P.T. Nguyen, personal communication, 2008). Two thirds of the total river catfish production in 2005 was from commercial pelleted feed which are less polluting than home-made feeds which are not stable in water and have a higher FCR (MOFI/WB, 2006). However, there is no pond effluent treatment so all wastes are flushed into the river. The long term effects of river catfish farming are unknown but it could increase the productivity of inshore fisheries of the South China Sea.

Discussion of Case study 14

As farming river catfish is one of the fastest growing aquaculture systems in the world with explosive development without government control, it is imperative that its adverse impacts on the environment and society are minimized in satisfying the growing market demand for the produce.

Moderate nutrient enrichment of some ecosystems may sometimes lead to increased production of commercial fisheries (ESA, 2000). Nutrient enrichment to concentrations slightly above natural levels may have a positive effect on lakes and rivers through increased fish production but hypereutrophication leads to fish kills at all scales from rivers and lakes to watersheds such as the Chesapeake Bay and Mississippi river watersheds and the Gulf of Mexico in the United States of America and the Baltic, Black and North seas in Europe (Novotny, 2007).

Stakeholders in river catfish, producers as well as buyers and other stakeholders met in Viet Nam in September 2007 to start the process of developing standards for certifying river catfish products, the dialogue coordinated by World Wildlife Fund (WWF). The main purpose of the meeting was to identify and agree on the main environmental impacts related to the farming of the two key market species of river catfish, tra (*Pangasius hypophthalmus*) and basa (*P. bocourti*). The process called the Pangasius Aquaculture Dialogue will continue though 2008 with participants meeting to develop credible, measurable and voluntary standards designed to minimize the key impacts identified in the initial workshop. Finalized standards will be handed to a new or existing certification body to manage the system (F. Corsin, personal communication, 2008).

TABLE A15
Relevant issues under each principle at different scales in case study 14

Principles	**1**	**2**	**3**
Scales	**Ecosystem functions and services**	**Improved human well-being and equity for all stakeholders**	**Context of other sectors, policies and goals**
Farm	• Ponds constructed in rice fields so no natural harvest modification	• Major benefits to farmers and farm workers as total production approaching 1 million metric tonnes	• Poor educational level of farmers led to poor farm planning and management
Watershed/zone	• About 1/3 of total production fed marine trash fish • Effluent and pond sediments flushed into rivers as there is no effluent treatment • Indigenous species farmed	• Major benefits to suppliers of inputs (fingerlings and increasingly pelleted feed) market intermediaries and processors	• Catfish production is threatened by increasing river pollution
Global		• Provides a relatively low-cut, high-quality fish fillet for international export markets	• Fishmeal and soybean meal ingredients in pelleted feed are mainly imported and compete for inclusion in livestock rations • Stakeholders dialog in river catfish are developing standards for certifying river catfish products.

CASE STUDY 15– INTENSIVE CAGE CULTURE IN LAKE TAAL, PHILIPPINES

Cage culture of Nile tilapia (*Oreochromis niloticus*) began in Lake Taal in the Philippines in the 1970s following the rapid development of cage and pen culture in nearby Laguna de Bay (ADB, 2004). In contrast to the shallow and eutrophic Laguna de Bay with dense plankton and detritus which provide considerable natural food for fish, Lake Taal has an average depth of 60m so cage culture is intensive and depends on pelleted feed.

Most cages consist of bundles of bamboo for a frame and flotation with a synthetic net enclosure. The most common cage dimensions are 10x10 m with a depth of 6-7 m. Tilapia is grown throughout the year in two 5-6 month cycles with an average production of 3 tonnes/cage/cycle. The daily addition of large quantities of pelleted feed to the cages places large nutrient and organic matter loadings on the lake. Fish kills are frequent, especially during overturns when deep turbid water with low dissolved oxygen rises to the surface layers where cages are located. Although Lake Taal has an area of 26 000 ha, favourable cage sites with shelter from storms and high water exchange, road and boat access and security are limited so cages are crowded, which reduces water quality.

