

Integrated marine and brackishwater aquaculture in tropical regions: research, implementation and prospects

Max Troell

*The Royal Swedish Academy of Sciences
Stockholm Resilience Center, Stockholm University
PO Box 50005
SE-104 05 Stockholm, Sweden
E-mail: max@beijer.kva.se*

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ABSTRACT

Global aquaculture development is at a crossroads with many critical aspects of sustainability that needs to be addressed. Mariculture, the production of aquatic organisms in brackish and saline water, has increased throughout the world and in many tropical countries; this increase has resulted in a shift from traditional extensive multiple-species farming systems to more intensive practices. Exposure to global markets made many farmers adopt specialized systems targeting only one economically attractive species. In terms of sustainability, and environmental impacts, coastal aquaculture systems should, among many things, endeavour approaches that minimize dependence upon fossil fuels, reduce wastes and increase efficiency of resource usage. In addition, there is a need for developing sustainable and suitable systems for poor small-scale farmers living in coastal settings; those systems should add to both income generation and food security. Even though technological development and improved management has resulted in increased efficiency and environmental performance in some intensive monoculture systems, we need to ask ourselves what information (being embedded in traditional integrated systems) is being lost in the transition toward monocultures. Thus, such knowledge could, together with more recent findings from research on integrated aquaculture, add important information to ongoing efforts aiming at increasing the sustainability of aquaculture. Integrated aquaculture is certainly not a panacea for aquaculture development, but should be looked upon as one potential tool among many others facilitating sustainable development.

Tropical mariculture is a highly diverse activity, which is also true for integrated farming in that region. Existing integrated mariculture systems can be classified into four main categories: a) *Polyculture* (i.e. multiple species co-cultured in a pond/tank/cage (also including enclosure of different species), b) *Sequential integration* (PAS, Partitioned aquaculture systems) on land and in open waters (differs from polyculture by the need to direct a flow of wastes sequentially between culture units with different species), c) *Temporal integration* (replacement of species within the same holding site, benefiting from wastes generated by preceding cultured species) and d) *Mangrove integration* (aquasilviculture, sequential practices – using mangroves as biofilters).

This global survey, covering almost 100 peer-reviewed articles, shows that the main objective of studies has been increasing profits from multiple species (IPMS), separately or in combination with waste mitigation (WM). Polyculture systems (60 percent) and sequential systems dominated the results of the survey, and more than 75 percent of the studies were conducted in earthen ponds. Shrimps were by far the dominating species group (76 percent), in combination with tilapia (29 percent) and milkfish (16 percent). Only few studies investigated integration in open waters (16 percent) and most of these included seaweeds. Seaweeds were included in 30 percent of overall studies, and 77 percent of these were performed in ponds. Filter feeders were represented in 24 percent of the studies, and the dominating species were green mussels and different oyster species. Many studies described positive effects of the integration – on growth of the cultured species, on biofiltration capacity, and/or on environmental quality. However, most studies were small-scale trials that isolated a specific mechanism of interest, resulting in only few studies that could perform any economic analysis or extrapolation of the results to a larger scale.

Waste mitigation, a key driver for development of integrated mariculture systems in Western countries, has historically played no significant role in tropical countries. However, more recent research has investigated how integrated practices may reduce waste emissions from tropical systems; work that has been mainly carried out in brackishwater ponds. The focus on brackishwater ponds is easy to understand as they dominate coastal fish and shrimp aquaculture in the tropics, and because e.g. wastes from shrimp farm ponds have been linked to coastal deterioration. Only few studies have been performed in tanks and open water environments. Many different possible combinations

of species and systems have been investigated; the main species in these trials being shrimp (*P. monodon*), milkfish (*Chanos chanos*), tilapia (*Oreochromis niloticus*) and red seaweeds (*Gracilaria* spp.). Pond aquaculture in mangroves, where the forest is either part of a polyculture system or is used as filter in sequential culturing, has been practised in Indonesia and China, Hong Kong Special Administrative Region (China, Hong Kong SAR) for centuries. This practice has also developed more recently in the Philippines, Malaysia, Viet Nam, and Thailand.

Integration can be directly beneficial to farmers either through additional valuable products, promoting re-circulation (improving water quality), preventing diseases (“green water”), habitat conservation (mangroves), or increasing allowed production volumes through waste reduction (regulations for emissions). However, in some cases the benefits from integration may not constitute any significant contribution to the farmer in terms of profits. Integration of species from e.g. different trophic levels may increase the degree of complexity, and hence the need for management (and skills). In traditional low input polyculture systems this does not constitute a problem, as labour is usually readily available. More recent approaches in sequential integrated systems rely to a larger extent on engineering inputs, something that can be costly and hence jeopardize the success of such systems. Thus, low input systems usually have low capabilities for investment as they mainly target on low valued species, or limited amounts of high valued species, whose main outlets are local or regional markets. Another aspect regarding the profitability of farming multiple species is the management of risks. A diversified product portfolio will increase the resilience of the operation, for instance when facing changing prices for one of the farmed species or the accidental catastrophic destruction of one of the crops.

Future expected increases in energy prices, costs for aquafeeds and the strengthening of environmental regulations could facilitate the development and practice of integrated systems. However, if integration of e.g. fed species with extractive species (e.g. filter feeders, seaweeds) results in beneficial environmental effects – either locally by waste remediation, or at a larger scale with respect to efficiency in resource utilization, such bioremediative and resource conservation services should preferably be internalized. Thus, these services may mainly benefit society as a whole (e.g. by way of waste mitigation improving coastal ecosystem quality) and maybe only indirectly benefiting the individual farmer whose choice of culture practice provides for the services. However, in order to estimate a value for any such service, the fundamental values of ecological support systems need first to be identified and somehow valued. Only then it will be possible to estimate the true costs of any aquaculture production, and make it more economically attractive for e.g. applying different mitigation measures (including integrated techniques, through for instance the “polluter pay principle”).

INTRODUCTION

It is anticipated that aquaculture will be increasingly called upon to compensate for expected future shortages in seafood harvests. Production from capture fisheries for the last 10 years has leveled around 90–93 million tonnes annually (FAO, 2006), and there seems to be little prospect for any further increase. Today, already nearly every second fish consumed comes from culture, and total aquaculture production of fish and shellfish in 2005 reached over 47 million tonnes (FAO, 2006). With an annual average growth rate of 10 percent (FAO, 2006), it seems feasible that the aquaculture sector will meet the future challenge of doubling its production within 30 years. Due to a global dwindling availability of adequate freshwater, much of this expansion is expected to occur in brackishwater and marine environments. However, aquaculture is now at a crossroads and there are many critical aspects of sustainability that need to be addressed. The sustainability of some sectors within the aquaculture industry are being

questioned, and those apprehensions stem out from multiple indicators i.e. resource usage, environmental degradation, negative social interactions and financial viability (Beveridge, Phillips, and Macintosh, 1997; Naylor *et al.*, 2000; Neori *et al.*, 2004). The interesting question is not *if* the anticipated aquaculture expansion will take place, because it will, but rather *how* it will be achieved and *what* the resulting environmental and socio-economic consequences will be. There is a need, pressure, and challenges, for the sector to adopt innovative alternatives and embrace a responsible development, leading to increased sustainability. This is not something unique only to aquaculture but it is also true for other food production systems as well, e.g. the agriculture industry. Thus, we need to develop and manage future food production systems in such a way that the resilient provision of multiple ecosystem services is ensured (Bennett and Balvanera, 2007) at both local and global scales, including a multiple stakeholder perspective in its wider context.

It has been argued that future advances in aquaculture development will come from further investment in biotechnology (Hardy, 1999; Hew and Fletcher, 2001; Myers *et al.*, 2001; Melamed *et al.*, 2002), including technologies ranging from protein expression and DNA vaccines (and chips) to transgenic technologies. On the other hand it has also been argued that increased production will have to come from simple farming technologies, which farmers can easily adopt, involving both production of more low priced food species and high valued species. Undoubtedly, increased knowledge and development of new methods within biotechnology resulted in important breakthroughs for the aquaculture industry, and further advances within this sector will continue to be important. However, along with the ongoing rapid development of modern aquaculture, involving diverse high-tech methods (both on land and more recently also in off-shore environments) the need for developing low-cost, low polluting, energy-saving, and resource efficient systems been stressed. One of many examples is the “Bangkok Declaration and Strategy Conference on Aquaculture in the Third Millennium” discussing how aquaculture could develop to meet the demand for increased sustainability (NACA/FAO, 2000). Recommendations of integrated farming techniques, and issues that may find solutions in such practices, are found in the final document from this conference, suggesting a future focus on “research and development of resource efficient farming systems”; “increased use of aquatic plants and animals as nutrient stripping”; “increased emphasis on integrated systems to improve environmental performance”; “emerging technologies e.g. re-circulating systems... and integrated water use”. Both, before and since the Bangkok meeting, there have been many other official aquaculture meetings where sustainability of aquaculture has been on the agenda, and where integrated farming techniques have been mentioned as a possible means for increased sustainability of aquaculture development. The western countries have focused on technical solutions for waste mitigation and also on integrated open water systems, e.g., “Sustainable Fish farming” (The Holmenkollen Guidelines (EAS, 1998)); “New species-New Technologies” (EAS, 2001a); “Better use of water, nutrients and space” (EAS, 2001b); “Sea farming- today and tomorrow” (EAS, 2002); “Beyond Monoculture” (EAS, 2003). Integrated aquaculture may offer opportunities for the efficient usage of water and utilization of nutrients, and increased productivity and profits, providing in a single package practical and creative solutions to most problems of waste management and pollution (Neori *et al.*, 2004). Thus, the resulting environmental impacts from aquaculture, and various resource limitations (water, feed, energy, etc.) (Troell *et al.*, 2004), may find their solutions in integrated cultivation techniques. In addition to existing traditional knowledge accumulated from various extensive pond polyculture practices, recent research on intensive integrated aquaculture techniques also add to the overall understanding of integrated aquaculture. The development of viable integrated aquaculture systems should build on the most suitable techniques, considering both the traditional practices and newer culture experiences.

The recent development and promotion of integrated aquaculture in coastal areas has focused on modern integrated approaches, mainly from temperate regions and in the Mediterranean Sea (i.e. IMTA systems (Integrated Multitrophic Aquaculture¹), Chopin *et al.*, 2001; Troell *et al.*, 2005; Neori *et al.*, 2007; Chopin *et al.*, 2008). This is somewhat surprising, considering the ancient tradition of integrated multi-species aquaculture systems (“polyculture”) widespread in China and other Asian countries. The reason for this may be that polycultures have been conducted in more extensive forms, based on the traditional and intuitive knowledge of the farmers (Lin, 2006). Traditional polyculture is practised today in many tropical Asian countries (mainly tidal pond farming) and is characterized by low inputs. Even though intensification and monoculture practices have been seen, even in Asia, as a modern way of developing aquaculture, advanced integrated approaches have also started to gain interest in these countries (Shyu and Liao, 2004). However, presently published details on such endeavors in tropical countries (i.e. parameterization, performance, economics, etc.) have been scarce (Shyu and Liao, 2004). There is therefore an urgent need for more thorough analyses of various systems from different geographical locations in the Tropics, as well as identification of drivers and constraints in modern integrated aquaculture techniques. The present report aims at filling this gap by considering technological as well as environmental and social aspects of tropical integrated aquaculture.

OBJECTIVES AND METHODOLOGIES

This review aims mainly at giving an overview of technical and ecological aspects of integrated marine and brackishwater aquaculture (mariculture) in the Tropics. It includes a compilation of available information describing actual farming activities, past and ongoing, and an additional compilation of results from scientific studies on integrated mariculture practices in the Tropics. The study provides an overview of the most important integrated aquaculture systems in tropical coastal environments and addresses important issues associated with sustainable aquaculture. Further, it discusses opportunities and constraints for integrated coastal aquaculture generally and also specifically for various integrated systems and regions/countries. Some key issues being addressed are:

- 1) The extent of traditional integrated tropical aquaculture systems today.
- 2) The types of integrated systems studied experimentally.
- 3) The impact of new knowledge about integrated technologies on actual practices.
- 4) The performance of these systems from environmental and socio-economic perspectives.

The focus of this study has been on brackishwater aquaculture in the intertidal zone, including salt impounded coastal areas, and marine open water cultures. This review does not cover the full range of integrated practices that exist. Species included in the study have a preference for saline environments (ranging from slightly saline to fully marine). However, as species today can be made tolerant to various salinity conditions (e.g. the shrimp *P. monodon* farmed in freshwater, tilapia and freshwater shrimp *Macrobrachium rosenbergii* in saline waters, etc.) the division into fresh and marine species may become somewhat ambiguous. In addition to integration of different aquaculture species with each other, integration of brackishwater aquaculture species with mangroves as well as with rice has also been included, since they are common practices and could be important in future aquaculture production. Only a limited amount of data describing socio-economic performance has been compiled.

¹ IMTA is here defined as fed aquaculture (e.g. fish) combined with inorganic extractive (e.g. seaweed) and organic extractive (e.g. shellfish) aquaculture. It also refers to more intensive cultivation of the different species in proximity of each other, connected by nutrient and energy transfers through water.

Such information remains either unpublished, or is published as “grey literature” and therefore difficult to obtain.

