FAO
FISHERIES AND
AQUACULTURE
TECHNICAL
PAPER

529

ISSN 2070-7010

Integrated mariculture

A global review

Cover:
Illustration by Doris Soto.

Integrated mariculture

A global review

FAO
FISHERIES AND
AQUACULTURE
TECHNICAL
PAPER

529

Edited by
Doris Soto
Senior Fishery Resources Officer (Aquaculture)
Aquaculture Management and Conservation Service (FIMA)
FAO Fisheries and Aquaculture Department
Rome, Italy

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2009

ISBN 978-92-5-106387-3

Preparation of this document

Considering the demonstrated relevance of integrated aquaculture for livelihoods and environmental sustainability in inland ecosystems, in 2005 the Aquaculture Management and Conservation Service (FIMA) of the Food and Agriculture Organization of the United Nations (FAO) Fisheries and Aquaculture Department began a study on "integrated mariculture". The main goals were to asses the current practice of integrated aquaculture and its potential in marine environments envisioning to use this information for the development of technical guidelines. The initial stage of this project included three desk studies encompassing global views of practices and future prospects for integrated aquaculture in coastal and marine areas in three climatic zones: temperate, tropical and Mediterranean Sea as a special Mediterranean enclosed ecosystem. Since integrated aquaculture can be considered a major tool for the implementation of an ecosystem approach to the sector, these global reviews were also presented and discussed during the Food and Agriculture Organization of the United Nations/Universitat de les Illes Balears Expert Workshop on *Building an ecosystem approach to aquaculture* convened in Palma de Mallorca, Spain, from 7–11 May 2007.

The commissioned review papers describing integrated aquaculture in coastal and marine environments were technically supervised by Mrs Doris Soto, Senior Fisheries Officer (FIMA).

The activity and the publication have been partly funded through a Japanese Trust Fund Project (Towards Sustainable Aquaculture: Selected Issues and Guidelines).

Abstract

While the concept and practice of integrated aquaculture is well-known in inland environments particularly in Asia, in the marine environment, it has been much less reported. However, in recent years the idea of integrated aquaculture has been often considered a mitigation approach against the excess nutrients/organic matter generated by intensive aquaculture activities particularly in marine waters. In this context, integrated multitrophic aquaculture (IMTA) has emerged, where multitrophic refers to the explicit incorporation of species from different trophic positions or nutritional levels in the same system. Integrated marine aquaculture can cover a diverse range of co-culture/ farming practices, including IMTA, and even more specialized forms of integration such as mangrove planting with aquaculture, called aquasilviculture. Integrated mariculture has many benefits, among wich bioremediation is one of the most relevant, and yet is not valued in its real social and economic potential although the present document provides some initial economic estimates for the integration benefits derived from bioremediation. Reducing risks is also an advantage and profitable aspect of farming multiple species in marine environments (as in freshwaters): a diversified product portfolio increases the resilience of the operation, for instance when facing changing prices for one of the farmed species or the accidental catastrophic destruction of a crop. Yet such perspectives are far from been considered in mariculture where, on the contrary, there is a tendency to monoculture.

Modern integrated mariculture systems must be developed in order to assist sustainable expansion of the sector in coastal and marine ecosystems thus responding to the global increase for seafood demand but with a new paradigm of more efficient food production systems. Successful integrated mariculture operations must consider all relevant stakeholders into its development plan government, industry, academia, the general public and non-governmental organizations must work together and the role of integrated mariculture within integrated coastal zone management plans must be clearly defined.

There is a need to facilitate commercialization and promote effective legislation for the support and inclusion of integrated mariculture through adequate incentives particularly considering the reduction of environmental costs associated to monoculture farming. Bioremediation of fed aquaculture impacts through integrated aquaculture is a core benefit but the increase of production, more diverse and secure business, and larger profits should not be underestimated as additional advantages.

In many cases, more research is needed to further integrated mariculture – particularly regarding the technical implementation of a farm. At this level, an important issue is to adopt adequate management practices that avoid or reduce the likelihood of disease transmission within and between aquaculture facilities or to the natural aquatic fauna. Also, careful consideration should be paid to the selection of species used in polyculture or integrated multitrophic aquaculture to reduce potential stress and suffering of culture individuals. Integrated aquaculture should be looked upon as a very important tool to facilitate the growth of marine aquaculture and promote sustainable development.

Soto, D. (ed.).
Integrated mariculture: a global review.
FAO Fisheries and Aquaculture Technical Paper. No. 529. Rome, FAO. 2009. 183p.