Average annual cage production of tilapia in Lake Taal was almost 20 000 tonnes from 1995-2002 according to official statistics (ADB, 2004). However, a more accurate estimation based on aerial photography and interviews undertaken in 2006 gives a total annual production of over 100 000 tonnes, at least five times more (Palerud *et al.*, 2007). In March 2000, there were 8 626 fish cages in operation in Lake Taal. This greatly increases the benefits of aquaculture from Lake Taal but also concerns about adverse environmental impact and sustainability of the practice. Calculation of carrying capacity of Lake Taal for fish culture alone indicates that at most 30 000 tonnes of fish can be supported based on negligible inputs from other sources. Since there are other sources of nutrients from the approximately 69 000 ha watershed which includes Tagaytdy City as well as surrounding communities involved in various activities including agriculture and poultry farming, the present maximum fish stock has probably overcome the carrying capacity. Fish caretakers appeared to overfeed fish by at least 30 percent.

The very success of cage farming in Lake Taal threatens its future with current production estimated to exceed the lake's carrying capacity by a factor of 2.8 (Palerud *et al.*, 2007).

Cage farming contributes to reducing poverty through direct employment of farmers/caretakers in cage aquaculture although it is mainly sustained by external financiers as high operating costs and risks of farming deter local people from using their own limited financial assets. It also provides employment in fish hatcheries and lakeside nurseries, in feed supply, and in fish harvesting and marketing.

Although there are laws and regulations to manage aquaculture in and around Lake Taal, the legislation is complex and confusing. Implementation is also hindered by vested interests and is widely ignored. A fish sanctuary established for conservation purposes is heavily occupied by fish cages which is a source of frustration for the lakes fishers. The expansion of cage farming has been largely unconstrained by attempts to limit entry and to manage aquaculture in relation to other uses of the lake, especially fishing and tourism.

Discussion of Case study 15

A major adverse environmental effect of intensive culture of fish in cages is organic enrichment of the sediments beneath the cages due to uneaten feed and fish faeces. Bacterial decomposition of sedimented organic matter may lead to anaerobic conditions in the sediments and overlying water, and to the formation gases of hydrogen sulphide and methane, both of which reduce fish growth and lead to increased disease. Under extreme conditions, anoxic water and toxic gases may cause fish mortality. Build up of nutrients may cause eutrophication and phytoplankton blooms in the water column which may adversely affect fish performance (Palerud *et al*., 2007). Where water currents are significant, organic matter and nutrients will be spread over a large area, possibly with minimal adverse environmental impact and stimulation of aquatic productivity but Lake Taal has limited exchange of water with the surrounding environment and a residence time of 20 years. While this reduces the adverse environmental impact of aquaculture externally, it leads to a build-up of nutrients and organic matter from aquaculture in the lake. The present aquaculture production of Lake Taal is 2.8 times greater than the calculated carrying capacity (Palerud *et al*., 2007). If steps are not taken to either limit the production or reduce the food conversion ratio, the lake has an increased risk of more frequent and larger fish kills.

The aim of the project "Environmental Monitoring and Modelling of Aquaculture in the Philippines " was to develop suitable aquaculture monitoring techniques and adapt predictive models to assist in identifying planned development of sustainable aquaculture. Lake Taal was the inland site chosen for the study as well as a marine site at Bolinas and a brackishwater side at Dagupan. Carrying capacity for fish culture was defined as the maximum number of fish of a given species that may be safely grown in a particular waterbody. As the concentration of phytoplankton is a key parameter which determines the carrying capacity of aquaculture in a given area, the highest phytoplankton concentration that guaranteed that the oxygen concentration would not drop below a healthy level for fish was determined. In computing the carrying capacity, the concentration and locations of other nutrient sources entering the waterbody were considered as well as those introduced to feed the stocked fish biomass.