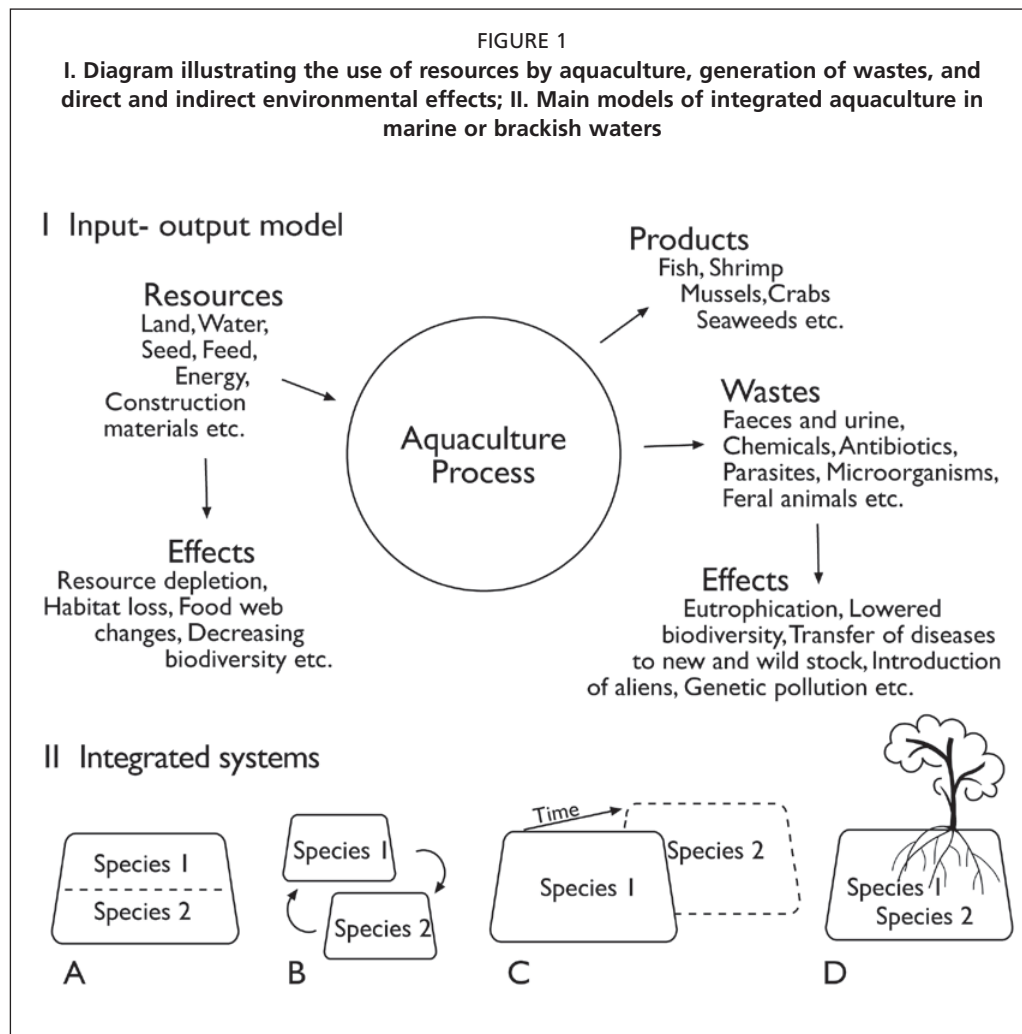
This work has been primarily a desktop study. Data and information have been collected from various sources. Initially, a shorter period was spent at libraries in the Philippines, at SEAFDEC (Southeast Asian Fisheries Development Center), and in Thailand, at the AIT (Asian Institute of Technology) and at NACA (Network of Aquaculture Centres in Asia-Pacific). Information was also obtained by searching in journals and by email enquiries to key informants (see Appendix 1 for sources). Literature in Chinese was generally not included, with the exception of some few publications with English abstracts. It is recommended that existing work from China and Thailand, published only in Chinese and Thai, should be retrieved in order to obtain a complete overview on the status of integrated mariculture (including both research and practices).

Data from available research conducted on integrated aquaculture systems in the tropics are shown in a matrix – Appendix 2. This gives a brief summary of the studies and also indicates the applicability of the findings.

AQUACULTURE DEVELOPMENT

In addition to increased inland production of freshwater fish (traditionally being an integral part of agriculture production) a large part of the aquaculture expansion is anticipated to take place in the oceans and coastal areas. Many coasts today, especially in tropical developing countries, experience increased pressure from human activities (Chuenpagdee and Pauly, 2004). Expansions of aquaculture in these areas can bring needed socio-economic benefits, but these may come at the expense of an increased pressure on coastal ecosystems for goods and services (Chua, 1997), eventually further jeopardizing people’s livelihoods. Fish and crustaceans have been farmed sustainably in Asia for at least 3000 years (Stickney, 1979), but the rising global demand for seafood has led to rapid technological development and new culture systems emerged. Extensive traditional sustainable farming systems, which use local resources and supply food fish to local markets, are increasingly being replaced by intensive systems which use imported resources (feed, energy) and export their products (Stonich, Bort, and Ovares, 1997).

Potential environmental impacts from aquaculture expansion are in general determined by the characteristics of culture systems (species, intensity, technology, etc.) and site characteristics (nature of the landscape and seascape, waste assimilating capacity, waste loadings, etc.) (Figure 1). An aquaculture activity can provide livelihood alternatives and employment opportunities, however, the interactions with the environment (Figure 1) from some aquaculture systems may, directly or indirectly, simultaneously impact negatively on existing livelihoods and people’s well being (Primavera 1993; Naylor *et al.*, 2000). This is especially true for some modern mariculture (marine and brackishwater) operations that result in environmental degradation of soil and receiving waters. However, extensive farming systems, e.g. traditional pond farming of milkfish/shrimps can, when enlarged, also result in negative environmental impacts from habitat destruction, e.g. clearance of mangrove forest (FAO/NACA, 1995). A number of national and international “best management practices”, “codes of conduct”, and “development criteria” developed to guide the industry and individual farmers towards sustainability, seem to over-generalize and lead to qualitative goals, without specific means of measurement and monitoring. Sustainability is a broad concept, but even so it needs to be reduced to specific actions to be useful as an objective for ongoing development of aquaculture. Main overall issues for sustainability include maintenance of capital stocks (natural, human, and man-made capital), efficiency for generating maximum aggregate welfare and equity in distribution of welfare gains and costs (World Commission on Environmental Development, 1987). Maintenance of



natural capital imply (1) secured, future provision of ecosystem goods and services to stakeholders across the entire socio-economic spectrum, and (2) avoidance of eroding resilience to natural and anthropogenic disturbance regimes (Jacobs, 1991). Earlier and also some recent developments of modern coastal aquaculture have focused to a large extent on environmental impacts at local scales. Thus, the industry has thereby failed to incorporate the overarching essence of sustainability, considering the ecosystem perspective stretching far beyond any farm border (regional to global) and including present and future generations of affected societies.

Tropical marine and brackishwater aquaculture

How to define tropical aquaculture? This may seem like an odd question with a likely simple answer, but information from various aquaculture status reports, journal papers, and book chapters shows that it is not that simple. It is however of importance for this review. Tropical aquaculture is primarily aquaculture carried out within the tropical zone (23° 27'N to 23° 27'S), but it can also be the production of tropical species able to tolerate sub-optimal conditions, outside the tropical zone. It could also include species not being of tropical origin which are cultured within the tropical region. FAO statistics do not exclusively present production figures for tropical aquaculture, and therefore such information need to be compiled from available statistics for the different tropical countries (or based on species production). This is straightforward for most countries, but for countries with land also outside the tropical zone one may instead need to look specifically at production of main tropical species. For example,

TABLE 1
An overview of the most common aquaculture species groups cultivated in the tropical coastal zone

Group	System	Method
Plants		
Eucheuma, Kappaphycus, Gracilaria Gelidium, Caulerpa	Stakes, rafts, longlines, beds	Extensive
Molluscs		
Oyster, Mussel, Cockel, Sea cucumber	Rafts, longlines, stakes, beds, Tanks, Ponds	Extensive, Semi-intensive
Crustaceans		
Shrimps, Lobsters, Crabs	Ponds, pens, cages	Extensive, semi-intensive, intensive
Marine/Brackishwater fish		
Milkfish, Grouper, Snapper, Tilapia	Ponds, pens, cages	Extensive, semi-intensive, intensive
Seabass, Seabream, Cobia, Mulletts Drums, Amberjack, Croaker, pompano, Siganiids, Barramundi		

Source: modified from Primavera (2006).

China – the main aquaculture producer in the world – contains coastlines within three climatic zones, the southernmost of which is tropical (Hainan Province).

Tropical mariculture contributes to local and regional food security but also to important export earnings. Its share of global mariculture production is significant, but less compared to production in temperate regions. De Silva (1998) showed that during 1984–1993 tropical production including seaweeds accounted for about 33 percent of global mariculture production by volume. Such study most probably included Chinese production because in a similar analysis with 2004 data and excluding China tropical mariculture only accounted for about 13 percent of global mariculture. This is rather low and not in accordance with the rapid mariculture development that has taken place during the last decade in southern China and other tropical countries.

Tropical coastal countries do not contribute equally to global mariculture production, but instead some regions and nations dominate. These are mainly found in South- and South-East Asia and along the Pacific coast of the South and Central American continents. African nations contribute little to global mariculture production. Mariculture in the tropics is a most diverse activity that encompasses many different species and culture systems. Table 1 shows species groups dominating tropical aquaculture. The bulk of the production comes from farming seaweeds, mussels (clams) and oysters in shallow coastal waters, and the rest from production in lagoons and in land-based ponds. Seaweeds and mollusks, that dominated tropical coastal aquaculture before, have now been accompanied by modern fish cage aquaculture and other open water practices.

Integrated aquaculture

Concept and traditional farming

Environmental pressures and economic drivers such as the rising costs of water, fuel, and other inputs are stimulating growing interest in options for eco-efficient production that minimize resource consumption and pollution. Integrated biosystems can satisfy these requirements because they conserve soil, nutrients and water, increase crop diversity, and can produce feed, fuel or fertilizer on-site as well as valuable chemicals (such as polysaccharides, nutraceuticals, and alternative medicines). Integrated biosystems can be relatively sustainable and resilient, and have the potential to do much to support local economies (Neori *et al.*, 2004). Edwards, Pullin, and Gartner (1988) defined integrated farming as “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”. This definition focuses exclusively on

waste utilization but benefits from integrated practices can be more than just this. Integrated aquaculture systems are dynamic, resilient and versatile. Their structure and function can change according to such variables as location, season, species, and social environment (Little and Muir, 1987; Edwards, 1998); thus, one particular system or solution working successfully in one place may not do elsewhere. Integrated aquaculture has been suggested as one mean by which sustainability can be improved in aquaculture, not only because such cultures aim at maximizing resource utilization but also because they have the possibility to reduce adverse environmental impacts (Brzeski and Newkirk, 1997; Chow *et al.*, 2001; McVey *et al.*, 2002; Troell *et al.*, 2003; Neori *et al.*, 2004). The definition given by Edwards *et al.* (1988) reflects to some extent the Asian perspective on integration, with a focus on resource usage and maximization of production. This can be compared to integrated practices in the western world, which mainly focused on waste mitigation efforts. The multiple objectives for integration are summarized in Table 2.

Polyculture systems in freshwater aquaculture have a long history and are probably the best examples of successful integrated aquaculture (reviewed in Edwards 1992, 1993). These have traditionally been practised in such parts of the world as the Pacific and Indian Ocean-bordering nations, particularly China (Fernando, 2002). Traditional integrated open water mariculture systems, located principally in China, Japan, and South Korea, also have a long history. These operations have consisted of fish net pens, shellfish and seaweed placed next to each other in bays and lagoons (Neori *et al.*, 2004). Through trial and error, optimal integration has been achieved, but the information for quantification and design has seldom been published (e.g. Fang *et al.*, 1996; Sohn, 1996 in Neori *et al.* (2004)). Polyculture in earthen brackishwater ponds has also been practised for a long time, with extensive polyculture systems of shrimp, fish, agriculture plants (including also mangroves and rice) found today mainly in China, Indonesia, Ecuador, India, the Philippines, Taiwan Province of China, Thailand, Japan and more recently in Viet Nam (de la Cruz, 1995; Brzeski and Newkirk, 1997; Binh, Phillips, and Demaine, 1997; Alongi, Johnston, and Xuan, 2000; Neori *et al.*, 2004). It is especially in Southeast Asian countries that considerable research and experience in brackishwater integrated farming has accumulated. However, with the exception of aquasilviculture and integrated shrimp-rice culture, existing information about socio-economics performance of such systems is scarce (de la Cruz, 1995).

TABLE 2
Combinations of objectives most common for the experimental studies included in the review

Objectives	Logistics	Examples
Additional products	Multiple species within same or added culture area, improved utilization of water and added feed, fertilisers, energy, etc.	Farming milkfish, tilapia and shrimps in same pond
Reduction of waste emission	Absorption of particulate organics and dissolved nutrients otherwise entering the environment	Seaweeds or mussels in same or separate pond as fish or shrimps, or placed adjacent fish cages
Improve culture environment for recirculation	Reduction of particulate and dissolved wastes otherwise deteriorating water quality	Seaweeds in re-circulation ponds or tanks
Habitat preservation	Facilitate for culture without destruction of natural habitats (i.e. Mangrove not cleared)	Mixed mangrove aquaculture systems- shrimp, crabs, coockles, fish in same pond with mangroves
Prevention of harmful bacterias	Prevent harmful bacterias by co-culturing species that stimulate growth of phytoplankton or harmless bacteria (e.g "Green water")	Fish and shrimp pond cultures receiving water from ponds with e.g. tilapia
Removal of pest species, or seed from unwanted spawning	Active predation or consumption of species/juveniles otherwise effecting main cultured species negatively	Fish consuming unwanted vegetation, mollusks, wild fish or juvenile recruits of farmed species
Improving growth on target species	Farming lower valued species as feed to higher valued targed species	Tilapia spawning free in ponds with seabass that consume tilapia seed

Intensive systems

Compared to extensive integrated farming, intensive integrated practices depend to a larger extent on inputs for growing one main “fed” targeted species, whose wastes are transferred (usually horizontally) and made available to extractive species. Such intensive integrated systems have been developed during the last two decades, principally in marine temperate environments (Chopin *et al.*, 2001; Neori *et al.*, 2004; Troell *et al.*, 2005; Schneider *et al.*, 2005).