Contents

Preparation of this document iii
Abstract iv
Acknowledgements vi
Acronyms and abbreviations vii

Introduction 1

REVIEWS

Integrated multi-trophic aquaculture (IMTA) in marine temperate waters 7
Kelly Barrington, Thierry Chopin and Shawn Robinson

Integrated marine and brackishwater aquaculture in tropical regions 47
Max Troell

Integrated aquaculture (INTAQ) as a tool for an ecosystem approach in the Mediterranean Sea 133
Dror Angel and Shirra Freeman

Acknowledgements

We acknowledge the participants of the Mallorca workshop for comments and suggestions to drafts of the present reviews during the meeting. We are also grateful to Mr A. Lovatelli and Mr F. Jara for insightful comments to earlier drafts and to Ms T. Farmer, Ms F. Schatto, Ms A. Colagrossi and Ms D. Rizcallah for their assistance with quality control and FAO style and Mr J. Castilla Civit for layout design.

Acronyms and abbreviations

AIT	Asian Institute for Technology
AARM	aquaculture and aquatic resources management, Asian Institute for Technology, Bangkok, Thailand
ASP	active suspension ponds
BFRI	Bangladesh Fisheries Research Institute
BMPs	better management practices
BOD	biochemical oxygen demand
BIFS	brackishwater integrated farming systems
CSSP	Canadian shellfish sanitation program
CPG	Charoen Pokphand Group
CZM	coastal zone management
DDP	dams and development project, United Nations Environment Programme
DFO	Fisheries and Oceans Canada
EAS	European Aquaculture Society
EAA	ecosystem approach to aquaculture
EEA	European Environment Agency
ECASA	ecosystem approach to sustainable aquaculture (an EU-funded framework)
EJF	Environmental Justice Foundation
ENGO	environmental non-governmental organization
FCR	feed conversion ratio
GAMBAS	Global Assessment of Mekong Brackishwater Aquaculture of Shrimp
HP	habitat preservation
IAAS	integrated agriculture-aquaculture systems
ICAR	Central Institute of Freshwater Aquaculture, Indian Council of Agricultural Research
ICES	International Council for the Exploration of the Seas
ICLARM	International Centre for Living Aquatic Resources Management (presently WorldFish Center)
IFAS	integrated fisheries-aquaculture systems
IFREMER	French Research Institute for Exploitation of the Sea
IMT	integrated multitrophic
IMTA	integrated multitrophic aquaculture
INTAQ	integrated aquaculture
IPMS	increasing profits from multiple species
IPUAS	integrated peri-urban aquaculture systems
IRR	internal rate of return
ISDA	integrated services for the development of aquaculture and fisheries
JIRCAS	Japan International Research Center for Agricultural Sciences
MEDPAN	Network of Managers of Marine Protected Areas in the Mediterranean
NACA	Network of Aquaculture Centres in Asia/Pacific
NELHA	Natural Energy Laboratory of Hawaii Authority
NPV	net protein value
PAS	partitioned aquaculture systems
R&D	research and development
R&D&C	research, development and commercialization

SEAFDEC	Southeast Asian Fisheries Development Center
STREAM	Support to Regional Aquatic Resources Management
TFP	total factor productivity (ratio of an index of total output to an index of all factor inputs)
WM	waste management/mitigation
WT	treating culture water + culture environment
WIOMSA	Western Indian Ocean Marine Science Association
YHD	yellow head disease

Introduction

The culture of aquatic species within, or together with, the undertaking of other productive activities is considered integrated aquaculture. Integrated aquaculture is described in the Aquaculture Glossary of the Food and Agriculture Organization of the United Nations (FAO, 2008) as: *aquaculture system sharing resources, water, feeds, management, etc., with other activities; commonly agricultural, agro-industrial, infrastructural (wastewaters, power stations, etc.).* In the same glossary FAO describes integrated farming systems 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.*

Integrated aquaculture has been widely practised by small households in freshwater environments, mainly in Asia. A review done in 2001 on integrated agriculture-aquaculture (IAA) covered technologies ranging from integrated grass-fish and embankment-fish systems, seasonal ponds and ditches livestock-fish integration of chicken-, duck- and pig-based systems, rice-fish systems, and included a few examples in coastal areas with shrimp and in freshwater areas with prawn (FAO/ICLARM/IIRR, 2001). The study concluded, among other things, that the diversification resulting from integrating crops, vegetables, livestock, trees and fish provides stability in production, efficiency in resource use and conservation of the environment. For example, uncertainty in markets and climate is countered by an array of enterprises. Little and Edwards (2003) also provided a comprehensive review of integrated livestock and fish farming systems (mostly in Asia), however the authors warn about the trend to monoculture with intensification and concentration of both livestock and fish, with a consequent potential decline of integrated practices.