TABLE A16
Relevant issues under each principle at different scales in case study 15

Principles	1	2	3
Scales	**Ecosystem functions and services**	**Improved human well-being and equity for all stakeholders**	**Context of other sectors, policies and goals**
Farm	• Caged fish kills are common due to adverse impact of fish culture wastes on lake water quality	• Major benefits to cage financiers and operators as total production over 100 000 tonnes	
Watershed/zone	• Estimated that cage aquaculture exceeds lake carrying capacity by factor of 2.8 • No convincing evidence that exotic Nile tilapia has had an adverse impact on the lake biodiversity	• Major benefits to suppliers of inputs (fingerlings and pelleted feed) and market intermediaries • Provides a relatively low-cost, high-quality fish for urban consumers in Manila • Reduces local poverty through direct and indirect employment in cage aquaculture	• Legislation exists to manage aquaculture in Lake Taal but it is complex and confusing and largely ignored • Lake fishers are frustrated by presence of cages in a fish sanctuary
Global			• Sustainable aquaculture monitoring techniques and predictive models to assist in identifying planned development of sustainable aquaculture were developed for the Philippines and are applicable in other similar environments.

CASE STUDY 16 – INTENSIVE CAGE CULTURE OF RED TILAPIA IN THE CHAO PHRAYA RIVER, CENTRAL THAILAND

The private company Charoen Pokphand (CP) has created a strain of red tilapia (*Oreochromis* sp.) and promoted it as a new premium fish product locally known as "pla taptim" or ruby fish (Belton, Little and Young, 2006). CP initiated contract farming in freshwater aquaculture in Thailand in which the company supplies fry and feed to franchised aquatic feed dealerships which nurse fry to a size of 25-50 g for stocking in cages, sell feed and harvest and market fish when they reach at least 600 g. The production of red tilapia in cages has been estimated at 30 000 tonnes/year, about 10 percent or more of total Thai tilapia production.

Cages are typically constructed of steel frames with polypropylene mesh nets with metal drums or plastic containers as floats. Farmers own between 4-25 cages each with an average volume of 62.5 m^3. All male fish are stocked at 1 500-2 500/cage and the harvest is about 1 tonne/cage after an average growout period of 4 months. Cages are floated in public waterbodies, usually rivers and canals.

Expansion of cage culture has been rapid and the vast majority of cage-farmed red tilapia is marketed live. The consumer perception of the fish as a high quality product is helped by a lower prevalence of off-flavour than fish raised in green water ponds.

Industrial pollution in rivers and canals can be severe in the dry season when water flows are low. Pollution appears to be increasing in severity and may ultimately threaten the sustainability of cage culture in some localities. Recently there was a mass fish kill of red tilapia in cages along a 20 km stretch of the Chao Phraya river due to a sudden decrease in dissolved oxygen (Pongpao and Wipatayotin, 2007). About 8 000 tonnes of fish worth more than US$ 1 million died suddenly due to the oxygen demand from either molasses on a barge which sank in the river or untreated effluents from a monosodium glutamate factory located on the side of the river which may have been discharging untreated effluents in to the river.

Discussion of Case study 16

Cages are open aquaecosystems with more or less continuous exchange of water with the surrounding environment which exposes them to changes in the water quality of the waterbody in which they are immersed. Aquaculture in waterbodies in particular needs to be protected from pollution from other human activities if it is to be sustainable as demonstrated by the mass fish kill of tilapia in the Chao Phraya river. One of the reasons that farmers in the Mekong delta in southern Viet Nam are moving from cage to pond culture of river catfish is the water quality of pond water can be more readily controlled than that of cages floating in the increasingly polluted river.