Nutrient retention capacity for N and P, being provided through feeds, is usually low and variable in fish and shrimp farming, resulting in significant releases of both dissolved and particulate wastes. Generally, for temperate regions less than 1/3 of the nutrients added through feed are removed by harvesting in intensive fish farming (Troell and Norberg, 1998). Similarly, retention capacity for nitrogen (N) in three different tropical fish species (sea bream, African catfish, tilapia), being fed conventional diets, varied between 20–50 percent and for phosphorus (P) it ranged between 15–65 percent (Schneider *et al.*, 2005). For intensive shrimp pond farming nutrient retention is even lower, ranging between 6 and 21 percent (Primavera, 1994; Briggs and Funge-Smith, 1994; Robertson and Phillips, 1995; Jackson *et al.*, 2003). The release of wastes mainly depends on species, feeding level, feed composition, fish size, and temperature (Iwama, 1991; Schneider *et al.*, 2005; D’orbcastel and Blancheton, 2005). The impacts of these releases ultimately depend on local/regional hydrodynamic conditions, the physical, chemical and biological characteristics of the receiving ecosystem (and on pollution pressure from other sources – e.g. urban and rural human settlements and sewage effluents, agricultural/industrial runoffs, precipitations, etc.). All this determines the assimilative capacity of the receiving waters. Towards the end of the 20th century, when the assimilative capacity of natural ecosystems seemed to be threatened by emissions from through-put monoculture practices, a renewed research interest in using extractive species as biofilters arose (Gordin *et al.*, 1981; Chopin and Yarish, 1998). In the western world, this has recently resulted in “Integrated Multitrophic Aquaculture” (IMTA), which is a systematic practice, mainly in open water cultures, where fed aquaculture (e.g. fish) is combined side-by-side with extractive species (e.g. seaweed, shellfish, etc.) aquaculture (Chopin, 2006; Ridler *et al.*, 2006; Neori *et al.*, 2007). The ultimate aims of IMTA are the balancing of production with environmental sustainability (biomitigation), economic stability (product diversification and risk reduction) and social acceptability (better management practices) (Chopin, 2006). It is important to note that “Integrated” in IMTA refers to the more intensive cultivation of the different species in proximity of each other, connected by vertical nutrient and energy transfers through water movements. This is different compared to e.g. integration in extensive polyculture systems where the cultured species – almost exclusively fish with different feeding habits – share the same culture unit or pond. In polyculture, the lower trophic levels in the same culture unit – microalgae, aquatic macrophytes, zooplankton, and heterotrophic microbes that convert nutrients into fish food – are “transparent” to the growers and are not considered as crops. Polyculture systems may require compromises in farm management, implying that production of one organism may have to be decreased for a better fit with the other cultured species. Integration of monocultures through horizontal water transfers between the organisms alleviates this deficiency of polyculture and more easily allows for intensification of each species (Neori *et al.*, 2004). However, the overall design will depend on the specific aims for integration, i.e. production or maximal biofiltering capacity. Even if IMTA now is being practised in larger scale at a few places, more research is needed before it can be applied more generally (Troell *et al.*, in press), especially so with respect to maximization of waste transfer between different species (Troell *et al.*, submitted) and application in tropical regions.

INTEGRATED TROPICAL MARICULTURE: AN OVERVIEW

Compared to the many integrated systems in freshwater aquaculture (being an integral part of agriculture) monoculture is basically the norm in mariculture. However, in the tropics we find many exceptions from such generalization, mainly in brackishwater pond systems. Even though it can be easy to visualize the combination of different species to treat effluents (i.e. using mollusks, seaweeds, etc. as biofilters) with effective resource utilization, only a limited number of intensive integrated farming techniques/systems have been implemented in the tropics (Phillips, 1998). Several literature reviews have compiled and synthesized information about these (Chien, 1993; Chien and Liao, 1995; de la Cruz, 1995; Lin, 1995; Gavine, Phillips, and Kenway, 1996; Brzeski and Newkirk, 1997; Lin and Yi, 1999; Browdy *et al.*, 2001; Fast and Metasveta, 1998; 2000; Shyu and Liao, 2004; Neori *et al.*, 2004; Lin, 2006). However, none of these manage to give a comprehensive overview, some being too general, and some focusing on specific systems (shrimp farms) or specific countries. With only a few exceptions these reviews concentrate on logistical constraints to integration.

Systems classification

The numerous types of existing integrated mariculture systems are distinguished from each other by the choice of species and design. A few attempts have been made for classification of such systems. Hambrey and Tanyaros (2003) pointed out the large number of systems, and classified them based on their own experiences from the field (i.e. especially in Southeast Asia) under a) integrated ponds (polyculture fish, agriculture inputs-fish), b) integrated ponds and field systems (intensive fish-extensive fish, rice-fish/shrimps, shrimp-oyster/seaweed, shrimp-mangrove, shrimp-fish) and c) cage-open water systems (fish/mollusks/seaweeds). De la Cruz (1995) identified three classes of brackishwater integrated farming systems (BIFS) for Southeast Asia: (1) aquaculture-agriculture, (2) aquaculture-silviculture, and (3) brackishwater and marine polyculture. He pointed out that only Indonesia, the Philippines, Thailand, and Viet Nam have had experience (or at least research) in both integrated brackishwater aquaculture-agriculture and aquaculture-silviculture. However, today such experiences exist also in the south of China and Malaysia. Taiwan Province of China has been a pioneer with respect to integrating marine seaweeds, particularly *Gracilaria* sp., with fish or shrimps in brackishwater ponds (de la Cruz, 1995). Lin (2006) in his overview on “Aquaculture-aquaculture integration” proposed the classification: “Animals and Animals” (fed fish/crustacean with filter-feeding fish and/or mollusks), “Animals and Plants” (fed fish/crustacean with macrophytes/seaweed), and “Animal and Plant plus Animal” (fed fish/crustacean with macrophytes/seaweed and grazing fish or mollusks). He provided examples, case studies and a more thorough analysis of the three classes from both temperate and tropical regions. Chien and Tsai (1985) classified pond farming into (1) monoculture systems; (2) crop rotation culture systems; (3) polyculture systems (simultaneously culture several species in a single culture unit), and (4) integrated culture; several species in discrete units, which maintain contact through flow of nutrients and food organisms.

In line with the last classification (Chien and Tsai, 1985) the present review classifies integrated mariculture systems into four main categories: a) *Polyculture* (i.e. multiple species co-cultured in a pond/tank/cage (also including enclosure of different species), b) *Sequential integration* (PAS: Partitioned aquaculture systems) on land and in open water (differs from category a) by the need to direct a flow of wastes sequentially between culture units with different species), and c) *Temporal integration* (replacement of species within the same holding site, benefiting from waste residuals from preceding cultured species), d) *Mangrove integration* (aquasilviculture, sequential practices – using mangroves as biofilters) (Figure 1). There are many other examples of integrated systems, that could fit under integrated mariculture practices, but these have been

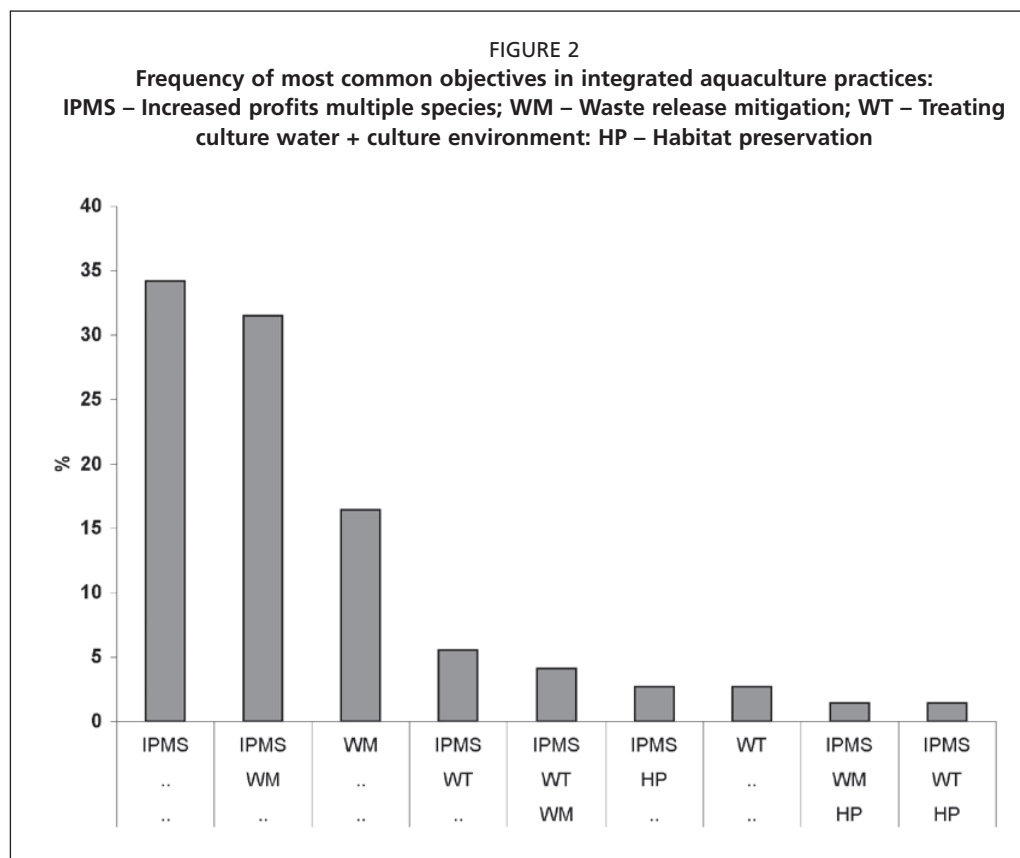
omitted in this survey. One example is the many forms of integration of brackishwater aquaculture with agriculture (de la Cruz, 1995) where animal wastes are being used for fish and shrimp production (milkfish, tilapia, *Penaeus indicus*, *P. monodon*, etc.). The only integration with agriculture being included is rice-shrimp (*P. monodon*) farming. This is because such cultivation mainly takes place in areas with saline soils, generates a significant production, and involves a brackishwater aquaculture species (freshwater shrimps/fish not included).

Other types of integration that have been omitted because they mostly encompass freshwater aquaculture includes: bacteria as biofilters, different halophytes, aquaponic systems, wetlands (i.e. cattail and reed, although mangroves have been included), microalgae (with the exception of “green water” and occasional studies), *Macrobrachium* spp. farmed in brackishwater environments, species from same feeding niches (like mixes of two carnivorous fish), artemia cultivation, Aquamats™, and construction of artificial reefs for biofilter function on a coastal scale. Integrated mariculture in the tropics is mainly found within a), c), and d), dominated by extensive pond systems. More intensive technologies have been developed within b), especially on land. Shrimp farming is included within all categories and represents the most studied system for integration under b). This is not surprising considering the importance of shrimp farming in many tropical countries, and also because its association with environmental degradation. Of the many research projects (and theoretical conceptual ideas) on integrated approaches that have been reviewed, only a small number have been implemented commercially.

Research

Nearly hundred experimental studies on integrated tropical mariculture, published in peer-reviewed journals for the last three decades, have been analysed and briefly summarized (Appendix 2). Several key national and international reports and PhD theses have also been included, while most literature in Chinese has been omitted. Besides describing the logistics of the studies, the review also briefly summarizes major results and conclusions with respect to function/applicability of the integrated techniques/practices being tested. A more in-depth analysis of the results from all the various studies is outside the scope of this report. This is because the studies cover so many different aspects of integration and focus on different species, systems and conditions. However, some general conclusions and trends are presented, and an attempt is made to identify general patterns that are applicable across regions or across systems.

The analysed studies mainly originated from South-East Asia, especially from the Philippines and Thailand. Only few studies originated from Latin America, Caribbean and Africa. The main aim of most studies has been increased profits from multiple species (IPMS), separately or in combination with waste mitigation (WM) (Table 2, Figure 2 and Appendix 2). Polyculture systems (60 percent) and sequential systems dominated the results of the survey, and more than 75 percent of the studies were conducted in earthen ponds. Only few were carried out in open water environments (16 percent), and most of these included seaweeds. Shrimp was by far the dominating species group (76 percent), in combination with tilapia (29 percent) and milkfish (16 percent). Seaweeds were included in 30 percent of overall studies and 77 percent of these were performed in ponds. Filter feeders were represented in 24 percent of the studies and the dominating species were green mussels and different oyster species. Many studies describe positive effects of the integration – on growth of the cultured species, on biofiltration capacity and/or on environmental quality. However, most studies were small-scale trials that isolated a specific mechanism of interest, resulting in only few studies that could perform any economic analysis or extrapolation of the results to a larger scale.



Practices

The subsequent section describes different existing integrated practices that were developed either by farmers from their own experience, or adopted by farmers from research.

Polyculture

Tropical coastal pond aquaculture has historically involved farming of multiple species in tidal influenced ponds i.e. with a production more or less reflecting the species composition in the incoming water. These ponds are usually low-lying impoundments along bays and tidal rivers, and can range in size from a few hectares to over 100 ha (Hempel, Winther, and Hambrey, 2002). Stocking densities are low, rarely exceeding 10 000 per hectare, and depend mainly on the abundance of wild seed. Shrimp production in these systems range from about 50 to several hundred kg/ha/year (Hempel, Winther, and Hambrey, 2002). Polyculture is also practised in ponds with mangrove stands- i.e. aquasilviculture (discussed under 4.3.4), aiming at protecting an important coastal habitat and simultaneously improving livelihood through aquaculture production.

Today many extensive pond farmers practice different varieties of improved extensive farming techniques. This implies active selection and stocking of targeted species for culture, either from wild-caught or hatchery reared seeds. Choice and combination of species does not only reflect present market situation, but also the underlying biological premise of polyculture i.e. that ecological feeding niches are most efficiently utilized when different species are farmed together. This does not only result in diversified and enhanced production, but also in a more efficient utilization of resources.

Polyculture in brackishwater ponds can involve farming of many species besides finfish. Mixed polycultures of fish and shrimps/crabs has been described from many tropical regions, e.g., Indonesia, Philippines, India, Hawaii, and China (Sudarno and Kusnendar, 1980; Joseph, 1982; Shen and Lai, 1994; Costa Pierce, 2002; Hempel,

Winther and Hambrey, 2002). In places with high availability of mollusk seeds, polyculture of shrimp with mollusks has been practised widely, e.g., in China (Wang, Wang and Zhang, 1993; Ding, Li and Liu, 1995). Pond polyculture that involves different seaweed species has also been described, mainly in Thailand and Taiwan Province of China (Chandrkrachang, 1990; Chiang, 1992).

Fish and shrimps/crabs – pond culture

Traditional polyculture pond farming in Indonesia, Tambaks, mixes milkfish (*Chanos chanos*) with different species of shrimp (*Penaeus vannamei*, *Penaeus stylirostris*, *Penaeus monodon*) and wildfish (i.e. mullet (*Mugil* sp.) and barramundi, (*Lates calcarifer*) (Sudarno and Kusnendar, 1980). Such farming has been sustainable for hundred of years, and constituted in 2003 nearly one third of brackish water culture (total culture area 480 762 ha) in Indonesia (FAO, 2007). Compared to intensive shrimp farming, these traditional systems need less inputs, as they are supplied by natural tidal inundations with larvae and most of their foods and nutrients (Hariati *et al.*, 1998; Berkes *et al.*, 1998). Polyculture practice in small-scale family owned extensive farms in e.g. Lampung Province, Indonesia stock ponds with either wild caught or hatchery raised milkfish fry. These are stocked after shrimps have been reared in the pond for a period of time to increase in size. While the shrimp is exported, milkfish is mainly consumed and sold at local or national markets (Martínez-Cordero, 1999; Tobey, Poespitari and Wiryawan, 2002). This adds another dimension to polyculture, i.e. providing both food security and export earnings. Polyculture of crabs (*Scylla* sp.) with milkfish is conducted in India, where production may reach over a ton/ha of crabs and 0.7 tonnes/ha of milkfish (ICLARM, 2002). In China the polyculture of shrimp with mussels, and clams plus crabs is becoming a popular practice (ICLARM, 2002). The yield of shrimp in these systems is around 300–600 kg/ha/yr, which is lower compared to shrimp monoculture (1 500–3 000 kg/ha/year and higher). While intensive shrimp systems usually use up to 5 times higher stocking densities (ICLARM, 2002), they suffer from increased pressure on the culture environment resulting in increased stress on the animals.

In the Philippines both monoculture and polyculture of shrimp/prawn (*Penaeus monodon* and *Metapenaeus ensis*), milkfish, tilapia, mudcrab and groupers takes place in brackishwater ponds (ICLARM, 2002), many of which have replaced mangrove forests. Yields of such ponds range between 0.5–1 tonnes/ha/crop (Guerrero, 2006). With the aim to present a typology of farming systems Stevenson *et al.* (2004) surveyed 137 farms in two of the regions that lead brackish water pond aquaculture in the Philippines, regions 3 (Pampanga, Bulacan, Bataan, and Zambales) and 6 (Iloilo, Capiz, Negros Occidental, and Aklan). Most of the farms used polyculture systems, prioritizing production of either shrimp or milkfish. Crabs and tilapia were sometimes added as minor species, for the purposes of aeration, or opportunistically if the market and environmental (i.e. salinity) conditions were favorable.

In Thailand co-culture of fish has been proposed as a means for removing particulate organic matter in shrimp effluents (Tookwinas, 2003). Tilapia has proved to be able to retain significant portions of excess nutrient, but its efficiency differs depending on the culture systems design. With respect to polyculture of tilapia and shrimps in brackishwater ponds, this was first reported from Ecuador, being a favored practice as it improved shrimp production by improving and stabilizing water quality (Yap, 2000). The practice could not only increase shrimp production (13–17 percent) and harvest size (18 percent), but it also lowered FCR (15 percent) (Yap, 2000). Beneficial effects from the co-culture involved utilization of different niches (e.g. the tilapia foraging and cleaning the pond bottom) and by tilapia having a probiotic type effect in the pond environment (“Green water” – see later in text) (Akiyama and Anggawati, 1999; Yap, 2000). Tilapias are omnivorous and in extensive cultures they filter-feed on phytoplankton and zooplankton, and in intensive cultures they can feed on pellets. Their faeces contribute

to the detritus that supports the shrimp (Yi *et al.*, 2004). In 1996–1997 polyculture of tilapia and shrimps reached Indonesia and then continued to spread to other South Asian countries (Anonymous, 1996a; Yap, 2000). Today also farmers in Thailand and the Philippines co-cultivate shrimp (*Penaeus monodon*) and Nile tilapia (*Oreochromis niloticus*) and there have been many studies investigating growth performance and water quality aspects under different stocking regimes (see Appendix 1). One practice of polyculture keeps fish and shrimps separated by partitioning nets (e.g. in the Philippines and Thailand), but these may reduce water exchange and therefore prevent efficient utilization of wastes by the fish (Yi *et al.*, 2004). However, the beneficial effects on bacterial densities (“green water”), as from fish cultured in separate ponds or kept in reservoirs, is still possible. In the Philippines farmers are advised to stock so called “biomanipulators” (tilapia, milkfish) inside walled net enclosures (100 m²) placed in the middle of shrimp grow-out ponds (Baliao, 2000; Baliao and Tookwinas, 2002). These fishes efficiently feed on the sludge that concentrates there by the circular movement of the water being generated by properly placed paddle-wheel aerators. Similar “biomanipulator” enclosures can be positioned at the corners of the ponds.

Hai Phong province is one of the main shrimp culture areas in North Viet Nam. Different shrimp farming systems exist along the entire coast depending on socio-economic and climatic conditions, and seed availability. The main cultured species *Penaeus monodon* is either cultured in monoculture or integrated – cultured alternatively with mud crab (*Scylla serrata*), greasyback shrimp (*Metapenaeus ensis*) and seaweeds (*Gracilaria gracilis* and *G. blodgettii*). About 15 percent of farms in Hai Phong province practice integrated shrimp/crab-seaweed culture (Giap, 2006).

In the beginning of the 1990s *P. monodon* dominated shrimp production in Taiwan Province of China, and most of the production originated from fish/shrimp polyculture ponds (Chen, 1995). These systems were extensive and combined shrimps with milkfish (*Chanos chanos*), black porgy (*Acanthopagus schlegeli*), grey mullet (*Mugil cephalus*), mud crabs (*Scylla serrata*), clams (*Meretrix lusoria*), and seaweeds (*Gracilaria* sp.) (Shen and Lai, 1994; Chien and Liao, 1995). The specific polyculture combination in each farm was mainly governed by geographical, climatic, ecological, and market conditions (Chien and Liao, 1995). It is, however, difficult to say how much of that polyculture still exists in Taiwan Province of China today, especially following the production collapse due to shrimp diseases in the mid 1990s (Kautsky *et al.*, 2000). Farmers moving towards intensification and monoculture practices may, however, have triggered this collapse.

Population growth and urbanization pressure have in many countries encroached on extensive polyculture farms and made them become smaller in size and increasingly intensified, and thereby more dependent on artificial stocking and feed inputs (Barracough and Finger-Stitch, 1996). Thus, instead of producing multiple species of both shrimps and fish, today many farmers focus on producing only shrimp. Still many coastal small-scale farmers, in different tropical countries, do operate in extensive polyculture mode. It is, however, difficult to estimate quantitatively the extent of these technologies. In many countries the practice of polyculture and more extensive farming, especially with shrimp, has been re-introduced following disease breakouts. For example in the Philippines many intensive shrimp monocultures, which developed and collapsed during the 1980s and 1990s, have been replaced by extensive polycultures of milkfish, shrimps, crabs and, in certain regions, tilapia (Morissens *et al.*, 2004). With lower stocking densities, extensive cultures depend less on feed input and more on “green water”, and also experience less frequent and less virulent breakouts of diseases (Morissens *et al.*, 2004). However, given the increasing knowledge that has accumulated about green water technology, farmers have in addition to extensive brackish water pond farming and intensive tilapia monoculture, attempted again to implement (or re-implement) with variable success intensive monoculture of shrimp (in ponds) and

milkfish in cages and pens (Morissens *et al.*, 2004). In Viet Nam (for example Nha Phu Lagoon), recent experiences with degraded quality of culture environment and breakouts of diseases in intensive shrimp aquaculture have led to an unintended return of intensive farms back to extensive production, often polyculture of shrimp and crabs (EJF, 2003).

Fish/shrimps and Seaweeds (and oysters) – pond culture

Seaweeds have the ability to recover dissolved nutrients in saline waters and this function has been explored extensively with effluents from fed mariculture of fish, shrimps, abalone, etc. (see among others Chopin *et al.*, 2001; Neori *et al.*, 2004). Only few of the studies have so far lead to commercial scale farms in temperate waters, most of them open water cultures (e.g laminaria (*Laminaria japonica*) integrated with scallops and fish in cages in Japan and China). In the tropics it is more common to find small-scale farmers practicing integration with seaweeds in ponds. In the past, farmers in China, Viet Nam, India, and the Philippines stocked *Gracilaria* spp. ponds with shrimp (*Penaeus monodon*), crab (*Scylla serrata*) or milkfish (*Chanos chanos*) (Chen, 1976; Gomez and Azanza-Corrales, 1988). In brackishwater polyculture systems in Indonesia, representing 30 percent of overall brackishwater production in 2003, integration of shrimp and seaweed (*Gracilaria* spp.) is not so common, and if practised it is mainly aimed for waste mitigation (FAO, 2007). However, surveys have shown that seaweed production in polyculture systems with shrimp and fish can improve overall farm performance (i.e. increased production and economic revenues). In central Sulawesi Martínez-Cordero, FitzGerald, and Leung (1999) compared different brackishwater polyculture combinations, of which some included seaweeds, with monocultures (Table 3). By using TFP index (Total Factor Productivity, ratio of an index of total output to an index of all factor inputs (Denny and Fuss, 1983)) they showed that *Gracilaria* was a key species for increasing productivity, and that polyculture in general increased TFP. The authors concluded that incorporating seaweeds was a good production strategy as they could occupy an empty niche and also minimize negative environmental impacts from pond effluents (i.e. dissolved nutrients). The latter was however not investigated in their study. As various conditions (markets, prices, etc.) have changed since the study was carried out, seaweed integration may not increase TFP today, however, this should be further investigated and also to what extent seaweeds in Indonesia are used in polyculture.

As part of a polyculture system with milkfish, farmers in South Sulawesi cultured *Gracilaria* in brackishwater ponds unsuitable for shrimp production (FAO/NACA, 1995). Environmental degradation in the northern part of Bekasi District, Java, Indonesia, also led to collapse of brackishwater shrimp farming and farmers switched

TABLE 3
TFP indexes (Total Factor Productivity) by culture system. Based on 55 farms.

Culture System	Mean TFP
Monoculture	1,23
Polyculture with seaweed	3,26
G + M	3,32
G + M + S	4,42
G + M + S + C	2,49
Polyculture without seaweed	1,39
S + M	1,28
C + M	3,57
S + C	1,13
S + C + M	1,21

S=shrimp (*Penaeus monodon*), G=seaweed (*Gracilaria* sp.),
M=Milkfish (*Chanos chanos*), C=crab (*Scylla serrata*)

Source: from Martínez-Cordero *et al.* (1999).

to milkfish in monocultures (Mauksit, Maala, and Suspita, 2005). Problems with deteriorating water quality remained, and to solve them polyculture was introduced in the form of integrated seaweed and milkfish or/and shrimp culture. This resulted in improved water quality and extra income from dried seaweed (Mauksit, Maala and Suspita, 2005).

Kappaphycus alvarezii and *Gracilaria* spp. dominate the seaweed production in the Philippines, one of the three leading seaweed growers in the world. Cultivation is mainly performed using long-lines or rafts in coastal waters. Polyculture involving seaweeds, particularly in pond culture, have been advocated in the Philippines for a long time (Gomez and Azanza-Corrales, 1988; Largo, 1989). Shrimps (*P. monodon*), at 10 000–20 000 /ha, or mud crab at 5 000–10 000 /ha, were stocked in seaweed ponds for generating additional income (Gomez, 1981). During the 1980s and 1990s seaweeds were also integrated with other aquaculture species; *Kappaphycus* and *Gracilaria* in barramundi cages and *Gracilaria* in ponds with groupers and shrimps (Largo, 1989; Huardo-Ponce, 1992; 1995). The main focus for integrating carnivorous fish with seaweed was primarily biological control of herbivorous fish. However, these practices were never really adopted commercially by farmers in the Philippines (Hurtado, Integrated Services for the Development of Aquaculture and Fisheries (ISDA), personal communication). *Gracilaria* with milkfish or grouper in ponds is not popular in the Philippines, however *Gracilaria* does accidentally enter into the ponds and then the farmers do not remove it as both the fish and the seaweed grow well in co-culture. The seaweed functions both as feed as well as providing shelter (Huardo, personal communication).