Pollution of water used by aquaculture is a severe problem in proximity to density populated rural and urban environments from industrial and urban sewage effluents. In addition, non-point source pollution, especially from agricultural run-off can negatively affect aquaculture (FAO/NACA, 1995). There are major problems with the adverse impact of polluted surface waters on aquaculture in China which provides a good example of the issues involved. China declared environmental protection a basic national principle in 1983, developed subsequently plans on environmental protection and has participated in international treaties such as the Convention on Biological Diversity and the UN Millennium Development Goals which include poverty alleviation, environmental protection and sustainable development (Liu and Diamond, 2005). More than 100 environmental policies, laws and regulations have been passed but economic development takes priority at local level. Water quality in most rivers and groundwater sources in China is poor and declining (Liu and Diamond, 2005). Only 20 percent of domestic wastewater is treated compared with 80 percent in the developed world; industrial wastewater discharges and agricultural run-off and aquaculture effluents also adversely affect water quality. With rising affluence leading to increased meat and fish consumption, pollution from animal husbandry and aquaculture is also expected to increase. China needs an "environmental miracle" over the next two decades to complement the "economic miracle" of the last two decades to achieve both socioeconomic and environmental sustainability as well as to set a good example for other nations (Liu and Diamond, 2005).

The relative contribution of various human activity systems such as the various types of farming (agriculture, animal, husbandry, aquaculture), industry and urbanization to environmental degradation remain to be quantified although aquaculture is likely to be the lowest contributor except in "hot spots" where aquaculture farms are clustered in high density such as Lake Taal (case study 15) and the Mekong river, Viet Nam (case study 14). A material flow analysis model (MFA) has been developed for the Tha Chin river basin, Thailand to assess the entire path of pollution generation from its origin through different transformations and diversions to its final discharge into the river (Schaffner *et al*., 2006). The relative contribution of aquaculture to the other major sources of nutrients to the river basin (rice, fruit and vegetable farms; feedlot pig and poultry farms; factories; urban areas) remains to be assessed although nutrient and water flows from different types of aquaculture farms have been modelled (Wittmer, 2005).

The major changes in the agricultural sector in the last 50 years have been a major shift from family farming which causes less diffuse pollution to large-scale commercial and mostly monoculture agri-businesses (Novotny, 2007). A similar change is occurring in aquaculture. These changes have led to excessive diffuse pollution and unsustainable adverse impacts on the environment.

TABLE A17
Relevant issues under each principle at different scales in case study 16

Principles	**1**	**2**	**3**
Scales	**Ecosystem functions and services**	**Improved human well- being and equity for all stakeholders**	**Context of other sectors, policies and goals**
Farm	• Fish culture wastes appear to have little to no impact on cage water quality due to river flushing (except in "hot-spots" where aquaculture farms are clustered in high density).	Major benefits to cage farmers	
Watershed/zone	• Fish culture wastes appear to have little to us impact on river water quality • No evidence that exotic Nile tilapia has had an adverse impact on the river biodiversity	• Major benefits to suppliers of inputs (fingerlings and pelleted feed) and market intermediaries • Provides a relatively low-cost, high-quality fish for urban consumers	• River pollution appear to be increasing and occasionally leads to mass fish kills
Global	• Trends in the aquaculture sector in China towards large-scale commercial and mostly monoculture business are also occurring in many other countries world-wide. These trends have lead to excessive diffuse pollution and unsustainable adverse impacts on the environment.		• China and many other countries are participating in international treaties such as the Convention on Biological Diversity and the UN Millennium Development Goals which include poverty alleviation, environmental protection and sustainable development.

CASE STUDY 17: RACEWAY CULTURE OF TROUT

Trout have been cultivated in raceways (long channels or ponds of relatively rapidly moving water) in N Europe and N America for more than a century. The process requires the use of high volumes of high quality water, typically derived from rivers, often in upland or mountain areas. Water quality is reduced slightly as it passes through the system– mainly in terms of reduced oxygen concentration and raised carbon dioxide, but also in terms of slight increases in nitrogen (mainly ammonia-nitrogen) and phosphorus. The concentration depends on the stocking rate and feeding rate per unit volume of water flowing through the system.

Raceway systems were originally designed to maximise aeration (increase oxygen; decrease CO_2) through tumbling or splashing of water into raceways, and to minimise any settling of solids in the system in order to maintain high internal water quality. In these systems the "solution to pollution was dilution" and no waste-water treatment is used or considered necessary. Many such farms still exist – mainly in N Europe and N America.