In the beginning of the 1990s polyculture of fish, mollusks, or crustaceans and different *Gracilaria* species in ponds and cages was described as a profitable aquaculture venture in Thailand and Taiwan Province of China (Chandrkrachang *et al.*, 1991; Chiang, 1992). Milkfish and tilapia was stocked in *Gracilaria* ponds to browse on and control the green and bluegreen algae, which otherwise tended to shade out the *Gracilaria* (Shang, 1976; Lin *et al.*, 1979; Chiang, 1981). Extensive cultivation of different *Gracilaria* species (i.e. *G. verrucosa*, *G. gigas* and *G. lichenoides*) was performed in brackishwater ponds in southern Taiwan Province of China, and about 5 000–6 000 kg/ha of seaweed was co-cultured with milkfish stocked at 1 000/ha (Lin *et al.*, 1979; Chiang, 1981). The larger juvenile milkfish were regularly harvested, as they otherwise would also consume *Gracilaria* when the other pest seaweeds were gone (Chiang, 1981). Today *Gracilaria* has become a major source of food for abalone in both southern China and Taiwan Province of China (O'Bryen and Lee, 2003), a situation that could stimulate the production of *Gracilaria* and additional seaweeds in polyculture systems.

The co-culture of seaweeds (*Gracilaria* spp., *Caulerpa* spp., *Ulva* sp.) with shrimps in ponds is still in practice in Thailand (Dr. Kwei Lin, Dr. Tsutsui (JIRCAS) personal communication). Preliminary research on green seaweeds (i.e. *Rhizoclonium* sp. and *Caulerpa lentillifera*) in polyculture with shrimps in Thailand has shown many potential benefits. Besides removal of dissolved nutrients, co-culture with the seaweeds significantly increased rates of shrimp growth and survival (Tsutsui *et al.*, 2007). An additional possible beneficial effect could be that *Rhizoclonium* sp. can provide resistance to YHD (yellow head disease) of shrimp, but further studies are needed to confirm this (Tsutsui *et al.*, 2007). *C. lentillifera* also stabilized the water temperature in the pond, something that lowered the stress to the shrimp. Many *Gracilaria* species have been tested in pond co-culture with shrimps in Thailand, i.e. *Gracilaria fisheri*, *G. fastigiata*, *G. tenuistipitata*, *G. salicornia* (Tsutsui *et al.*, 2007) and shrimp farmers have been encouraged to grow *Gracilaria* in their pond wastewater to meet the feed demands for abalone culture (O'Bryen and Lee, 2003). *Gracilaria* spp. are most suitable to integrate with shrimp culture due to their ability to thrive in a wide range



Oysters farmed in shrimp drainage channels in Brazil.

PHOTO: ALEXANDRE WAINBERG

of pond conditions (i.e. salinity and temperature) (Anonymous, 1996a). The practice of co-culture of seaweeds and grouper in off-shore cages has also been tested in Thailand (Wongwai, 1989), but as in the Philippines, the practice has not yet got adopted by farmers.

Brzeski and Newkirk (1995) described polyculture of shrimps/crab and seaweed as common in Viet Nam during the beginning of the 1990s. The practice still exists today but to what extent is not known (Giap, 2006). Wyban (1992) described a “modern” approach to brackishwater polyculture in Hawaii involving the combined stocking of mullet, milkfish, flagtail fish (*Kuhlia sandvicensis*), red tilapia, mangrove crab (*Scylla serrata*), and threadfin in coastal ponds. However, these systems have been phased out in favor of “high technology” farming systems – on land and in open oceans. The ancient brackishwater polyculture systems in Hawaii have been regarded by some as inefficient and unproductive in biomass per unit area, compared to Asian practices. However, these interpretations may have been misleading as they did not consider production from the overall integrated watershed (Costa-Pierce, 2002).

Falling prices for shrimps (*P. vannamei*) in Brazil have resulted in increased interest in farming other species, like tilapia and oysters, together with shrimps. Some farms successfully co-cultivate oysters (*Crassostrea brasiliiana*) on floating trays in shrimp ponds, further offering their product as certified organic and thus obtaining better prices in the markets (Wainberg, 2005). Some oysters can reach market size in 10–12 months in such conditions. Other examples of polyculture initiatives are seahorses kept in net pens in the drainage canals, and also many other species (mostly fish) are being researched (Wainberg, personal communication).

Sequential integration

Technologies for mitigation of wastes from aquaculture, by sequential practices (i.e. passing aquaculture effluents through subsequent culture units, stocked with biofiltering/extractive organisms, before discharge, have been developed mainly for intensive or semi-intensive land based shrimp pond farms. The motivation for doing this has been to minimize environmental impacts associated with intensive through-

flow shrimp farming, i.e. water pollution, and to avoid of disease infection through water intake by means of recirculation (i.e. a need to close the system and therefore improve water quality). Any modern shrimp farms treat effluents in settlement ponds. Integration is regarded as a possibility to further improve water quality by utilizing the natural functions of different species and, even if not a primary goal, to diversify the production. Sequential integration, however, proved to involve more technical intensive practices compared to polyculture (i.e. especially those related to on land constructions and solutions for facilitating water flows).

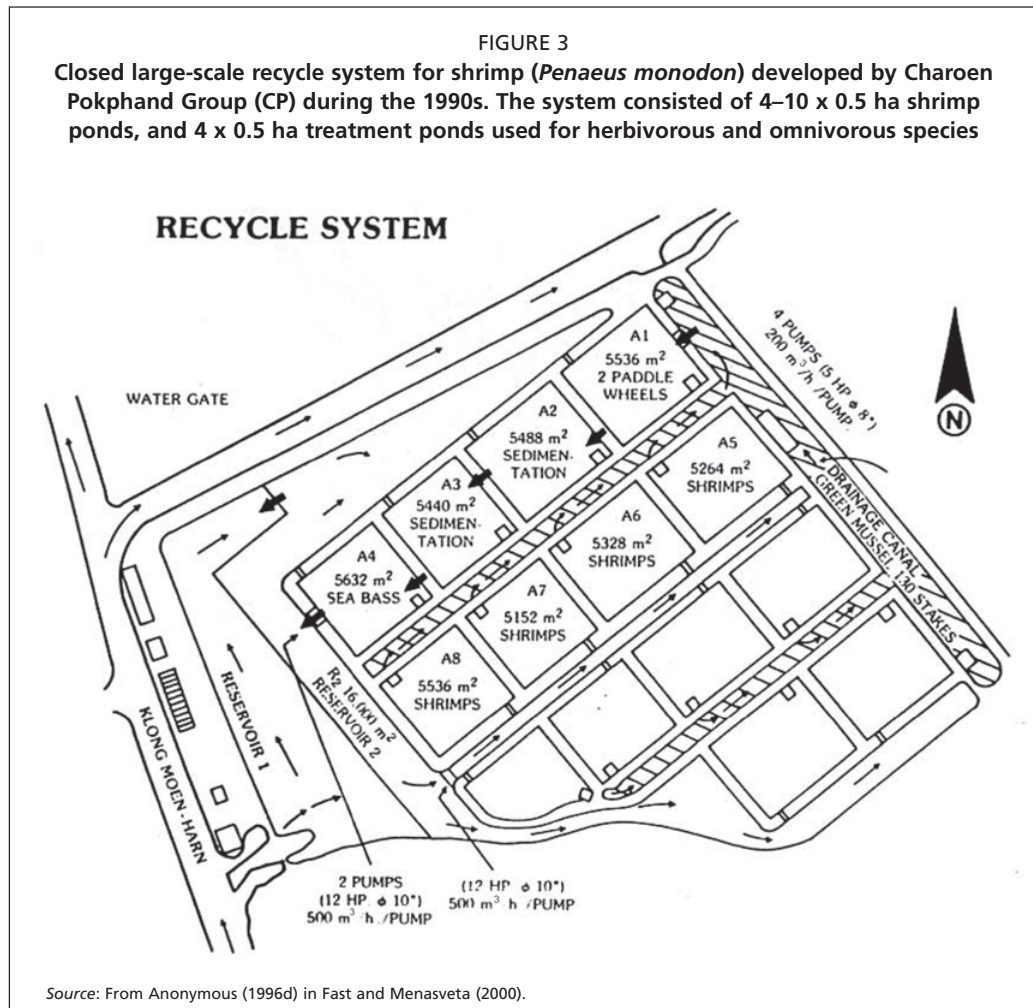
While a number of investigators have reported on the biological, technological and environmental performance, and also the economic feasibility of sequential aquaculture technologies, surprisingly few commercial scale practices are in place today. The literature indicates the high investments that will be needed, in constructions and hydrological solutions, to achieve effective biofiltering functions or/and growth of integrated species. This is something that easily disqualifies many small-scale farmers with limited access to capital.

The search for suitable species and systems for efficient treatment of shrimp wastes intensified during the 1990s (Hopkins, Sandifer and Browdy, 1993; Hopkins *et al.*, 1995; Lin and Nash, 1996; Fast and Menasveta, 1998; 2000). The Charoen Pokphand Group (CP) developed a large-scale (4-10 x 0.5 ha shrimp ponds, 4 x 0.5 ha treatment ponds, reservoir pond and drainage canal) closed recycle system for shrimp (*P. monodon*) (Anonymous, 1994; 1996c, 1996d, in Fast and Menasveta [2000]), in which the area for shrimp growing was reduced and allocated instead to water treatment ponds, with approximately one ha of water treatment for each ha of farming area. Water treatment units consisted of sedimentation ponds, herbivorous and omnivorous species (green mussels (*Mytilus smaragdinus*), oysters (*Crassostrea* sp.), barramundi (*Lates calcarifer*) seaweeds (*Gracilariaria* sp., *Polycavernosa* sp.) and aeration ponds (Figure 3). The water treatment process reduced suspended organic solids by 30 percent, ammonia by 90 percent, and nitrites by 60 percent. The integration also resulted in more stable algal blooms compared with stand-alone shrimp ponds. Despite the successful results of the trials, there are no reported further developments or commercial implementations of this system.

Work along these lines has also been carried out by the Department of Fisheries in Bangkok, Thailand, where green mussels and seaweeds have been used for treatment of waste-water intensive shrimp ponds (Darooncho, 1991; DOF, 1992; Chaiyakam and Tunvilai, 1989; Chaiyakam and Tunvilai, 1992). One important driver for such research has been the Thai Government regulations that came into effect in 1991, stipulating that at farms greater than 50 *rai* (8 ha) effluent waters must be treated via settlement ponds of a size equivalent to, or larger than, 10 percent of the total farm area, and that water released from shrimp farming areas must not surpass BOD greater than 10 mg/L.

In Indonesia, recirculation systems consisting of shrimp culture and treatment ponds at an area ratio of 1:1 were implemented commercially (Anonymous, 1996e). Treatment ponds were stocked with milkfish (*Chanos chanos*), mullet (*Mugil* spp.) and green mussels (*Perna perna*) or oysters (*Crassostrea* sp.). The water flow in this system was totally closed or partly closed, and shrimp yields of 8 600 kg/ha per crop (145 days) were reported. Shrimps were stocked at 50 post-larvae/m² and milkfish at 1 000 ind. per ha (Anonymous, 1996e, in Fast and Menasveta [2000]).

The large Taiwanese (POC) shrimp aquaculture industry examined biofiltering organisms during the 1990s. The Council of Agriculture (COA) launched at that time many studies on water reuse in pond aquaculture – including saline ponds (Ting and Wu, 1992; Chen, 1995). Various imported and locally-made recirculation mechanical devices in combination with biological filter media were used. Concurrently, extension projects funded by Taiwan Province of China Fisheries Bureau were carried out along with the research projects (see references in Chien and Liao [2001]). These projects



involved integration of shrimp (*P. monodon*) with mud clam (*Meretrix lusoria*), seaweed (*Gracilaria* sp.) and milkfish (*Chanos chanos*), longneck purple clam (*Sanguinolaria rostrata* and *S. adamstii*) with the aim of quantifying their respective filtering capacities (Chien and Liao, 1995). Several designs were proposed and tested, but no upscaling or commercial implementation has been reported for any of them, possibly due to the collapse of the industry.

During the 1990s, the Marine Resources Division at James M. Waddell Jr. Mariculture Research and Development Center in South Carolina, USA, carried out several studies on environmentally friendly mariculture systems. Among other things they developed an intensive shrimp pond culture with water re-circulating through ponds with extractive species (mussels, oysters (*Crassostrea virginica*), clams (*Mercenaria mercenaria*), mullet and tilapia) (Hopkins *et al.*, 1993; 1997). Some of their findings showed that nutrients in the shrimp pond effluents could be efficiently transformed into valuable crops without harming shrimp performance (Table 4).