The quality of the effluent in these systems is determined by the water quality requirements of the trout, which are high. DO should be at least 7mg/l; levels of 4mg/l will cause significant stress. In most cases total ammonia nitrogen (the main nitrogenous waste product from fish) should be less than 1mg/l (unionised ammonia should be less than 0.01mg/l). These levels are likely to be well within drinking water and other water quality standards. Nonetheless, the total annual loading of nitrogen on the surrounding waterbody may be significant. It has been estimated that roughly 0.03kg of dissolved ammonia nitrogen is generated per kg of (38 percent protein) fish feed (Losordo, Masser and Rakocy, 2001). A small farm producing 200 tonnes of fish per year, achieving food conversion rate of 1.4:1 would therefore discharge roughly 8.4 tonnes of ammonia nitrogen to the wider environment. In addition, significant quantities of ammonia nitrogen and phosphorus may be associated with suspended solids. Depending on local hydrodynamics this is likely to be assimilated with no significant impact. Only where other activities (e.g. farming) were generating high loads would this be a significant issue.

However – as with all activities, there has been an inherent tendency to increase production. Since abstraction of a high proportion of a water source (e.g. river) is generally resisted by the authorities, farmers have often found ways to increase stock without increasing abstraction. More efficient aeration of the water, and in some cases direct injection of oxygen allows for substantially reduced water flow, or increased production within a given flow. The converse of this is that nutrient concentrations in the water increase, and this may lead to greater impact. Furthermore, as the stocking density increases, so there is a greater tendency for solid wastes to accumulate in the system. When these are flushed out, they can have pulse effect on receiving waters – suspended solids causing significant falls in DO, especially where they accumulate, and nitrogen contributing to eutrophication. In Denmark, environmental regulation has now become so strict, that farmers have been unable to expand production using conventional through flow systems of this kind, and this has stimulated interest in waste-water treatment.

Simple settling of effluents is highly effective and typically takes out 50 percent suspended solids and associated nitrogen and phosphorus. This is well and good, except that the solution to pollution which was dilution in the original systems is now compromised; indeed we have *concentrated* the waste. This then requires removal and use. The sludge can be, and indeed is used as a field fertilizer in Denmark, and there is no reason why this practice should not be more widespread. In a sense this is just another form of dilution, although a significant proportion may be removed as agricultural produce, and in so far as it substitutes for the addition of fertiliser, may amount to no net increase in nutrient loading on the environment.

However, in Denmark in particular the environmental regulations are such that expansion of production is not possible without more comprehensive recycling and waste treatment (Jokumsen, 2004, case study 18)

Trout farming is not a major employer, but contributes to rural social and economic diversity in N. Europe. The United Kingdom of Great Britain and Northern Ireland and Denmark each have around 350 trout farms – the latter producing 30-40 000 tonnes and generating around 700 jobs, the former rather fewer of each.

TABLE A18
Relevant issues under each principle at different scales in case study 17

Principles	**1**	**2**	**3**
Scales	**Ecosystem functions and services**	**Improved human well- being and equity for all stakeholders**	**Context of other sectors, policies and goals**
Farm	• Local impacts related to nutrients usually insignificant, though context dependent • Open system means any chemical use potentially damaging • Open system means vulnerable to pollution from other sources	• Trout farming often a small family business	• Settled wastes may be used on fields to increase fertility
Watershed/zone	• Minor effect	• Contributes to rural social and economic diversity	• In Europe Water Framework Directive ensures this is implemented • Settled wastes may be moved to areas short of nutrients
Global	• Import of nutrients from marine systems for feed. • Potential impact on wild capture fisheries where these are not managed sustainably	• Support employment in industrial fisheries; • High quality and healthy food production	

CASE STUDY 18 – RECIRCULATING SYSTEMS

Experimental recirculation systems have been around in aquaculture for decades. The '70s saw a proliferation of experimental and pilot systems throughout the globe – involving salmonids, common carp, Tilapia and eels. Some of these, especially in N America, were also associated with hydroponic systems as the final stage in water treatment prior to recycling (Naegel, 1977; Lewis *et al*., 1978). Many such systems were similar to the contemporary trials with "integrated multitrophic aquaculture". What is striking about these trials is how few have survived in commercial form for growout production. Eel farming in Denmark , and one major producer of live Tilapia in the United States of America (Blue Ridge farm, Martinsville the United States of America) are exceptions – both targeting high value niche markets. Recirculation systems are however relatively common for hatcheries.

Recirculation systems have some significant advantages, and in particular capacity to maintain stable temperatures close to the optimum for growth, year round or better planned production, high bio-security, and minimal impact on the environment. On the downside are the need for highly skilled personnel, the risks of system failure, and the high capital costs. The increasing rigour of environmental regulation has stimulated increased interest in recent years, as have the opportunities for "chemical free" or organic production.

Needless to say, the main impediment to the introduction of recirculation systems is cost. Capital costs per tonne of annual production are likely to be substantially more (US$2 250-8 800/tonne annual production) than for pond or through flow systems (US$2 000/tonne) (Losordo, Masser and Rakocy, 2001). The great variation for recirculation systems reflects the fact that cheap systems can be designed, but if risks of failure are to be avoided, costs must be substantially increased to allow for high quality system management and monitoring, and comprehensive system backup. Either way recirculation is higher risk – risk of system collapse or risk of high investment in an increasingly competitive market. This is why the only real success has been achieved by companies producing a high value, preferably live product for a niche market where competition is limited.

However, environmental regulation may stimulate mainstream producers to examine recirculation options more carefully, as has happened in Denmark (Jokumsen, 2004). With water recirculation, the same abstraction rate can be used to support ten times or more production (Summerfelt and Vinci 2004), and wastewater treatment technology can ensure very high quality of final effluents. As with the settling basins described in case study 17 however, recirculation necessarily concentrates nutrients within the system – typically as sludge from settling basins or sloughed/washed from biological filters. Recirculation does not therefore eliminate the environmental impact of nutrients – rather it changes its nature. However, if sludge can be used to substitute nutrient inputs to agriculture, then this can be a way of delivering no "net" or marginal impact.

Tying an agricultural enterprise to a fish recirculating system is one way of doing this directly, but this creates significant management problems. Large areas of land are required for the agricultural/hydroponic exercise (typically at least 10x that required for the fish production) effectively converting this into a plant rather than fish production enterprise. And the effluents may not be the ideal nutrient medium for the plants (Rakocy, 1999).

The key to sustainable recirculation is to combine fish culture with plant production – either directly in integrated (hydroponic) systems, or indirectly, by processing sludge wastes from settling chambers and biofilters, as a fertilizer or soil conditioner to agricultural enterprises elsewhere. From a management/economic perspective, the latter is a far more flexible solution.

TABLE A19
Relevant issues under each principle at different scales in case study 18

Principles	**1**	**2**	**3**
Scales	**Ecosystem functions and services**	**Improved human well-being and equity for all stakeholders**	**Context of other sectors, policies and goals**
Farm	• Recirculation minimises direct impact on local environment		
Watershed/zone	• Recirculation generates solid wastes which are usually disposed of within the watershed. • Use for agricultural production (fertiliser/ conditioner substitute) may reduce net addition of nutrients to near zero • High biosecurity may result in lesser chemical use	• Still very limited social and economic impact	• In Europe this done through Water Framework directive • Opportunities for agricultural use of sludge
Global	• Import of nutrients from marine systems for feed. • Potential impact on wild capture fisheries where these are not managed sustainably • Wastewater treatment technology can ensure very high quality of final effluents	• Support employment in industrial fisheries; • High quality and healthy food production • Success has been achieved by companies producing a high value, preferably live product for a niche market where competition is limited.	• The key to sustainable recirculation is to combine fish culture with plant production either directly in integrated systems, or indirectly, by processing sludge wastes from settling chambers and biofilters.