Shrimp with fish

Polyculture and sequential practices for integrated shrimp farming with fish, has been developed in the Philippines (Baliao, 2000; Balia and Tookwinas, 2002). The new practices primarily improved water quality for shrimps, and secondly, generated a diversified production (milkfish, tilapia, siganids). The practices involve low stocking densities of shrimp, special pond preparations, increased aeration by the establishment of a large reservoir, stocked with fish, crop rotation (e.g. with tilapia or milkfish), separate treatment ponds holding fish (like all-male tilapia and milkfish at 5 000 to

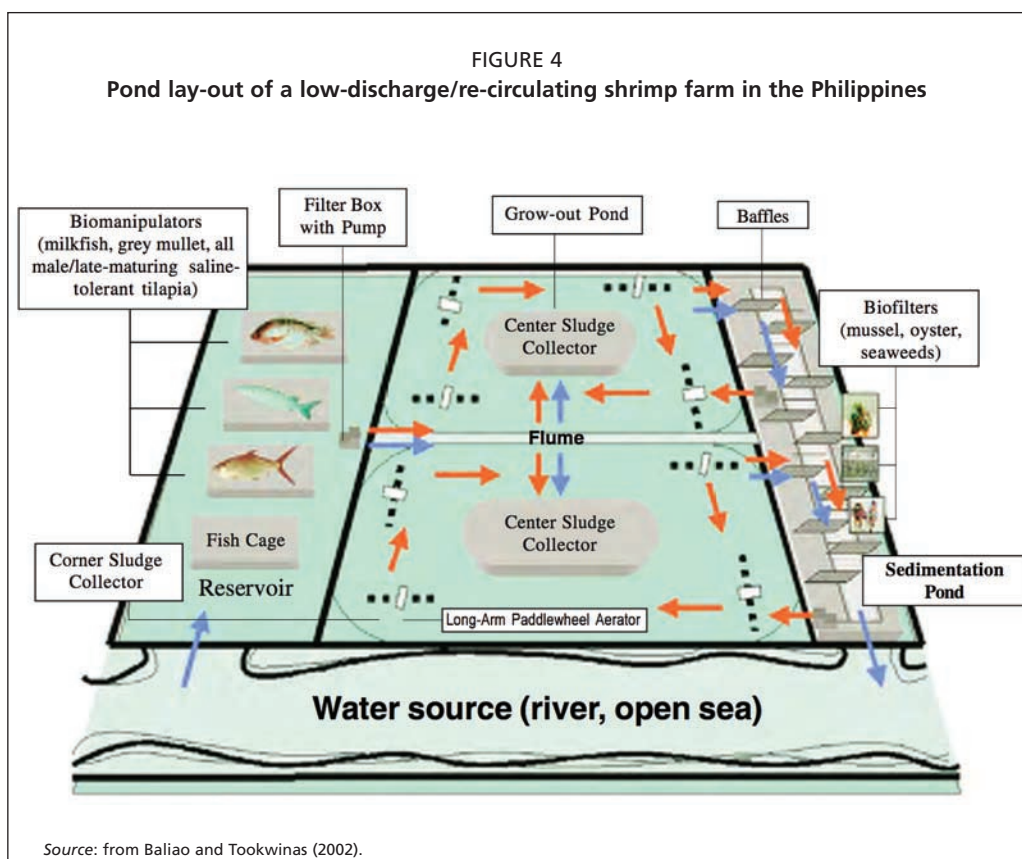
TABLE 4
Production from mono- and integrated culture in earthen ponds. From Hopkins et al. (1993)

	Harvest survival (%)	Harvest size/weight	Production (kg ha ⁻¹)
Monoculture			
Shrimp	92,1	20.8**	11 517
Integration			
Shrimp	83.5	21.3**	10 649
Clams	53.4	25.7***	7.050
Oyster*	95	53.1***	7.020

* Survival in trays, ** gram, *** mm

10 000 fish per ha), bivalves (like oyster) and seaweeds (*Gracilaria*), and fish stocked in net enclosures within the shrimp pond (Figure 4) (Baliao, 2000; Baliao and Tookwinas, 2002). Water can be fully re-circulated, while low concentration effluent waters can be discharged through a mangrove area or impoundment for final nutrient “scrubbing”. The new technology adds about 9 percent to the cost of shrimp production. This is an acceptable cost, considering that shrimp farmers lose their entire stock if hit by diseases. With increased knowledge about the beneficial effects of fish on e.g. shrimp health, this technique could be increasingly adopted by farmers (Fitzsimmons, personal communication). Transfer of these successful practices to farmers has, however, been slow (Hurtado, personal communication).

Most integration with seaweeds in the tropics is found in ponds and mainly as polyculture. In the Philippines, seaweeds (*Kappaphycus* and *Gracilaria*) integrated with fish in cages (grouper and barramundi) (Largo, 1989; Huardo-Ponce, 1992; 1995) never got adopted by farmers. However, in Thailand fish farmers have been described to harvest *Gracilaria* that grows on polyethylene net and on the bottom of cages stocked with barramundi (*Lates calcarifer*). Total yearly production of seaweed and fish is 50–100 kg per 10/m² of cage area (Tachanavarong, 1988).



Shrimp/fish with filter feeders (mussel, oyster) and seaweed

An integrated suspended bivalve culture (e.g. mussels, oysters, etc) with finfish cage culture, or the placement of filter feeder units in shrimp effluent channels, or in separate sedimentation ponds, are easy to visualize and feels intuitively promising.

However, despite the many suggestions for using filter feeders in e.g. re-circulated shrimp systems, and the many experimental pieces of evidence showing their potential (e.g. in Thailand, China, Viet Nam, Malaysia, Mexico, Australia, etc. See Appendix 2) still commercial practices can be found. Mollusks, such as oysters, mussels, scallops, cockles and clams, were co-cultured with shrimps in Thailand at the beginning of 1990, but it is not clear what practices and to what extent (Anonymous, 1996a). Most probably these cultures were some forms of polyculture, but not sequential pond or tank systems.

There are no commercialized practices of sequential integrated mariculture in tropical parts of Africa. This is not surprising, as mariculture with the exception of Tanzania, Mozambique, Madagascar, and Seychelles, is not well developed. There have been early suggestions for integrated practices involving polyculture schemes to utilize native clams and water snails in Nigeria (Ekenam, 1983). Bwathondi (1986) also discussed the potential for combined rabbitfish and oyster culture in floating cages in Tanzania. Recent research has investigated different pond practices involving sequential systems composed of milkfish, siganid, shellfish (*Pinctada margaritifera*, *Anadara antiquata*, and *Isognomon isognomon*) and seaweed (*Ulva*, *Gracilaria*) (Mmochi *et al.*, 2002; Msuya and Neori, 2002; Mmochi and Mwandya, 2003). However, those investigations have not resulted in any implementation or adoption by farmers. The reason may be that more information about performance, both from a biological and an economic perspective, still are needed.

Kona Bay Marine Resources, Hawaii, was founded to commercialize biotechnology developed at the University of Hawaii, for the provision of disease-free and disease-resistant white shrimp (*Penaeus vannamei*). The company has also developed a proprietary polyculture biotechnology approach, which allows two different species to coexist in one system (Wang, 1990; Wang and Jakob, 1991), while bivalves (oysters,



PHOTO: DAO GIAP

Seaweed harvested from a shrimp pond in Nam Dinh, Viet Nam.

clams) are placed in sequential ponds for continuous cleaning of shrimp effluents (Wang, 2003). Today Kona Bay concentrates on clam seed and shrimp broodstock. Besides Kona Bay, a few other farms in Hawaii practice integration but mainly on small scale (A. Tacon, personal communication). However, despite the positive outcomes of the studies, the trend seems to be towards monoculture of *P. vannamei* (using the new “flock” approach, Rosenberry, 2006).

Since 2001, the Institute of Oceanography in Van Ninh district, Viet Nam, has carried out experiments on rock lobster farming in the central province of Khanh Hoa’s Xuan Tu hamlet, Van Ninh district (Pham *et al.*, 2004; 2005). Studies have shown that green mussels (*Perna viridis*) can grow well hanging around lobster cages. Lobsters being fed the mussels demonstrated faster growth and better health than those fed ‘trash’ fish. Water around cages with co-cultured mussels had reduced concentrations of organic matter in the water column and in the sediments (Pham *et al.*, 2004; 2005). The project also investigated the potential of culturing the detritivorous seacucumber sandfish (*Holothuria scabra*) in net enclosures under the lobster cages. Despite the need for more research, many farmers already practise this form of integration (Pham, 2004).

In a recent project entitled “Study on technology for sustainable integrated marine polyculture”, the polyculture of grouper, green mussel, seaweeds, and abalone was carried out in an open system in Viet Nam (Khanh, Thai and Dam, 2005). Preliminary results show that the profits from polyculture system were 21.23 percent higher compared to monoculture. Investments and total production costs were only 9 percent and 17.5 percent higher, respectively. However, the results of the study showed no significant difference between the polyculture cage and the monoculture operations in terms of environmental quality.

Temporal integration – rice/shrimp pond farming

An alternative to the traditional coastal shrimp pond aquaculture that is being practised in tidal areas, or in areas with saline soils, is the farming of shrimps in agriculture fields. This practice makes use of the changing conditions (i.e. freshwater availability and salinity) during a year. Rice is grown during the rainy season (winter) and shrimps



Extensive mixed shrimp pond – Ganges delta, Bangladesh.

during the dry season (summer). The benefits from such temporal integration are that feed residues and shrimp metabolites remain in the field and act as fertilizer for the rice. Thus, rice cultivated after the shrimp harvest utilizes and absorbs any excessive organic loads that may affect the shrimp negatively. This mutual interaction also takes place in the integration of fish with rice and has been proposed as an environmental benign way to boost aquaculture production (Frei and Becker, 2005). Integration of shrimps with rice is practised in e.g. Bangladesh, India, and in Viet Nam. In India, the practice is known as *kbazans* in Karnataka, *bheri* or *jalkar* in West Bengal and *pokkali* in West Bengal, Kerala, Goa, and Karnataka (Shiva and Karir, 1997; Mohan, Sathiadhas, and Gopakumar, 2006; Mukherjee, 2006), and in Bangladesh the practice is called *ghers* (Ghosh, 1992; Milstein *et al.*, 2005). Besides the alternating cropping system, year-round brackishwater shrimp or fish cultivation in rice paddies can be found in Viet Nam, e.g. in Giong Co in My Xuyen District (Mai *et al.*, 1992); barramundi (*Lates calcarifer*), mullets (*Liza parsia*, *L. tade*, *Mugil cephalus*), catfish (*Mystus gulio*) are cultivated in brackish water rice paddy fields in West Bengal and Orissa, India. Fish production of 400–1 500 kg/ha can be obtained after six months culture in brackish water paddy fields (ICAR, 2007). Fish integration (as well as *Macrobrachium* in rice fields) is, however, not included in the present review.

Bangladesh

Traditional bheri/gher aquaculture has been practised in the coastal areas of Bangladesh to farm shrimp and fish long before the introduction of current shrimp culture practices (DDP, 1985). During the last century the practice has evolved from natural stocking in post-harvest rice fields flooded with incoming tide, to enhance extensive and semi-intensive farms with artificial stocking of hatchery reared post-larvae and improved management (i.e. feeding) (Milstein *et al.*, 2005). Shrimps in Bangladesh (170 000 ha in 2003) are mostly cultured in ghers (Milstein *et al.*, 2005). Most of the farmers (> 90 percent) use extensive-traditional methods, characterized by ghers that cover large areas (up to 100 ha), with low stocking density, no additional feeding or fertilization, and poor management of water quality (Islam *et al.*, 2005). Along with the shrimps, a number of finfish species are also trapped in the traditional extensive ghers, including the genera *Mystus*, *Wallago*, *Pangasius*, *Glossogobius*, *Liza*, etc. (Islam and Wahab, 2005). High shrimp mortality in larger ghehrs results in low production and in negative or low net returns. The few smaller ghers (1 to 10 ha) usually apply some fertilizers, have higher stocking densities and more active water management, resulting in increased shrimp production and higher profits (Nuruzzaman *et al.*, 2001; Wahab, 2003; Islam *et al.*, 2005) (Table 5). Annual yields as high as 1 000 kg of shrimp per hectare have been reported in this type of ghers from Bangladesh (Mazid, 1994; Ahmed, 1996).

TABLE 5
Production, survival, total cost and net economic return (mean \pm SD with range) of *Penaeus monodon* in Ghers of different sizes

Gher size	Gher area (ha)	Survival (%)	Shrimp production (Kg ha ⁻¹)	Total cost (US \$ ha ⁻¹)	Net return * (US \$ ha ⁻¹)
Small	2.3 \pm 0.4	49.7 \pm 18.6	204.5 \pm 62.6	5 600	6 391
Medium	6.1 \pm 1.0	37.1 \pm 2.1	155.9 \pm 10.6	5 632	4 315
Large	54.2 \pm 36.9	17.6 \pm 9.6	83.5 \pm 48.5	5 673	82

*Value of shrimp plus those of finfishes, other shrimps and mud crab

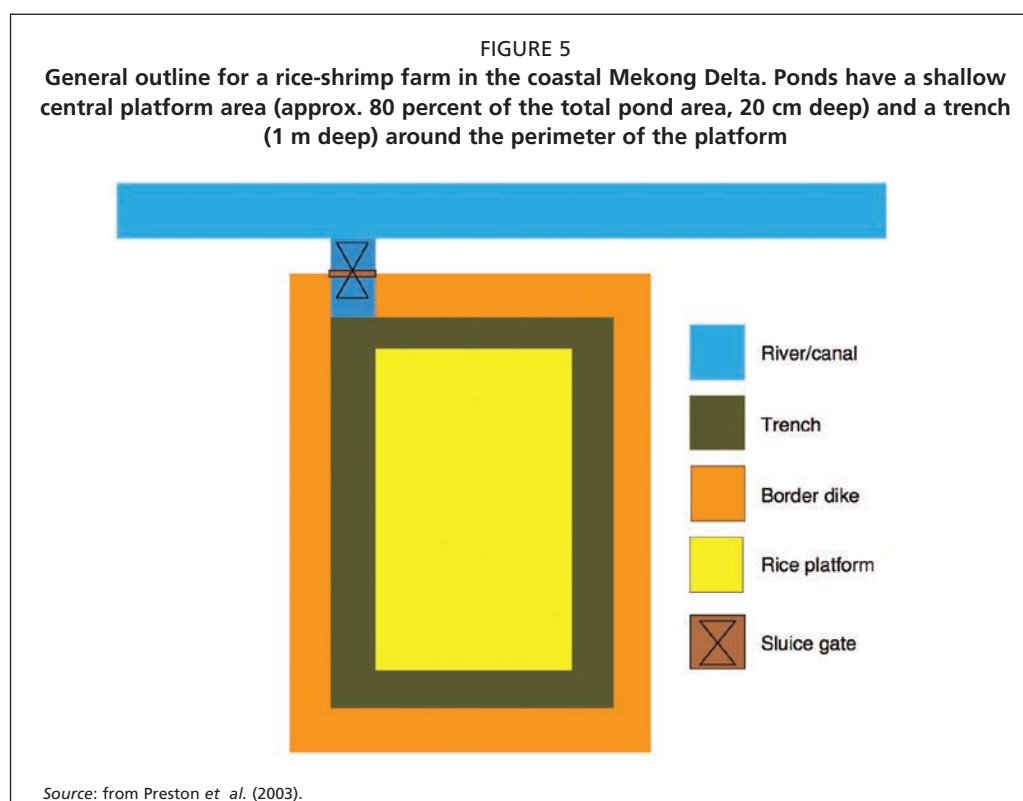
Source: From Islam *et al.* (2005)

Viet Nam

In the coastal zone of the Mekong Delta, where saline water intrusion in the dry season is a major constraint to agricultural production, many farmers have developed integrated rice-shrimp farming systems over the past 30–40 years (Le, 1992; Brennan

et al., 2002; Preston, Brennan and Clayton, 2003). Temporal integration of shrimp (*Penaeus merguensis*, *P. indicus* and *Metapenaeus ensis*, and more recently *P. monodon*) in shallow ponds and rice fields has provided traditional rice farmers an extra income also during the dry season (Tran, Dung and Brennan, 1999; Preston, Brennan and Clayton, 2003). This practice has increased during the last two decades, reaching around 40 000 ha in 2000 (Brennan *et al.*, 2002; Preston, Brennan and Clayton, 2003). A comprehensive research initiative (by the Australian Centre for International Agricultural Research, ACIAR) carried out in 1990, has confirmed the economic profitability of the practice. This multidisciplinary research included both socio-economic aspects and environmental performance. General conclusions were that a variety of farming practices existed (i.e. intensities) and that the addition of shrimps to the farmers' production portfolio had a positive impact on family income, and that crop diversification also increased the economic resilience of the farmers during time of disturbances (e.g. during shrimp diseases they still have an alternative staple crop) (Preston, Brennan and Clayton, 2003). However, rice production has declined in some areas, due to either the preference of farmers for monoculture of shrimps all year round (potential for higher profits) or due to soil salinization resulting in poor rice growth. In Viet Nam, shrimp are either stocked in low densities, relying on natural recruitment during water exchanges, or in high densities relying on seed stocking and input of high quality feeds (farm made or manufactured). Shrimp survival in rice-shrimp cultures is generally lower when compared to well managed, semi-intensive or intensive monocultures, and also when compared to extensive shrimp systems in the Philippines and Bangladesh using similar stocking densities (Be, Clayton and Brennan, 2003). The reasons for this may be related to differences in seed quality and pond structures (Figure 5 – a plateau in the center can potentially generate a stressful environment with respect to e.g. temperature) (Minh *et al.*, 2003).

During the shrimp-farming period, saline water is contained on the land but this does not prevent rice from growing during the rainy season, as the salts seem to wash away by the rain. However, periods of prevailing droughts affect rice negatively. There





Rice-shrimp ponds in Mekong Delta, Viet Nam.

PHOTO: JOFFRE OLIVIER

are also some concerns about the water exchange regime leading to loss of culture land. Frequent water exchanges in the pond, during the shrimp farming period, increase sediment accumulation and deposition. If those sediments are deposited in piles on farmland they prevent that land from being cultivated.

Interactions rice – shrimp in temporal integration

In this report, integrated aquaculture systems have been defined in a certain way, and the question is how these types of rice-shrimp systems fit within the proposed definition. In what ways do these two crops interact with each other and what are the synergistic effects (resulting in environmental/social benefits)? The alternation of rice farming with shrimp aquaculture could potentially reduce nutrients (N and P) being discharged from shrimp farming. The waste nutrients bind to the bottom sediments, and then become utilized by the rice plants in the next cultivation cycle (Wahab, 2003). Vuong and Lin (2001) and Be (1994) concluded that rice-shrimp farming fits well within “environmentally friendly” farming systems as “farmers avoid using agriculture chemicals”, and “rice utilizes shrimp farm wastes accumulated in the field”. However, none of these studies supports these statements or gives any detail about the mechanisms behind them. It is easy to understand that chemical applications in rice culture are being restricted, as these potentially could impair negatively on shrimp health and growth. However, as the different crops are being separated in time it is difficult to see how benefits from shrimps, as natural pest controllers, could benefit rice growth. This is only possible if the species overlap during some parts of the year and from the literature this seems not to be the case. Also, as the soil needs to be flushed with freshwater before planting rice (Vuong and Lin, 2001) and as sediments are being removed and transported away it is difficult to understand how shrimp wastes can be retained in the soil and utilized by the rice. Different farmers may conduct flushing to different degrees, and all nutrients are probably not being flushed out but instead accumulated in the remaining pond sediment. Ghosh (1992) described how the rice fields (*pokkali*) are desalinated after the shrimp crop in time for the rice crop. Besides having crisscross trenches to quickly drain the runoff water, and wash away the surface salts, the topsoil is also scraped off. After the solids have been washed by the rain, the desalinated soil is again spread over the rice plots. Such practice would conserve some of the nutrients.

A comparative study of a rice monoculture with the shrimp-rice system would reveal if shrimp culture improves rice growth in a subsequent rice culture. De, Thai, and Phan (2003) compared different rice varieties, and also monocultures of rice, with rice-shrimp culture. The growth and yield of rice in monocultures were always better compared to the rice–shrimp system. The soil in the rice–shrimp system contained higher salinity and also higher amounts of available phosphate. Nitrogen content in the soil varied substantially during the culture period and no significant differences were found between monocultures and rice-shrimp culture. However, the nitrogen content was higher in the rice plant growing in monocultures. The building of dike walls with sediment materials from the shrimp ponds (dikes) may later serve as a nutrient source for the rice (leaching out to the rice field), but the subsequent salt leaching may prevent any higher growth. To fully evaluate the beneficial effects from integration there is a need for more studies like that of De, Thai and Phan (2003) focusing on how residuals from one species influence growth of the other species. Detailed studies of nutrient dynamics during shrimp culture do exist (e.g. Milstein *et al.*, 2005), but such studies do not include the transfer and utilization of wastes between shrimp and rice. The rice-shrimp systems are complex and demand appropriate field and land preparations for good water management. Islam *et al.* (2005) recommended that large sized ghers should be divided into smaller units of up to 1 ha. This would facilitate implementation of better water management practices, and encourage farmers to more efficiently use inputs such as fertilizers, seeds, and supplemental feeds. The raised embankments and the smaller water surface of the smaller ghers also reduce wind action and thereby increase particle sedimentation. However, the authors did caution for that such new practices must be implemented with caution.

In some places the trend has been to abandon the rice component in favor of intensified shrimp farming (Brennan *et al.*, 2002; Islam *et al.*, 2005). This is worrying as it may increase the farmer's vulnerability and also decreases production of an important staple food product; in some cases policy makers have installed regulations to limit this process. In some places (i.e. Bangladesh) zones limited to mainly rice-shrimp farming have been established (Milstein *et al.*, 2005). The future for these systems probably lay in combining the traditional practices with modern technologies.

Mud crabs also have the potential to be farmed in coastal rice fields during the dry season where both crab grow-out and crab fattening are practised (e.g. in Tra Vinh Province, Viet Nam) (Keenam and Blackshaw, 1999). Artificial stocking is practised in extensive grow-out but only fattening requires feeding with low-cost fish resources. Survival is usually low in the extensive systems, mainly due to cannibalism. The system seems profitable as long as the salinity levels are kept low to ensure a good rice crop. It also helps farmers save money by avoiding the use of pesticides, which are detrimental to the health of the mud crabs. One species of mud crab used in Tra Vinh Province is *Scylla paramamosain*. It does not burrow, therefore, does not affect pond infrastructure. The usage of local low-cost fish as feed may, however, be questionable in resource poor areas.

Mixed aquaculture-mangrove systems

There is still a need for alternative activities within the mangrove intertidal zone that brings economic benefits and subsistence production without jeopardizing the many functions on the mangrove ecosystem also add to mangrove and coastal conservation. Besides brackishwater ponds being created through mangrove clearance there are aquaculture systems that instead make use of a standing mangrove forest in an integrated mode. These *silvofishery* or *aquasilviculture* systems² have in some

² Aquasilviculture is here defined as a “management strategy which combines and harmonizes fishery production and mangrove vegetation” and will hereinafter be used in the text.

countries been around for many decades or even centuries (e.g. in Indonesia - empang parit or tambak tumpang sari; China, Hong Kong SAR - gei wai) and others have been developed more recently (e.g. in Viet Nam, the Philippines and Malaysia). Information about these systems has been comprehensively reviewed in FitzGerald (1997; 2002), and Primavera (2000). The following text outlines some relevant characteristics of these integrated farming practices from a multi-species and system perspective.

Mangrove ecosystem

Mangroves are tropical intertidal forests that can contribute significantly to the well-being of coastal communities through their provision of a wide array of goods and services (Saenger, Hegerl and Davie, 1983; Macintosh and Phillips, 1992; Primavera, 1993; 2000; Rönnbäck, 1999). In addition to the direct utilization of forestry products (e.g. fuel, timber, forage for livestock, honey, medicines, etc.) mangroves also serve as important nursery grounds and breeding sites for various commercially (or for subsistence fisheries) important fish, crustaceans and other shellfish (Boesch and Turner, 1984; Robertson and Duke, 1987). Positive correlations between mangrove area and shrimp/fish catches have been documented for the Philippines, Malaysia, Indonesia and Australia (Primavera, 1995; 1998; and references therein). The forest also provides services like protection against floods and hurricanes, reduction of shoreline and riverbank erosion and maintenance of biodiversity, etc. (Saenger, Hegerl and Davie, 1983; Rönnbäck, 1999; Barbier, 2007).

Aquaculture and mangroves

Development of aquaculture has contributed significantly to deforestation and degradation of mangroves in tropical countries during the last two centuries (Hamilton, Dixon and Miller, 1989; Primavera, 1993; Spalding, Blasco and Field, 1997; Primavera, 1998). Urban development, degradation from land catchments, salt mining, and overexploitation for timber (Saenger, Hegerl and Davie, 1983; UNEP, 1995), are other causes for mangrove destruction (Hambrey, 1996a; Fast and Menasveta, 2000). The acidic soils typical of mangroves are not optimal for aquaculture ponds. However, the benefits from ready access to water, natural food and larvae by the tidal movement, together with cheap land or the historical low protection status of mangroves (Martínez-Cordero, FitzGerald and Leung, 1999), have resulted in systematic establishment of farms in such areas.

The inability to recognize and value the many natural products and ecological services produced by mangroves has been argued to be one important reason for the massive loss of mangroves during the last decades (Barbier, 1994; 2007; Rönnbäck, 1999; 2000; 2001; Rönnbäck and Primavera, 2000; Thornton, Shanahan and Williams, 2003). Sathirathai (1998) revealed that conversion of a mangrove ecosystem in Thailand to shrimp aquaculture only made sense in terms of short-term private benefits when external costs were excluded. In that study, the total economic value of goods and services of the intact mangroves far exceeded that of shrimp farming by around 70 percent.

As a response to the negative environmental impacts from development of semi- and intensive shrimp pond aquaculture in mangroves, the industry has moved toward more closed systems able to operate outside mangrove areas (reviewed in Fast and Menasveta [2000]). Active suspension ponds (ASP), where waste treatment occurs in the water column by heterotrophic bacteria allow high production per unit area with limited water exchange. The latest in this development are “Bio-flocs” systems that facilitate high microorganism activity within a closed culture through high oxygenation rates (Fast and Menasveta, 2000; Moss *et al.*, 2001; Rosenberry, 2006). These farms are suitable for mechanization and use less land (i.e. mangroves) and water than conventional ponds. The production in intensive ponds systems can reach up to

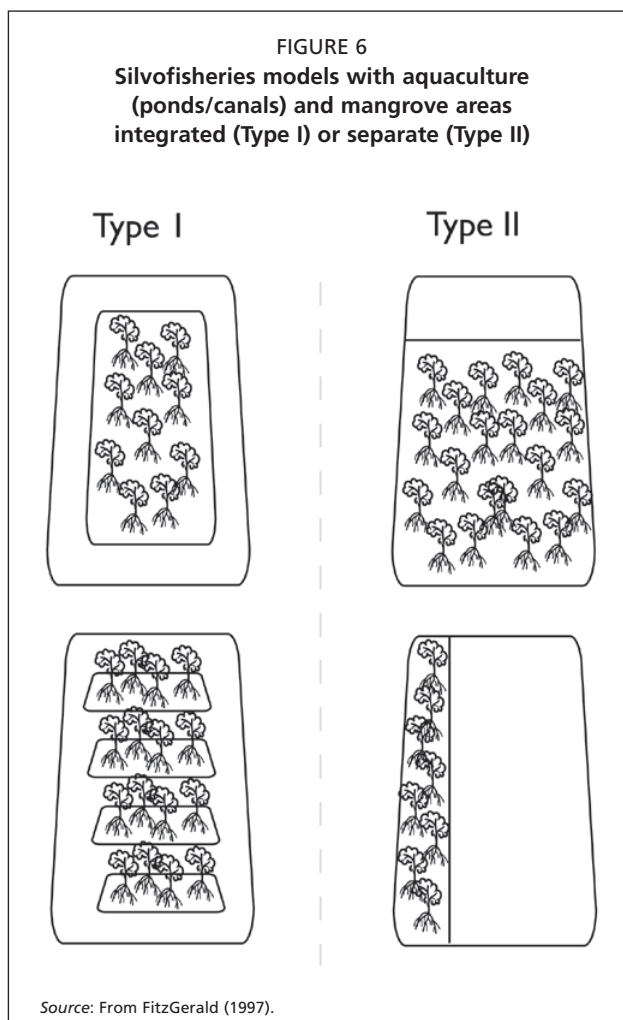
and over 100 tonnes/ha/yr (Fast and Menasveta, 2000; Avnimelech, 2006). However, such low water exchange systems requires specific conditions and depend on expert management, something that probably will slow down its application in traditional shrimp farming countries. Thus the bulk of the global shrimp production will probably continue to occur in extensive ponds at least for some time.

Silvifisberies – aquasilviculture

The rearing of fish, mollusks, shrimps and other crustaceans in mixed mangrove-aquaculture systems is argued to allow for the maintenance of a relatively high level of integrity of the mangrove forests, as aquaculture production mainly depends on natural productivity of mangrove litter (and residues from agriculture and households) (FitzGerald, 2002). The success of any farm depends on technology, skill, and environmental factors (Martinez-Cordero, FitzGerald and Leung, 1999), but in these mixed systems relatively few man-made inputs can generate multiple species, including both aquatic animals in the pond, together with forest products and plants on integrated cropland.

Aquasilviculture has in some places been practised as a way to restore and rehabilitate mangroves (i.e. using abandoned shrimp ponds in e.g. Thailand) (FitzGerald, 2002). Various input factors contribute to the success of extensive aquaculture systems. Today these extensive traditional systems are increasingly receiving man-made inputs (fertilizers, feed, and hatchery seeds) and increased management efforts (Minh, 2001; Primavera, 2000; Minh, Yakupitiyage and Macintosh, 2001). This is not necessarily something negative as development should make use of available techniques to refine culture methods, but the question is if these so called “mangrove friendly” systems of today still are able to maintain the ecological functions of natural mangroves, and also, if they provide economically viable alternatives for sustainable production within the intertidal zone. Ecological arguments against successful production in mixed mangrove-aquaculture systems have been put forward, including accumulation of organic acids and tannins (from mangrove leaves), decreased pond primary production due to tree shading, increased sedimentation and increased mortality from multiple predators able to hide in the vegetation (Anonymous, 2004). Reported decreased yields in ponds with 8–10 years old mangroves, could be linked to shading problems and/or increased concentration of tannins from mangrove leaves (Clough *et al.*, 2002). In contrast to these potentially negative interactions with mangrove vegetation, other studies report on the beneficial effects from mangrove litter on production (FitzGerald, 2002). Some areas in the Mekong Delta have experienced a decline of systems depending on natural stocking due to over exploitation, destruction of mangroves, and the presence of sluice gates within the mangroves limiting the migration of natural shrimp and fish (Joffre, in press). Thus, it is important to acknowledge that a mixed farming system such as this needs to be looked upon as a compromise between forestry and aquaculture, and will therefore not be optimal for either (Clough *et al.*, 2002). Negative interactions may also become more profound when a system moves towards intensification (i.e. higher input and less diversified production) aiming for higher yields of fewer crops (Clough *et al.*, 2002). It is therefore necessary to better understand potential conflicts between mangrove preservation and profitability from mixed farming systems, and how such mixed farming can embrace sustainability at a much larger scale compared to semi-intensive and intensive shrimp pond farming. To answer this there is a need to analyse the ecological role of these integrated systems in a CZM perspective, i.e. to study how functions of mangroves within aquasilviculture system (and in adjacent mangrove stands) change, and also look at profitability at both the farm level and the society as a whole.

Two basic models of aquasilviculture systems can be identified: (i) a *mixed* farm, where mangroves are grown entirely within the pond system together with fish



and crustaceans at low densities, and (ii) a *separate* mangrove forest, situated near the culture ponds (Figure 6). In the latter the mangroves can, in addition to being used for forest products, also facilitate absorption of wastes from the culture ponds and control inputs to the pond culture during high tides (Primavera, 2000; FitzGerald 2002; Clough *et al.*, 2002). The basic models have generally a ratio of 60–80 percent mangrove and 20–40 percent pond canal culture water area (FitzGerald, 2002). The ratio and design can, however, diverge significantly from these basic models (see review in Primavera (2000) and FitzGerald [2002]). In some countries there seems to be a trend towards reduced mangrove ratios, a development that is against existing guidelines and, in some countries, also against regulations (FitzGerald, 2002). Research and production data from large-scale application exist mainly for aquasilviculture systems belonging to the former type, focusing on pond water quality and production aspects. However, some pioneering research exists on efficiency in using natural or constructed mangrove wetlands to treat effluents from shrimp pond aquaculture (Rivera-Monroy *et al.*, 1999; Primavera, 2000; Fujioka, 2005; 2006).

Traditional aquasilviculture systems are found in Indonesia and China, Hong Kong SAR, and more recent technologies have been developed in Indonesia, Viet Nam, the Philippines, and Malaysia. With the exception of Indonesia and Viet Nam, most countries practicing aquasilviculture are still in the verification and demonstration phase of integrated mangrove ponds and pens for fish and crabs (Primavera, 2000). The approaches differ between countries but also within countries (FitzGerald, 2002). The present extent of culture areas is difficult to estimate. In Indonesia the main aquasilviculture areas are found in West Java (covering approx. 26 000 ha in the beginning of 1990s) and in Southern Sulawesi (FitzGerald, 2002). The total tambak area, also including extensive ponds with no mangroves, was in 1994 estimated at 326 910 ha (Martinez-Cordero, FitzGerald and Leung, 1999). Sukardjo (1989) showed that the tambak tumpang sari system in Java increased food supplies and contributed significantly to the socio-economic well-being of the coastal rural population. Thus, the tambak tumpang sari was more profitable than just direct planting of mangrove trees, and the net financial benefits to the reforestation program of the State Forestry Corporation was considerable, particularly with species of *Rhizophora* (Sukardjo, 1989).

In China, Hong Kong SAR there is only one aquasilviculture area, the Mai Po Marshes Nature Reserve covering approx. 272 ha (Young, 1996; Cha, Young and Wong, 1997; Young, 1997). In southern Viet Nam, in the Mekong area, total aquasilviculture area was estimated to be about 50 000 ha or more (Minh, 2001; FitzGerald, 2002), consisting of both natural and planted mangroves. Experimental and demonstration cultures dominate aquasilviculture in the Philippines (Baconguis, 1991; Primavera

and Agbayani, 1997; Aypa and Bacongus, 1999; Primavera, 2000) and few, if any, commercial farms seem to be in operation. Pen culture of mudcrabs (*Scylla olivacea* and *S. tranquebarica*) has been introduced in the mangroves in the Sematan District, Western Sarawak, Malaysia. It is difficult to estimate the aquasilviculture area today, but in end of 1990s it was still only a few hectares (FitzGerald, 2002). In addition to controlled stocking of hatchery-produced larvae (e.g. shrimps), active stocking of collected larvae of mangrove crabs and high valued fish species also takes place. Such activities significantly increase the profitability of the farms and have been introduced in many countries where aquasilviculture is practised (e.g. Minh, 2001; FitzGerald, 2002). Again, the question is how this will impact on the functions of the forest, i.e. effecting the overall seascape. Table 6 outlines some key information and status of aquasilviculture in the countries where such practice is, or has been, significant. Aquasilviculture does also exist in other countries, but on experimental basis (India and Sri Lanka) or just at planning stages (Tanzania, Senegal and Kenya) (FitzGerald, 2002).

Case study 1 – Aquasilviculture in Viet Nam

Mixed shrimp-mangrove ponds in Viet Nam have been primarily extensive integrated systems but improved extensive and semi-intensive ponds have been increasing (Beukeboom, Lai and Otsuka, 1993; Binh and Lin, 1995; Binh, Phillips and Demaine, 1997; Minh, Yakupitiyage, and Macintosh, 2001; Joffre, in press). The aquasilviculture systems in Ca Mau province, Viet Nam, are examples of mixed mangrove-aquaculture systems that have been thoroughly studied recently. This has been done under the World Bank/Network of Aquaculture Centres in Asia-Pacific (NACA)/World Wildlife Foundation (WWF)/FAO Consortium Program on Shrimp Farming and the Environment (Clough *et al.*, 2002), established in 1999 and continuing previous work (1996–2000) within ACIAR/ Research Institute for Aquaculture No2 (RIA-2)/NACA Project (PN9412) on “Mixed shrimp farming-mangrove forestry models in the Mekong Delta (AIMS, RIA-2, NACA, 1999a; 1999b; Clough *et al.*, 1999). Also within the integrated coastal zone management program at AIT (Asian Institute of Technology, Bangkok) has work been conducted on mixed mangrove-aquaculture systems in Ca Mau and Bac Lieu provinces (Binh, 1994; Minh, 2001; Minh, Yakupitiyage and Macintosh, 2001). The European Union (EU) Project GAMBAS (Global assessment of Mekong brackishwater aquaculture of shrimp, 99/362-B7/6200, Institute of Oceanography, Nha Trang, IFREMER) carried out a detailed survey in the Ca Mau province during 2000–2004 (Anonymous, 2004). There is also ongoing work within the World Fish Center/Bangladesh Fisheries Research Institute (BFRI) Challenge Program Water for Food n°10, focusing on Bac Lieu province, in the framework of a broader coastal scale analysis of various livelihood options (Joffre, in press). A great amount of information about older aquasilviculture exists from Indonesia (FitzGerald and Sutika, 1997), but more recent data from Viet Nam has been used below for analyzing performance and viability of aquasilviculture.

The practice of aquasilviculture in Viet Nam has mainly taken place under state Fishery-Forestry Enterprises. These were established in 1986 as a means to solve conflicts over land use and quality degradation of coastal environments (i.e. rapid development of intensive and semi-intensive shrimp pond farms, resulting in mangroves being clear cut, decline in shrimp production) (Hong, 1996; Binh, Phillips and Demaine, 1997; Johnston *et al.*, 1999a; 2000a). Two of these Enterprises – TG3 and SFFE 184, located in Ngoc Hien District, Ca Mau Province (Figure 7), have been analyzed in greater depth within the above mentioned programs and other projects, resulting in several publications (Binh, 1994; Alongi *et al.*, 1999; Alongi, Johnston, and Xuan, 2000; Clough and Johnston, 1997; Johnston *et al.*, 1999a; 1999b; 2000a; 2000b; 2002, Minh, 2001; Minh, Yakupitiyage and Macintosh, 2001; Clough *et al.*, 2002).

TABLE 6
Outline of main characteristics for aquasilviculture in a selection of countries. Reworked from Primavera (2001), with additions from Fitzgerald (2002) and Clough et al. (2002)

	Hong Kong		Indonesia		Viet Nam	Philippines	Malaysia
	Traditional Tambak	Recent Silvofisheries	Traditional Tambak	Recent Silvofisheries			
Technology and source, year started	traditional gei wai; (mid-1940s)	silvofisheries; State Forestry Corp; 1976 (but trials in 1950s)	traditional tambak (Empang parit); (circa 1400s)	silvofisheries; State Forestry Corp; 1976 (but trials in 1950s)	mixed shrimp-mangrove systems; State Forestry & Fishery Enterprises; (mid-1980s)	aquasilviculture; Fisheries Bureau and Environment Dept. (Forestry); 1987	mud crab pens (Inland Fisheries Division); 1992
Objectives	shrimp, fish production; mangrove, wildlife conservation	to solve forestry-fisheries conflict; mangrove rehabilitation, conservation	for food, fuel, fodder, fertilizer, soil stabilization	to solve forestry-fisheries conflict; mangrove rehabilitation, conservation	to relieve land use conflict; mangrove rehabilitation	mangrove management & conservation; fish production	increased incomes of artisanal fishermen
Area covered, present status	~250 ha, Ramsar Wetland Site	wide area	wide area	wide area (e.g., Cikiong: 6,600 ha, Balanak: 5,300 ha in West Java)	widespread, mainly Ca Mau Province (50 000 ha)	~10 experimental verification projects	130 pens in Sematan, Sarawak
Pond/pen size; mangrove:water ratio	~10 ha ponds; 30:70	1-4 ha ponds	0.1 – 1 ha ponds; 60-85:40-15	0.1 – 1 ha ponds; 60-85:40-15	2-17 ha ponds; 70:30	pens: 0.2-1 ha, ponds: 0.13 – 2.6 ha; 80:20	18 m x 9 m pens
Mangroves	natural <i>Avicennia</i> , <i>Kandelia candel</i>	natural & planted <i>Avicennia</i> , <i>Rhizophora</i>	planted <i>Rhizophora</i>	planted <i>Rhizophora</i>	planted <i>Rhizophora</i>	natural, planted	logged over, planted <i>Rhizophora</i>
Aquaculture	wild shrimp, fish, natural food species: <i>P. monodon</i> , <i>P. merguensis</i> , <i>P. penicillatus</i> , <i>metapenaeus ensis</i> , <i>M. affinis</i> , <i>M. burkenroadi</i> , <i>Macrobrachium nipponense</i> , <i>Palaemon orientalis</i> , tilapia, mullet, seabream, seabass, carp	stocked milkfish, wild fish, shrimp; natural food	stocked milkfish, wild fish, shrimp; natural food	stocked milkfish, wild fish, shrimp; natural food, supplement. feeding	stocked hatchery reared shrimps (some use wild) + wild mud crabs, blood cockle, tilapia, local fish; wild shrimp and fish; natural food.	stocked milkfish, mud crab; wild fish, shrimp; natural food, supplement. feeding	stocked mud crab; raw (trash) fish feed
Problems	declining shrimp yields; industrial pollution; wildlife vs. aquaculture management,	pond intensification	difficult management; conflict in choice of mangrove species	difficult management; conflict in choice of mangrove species	declining shrimp production; illegal mangrove conversion, training; low income; pollution; complex institutional setting; sediment build-up	mangrove tree mortality; raw (trash) fish substitutes	seed supply, feeds
Production; net profits	shrimps: before 1990: 190 kg ha-1 yr-1 1995: 15 kg ha-1 yr-1	small-scale farmers	small scale-medium farmers	small scale-medium farmers	200-400 kg ha-1 yr-1; US\$ 280- 1200 ha-1 yr-1	family, villages	
Owner structure	government	small-scale farmers	small scale-medium farmers	small scale-medium farmers	family	family, villages	
Trends	Managed more or less as bird sanctuary, <i>Phragmites</i> replacing mangroves	Intensification, conflicts owner structure					