Within all integrated aquaculture practices, rice-fish farming is probably one of the oldest, demonstrating a kind of co-evolution of agriculture and aquaculture, mostly in Asia, and more recently spread to other regions (Halwart and Gupta, 2004). Rice fields provide the environment and habitat for fish and other aquatic animals while the fish contribute to nutrient cycling in the process of feeding on invertebrates and other organic particles that are produced in these inundated fields. Rice-fish farming often reduces the need to use chemicals for pest control, helping preserve biodiversity; additionally, rice-fish farming facilitates the use of existing native fish species.

However, in the marine environment, integrated aquaculture has been much less reported. Yet, in recent years the idea of integrated aquaculture has been often considered a mitigation approach against the excess nutrients/organic matter generated by intensive aquaculture activities. In this context, integrated multitrophic aquaculture (IMTA) has emerged recently, where multitrophic refers to the explicit incorporation of species from different trophic positions or nutritional levels in the same system (Chopin and Robinson, 2004). These authors distinguish it from the practice of aquatic polyculture, which could simply be the co-culture of different fish species from the same trophic level. Interestingly this practice has been defined based on pilot studies in marine habitats involving joint aquaculture of fed species, usually fish, together with extractive species such as bivalves and/or macroalgae. IMTA can also allow an increase in production capacity (for harvesting) of a particular site when regular options have established limitations.

In recent years, FAO has been working on the implementation of the ecosystem approach to aquaculture (EAA) as a way to improve the governance of the sector; *an* *ecosystem approach to aquaculture is a strategy for the integration of the activity within the wider ecosystem in such a way that it promotes sustainable development, equity and resilience of interlinked social and ecological systems* (Soto, Aguilar-Manjarrez and Hishamunda, 2008). The EAA promotes the efficient use of nutrient resources as well as the opportunity of diverse products and benefits (and beneficiaries) while reducing impacts, and therefore integrated aquaculture becomes a very important practical way to implement such an approach.

The increasing use of coastal areas worldwide, coupled with the rapid growth and expansion of mariculture, has created a demand for more sustainable practices from the consumers and other users of coastal zones thus providing an opportunity for integrated mariculture. However, the rapid development of global markets calls on more specialized systems focusing on one species where intensive monoculture marine farming seems to become more widespread and favoured. Nevertheless, one of the main problems is that the practices of integrated aquaculture in marine and coastal environments are a less-known and understood, its potential have not been explored in the light of sustainability of the aquaculture sector within an ecosystem perspective. This gap is the main driver for developing this technical document, thought to provide comprehensive information on current practices and the potential for integrated aquaculture in brackish and marine ecosystems.

The reviews presented here are divided by climatic zones, rather than by regions, and consider: a) temperate mariculture including experiences and potential applications in North America, Europe, South America, Southern Africa; b) tropical coastal marine and brackishwater aquaculture; including experiences from Asia, Polynesia, Central America, Africa; c) a view of a large semi-enclosed ecosystem, the Mediterranean Sea, including experiences and potential applications in Europe, the Near East and Northern Africa.

Each review provides a synthesis of the practice, major requirements for expansion and recommendations for the future development of integrated aquaculture in coastal and marine environments. The review on integrated mariculture in tropical zones involved some field work to obtain more information while the other two were prepared as desktop studies. This effort is considered a necessary step prior to the development of technical guidelines to facilitate the adoption of integrated marine aquaculture considering an ecosystem approach to the sector worldwide.

The paper on the temperate zone (Barrington, Chopin and Robinson, 2009) provides an extensive review of integrated multitrophic aquaculture (IMTA) defined as the practice which combines, in the appropriate proportions, the cultivation of fed aquaculture species (e.g. finfish/shrimp) with organic extractive aquaculture species (e.g. molluscs and macroalgae), covering northern and southern hemisphere case study countries. All countries discussed have enormous potential for IMTA growth and development although at the moment only seven present IMTA systems near or at commercial scale, most case studies are of pilot nature. The authors include a comprehensive list of algae, molluscs, polychaetes that can grow together with fed fish in different combinations and with great economic and biomitigation potential. They also suggest several steps and requirements for the expansion of IMTA in temperate zones, including establishing economic and environmental values of IMTA systems and their co-products, carefully selecting the right species, capable of growing to a significant biomass in order to capture many of the excess nutrients and remove them efficiently at harvesting time, and adequately selecting habitats and technologies for a more efficient integration. The review also highlights the need to facilitate commercialization to avoid cumbersome regulatory hurdles and promote effective legislation, regulations and incentives to further IMTA; to educate government/industry/academia and the general public about the benefits of IMTA particularly when environmental costs of monoculture are internalized; and to establish the research and development continuum to ensure success in the long term for this practice to become a widespread reality.

In the most extensive review, Troell (2009) covers integrated aquaculture in tropical coastal brackishwaters and marine environments. Tropical mariculture is a highly diverse activity, including several integrated farming practices that the author classifies into four 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).

The author provides a global survey, covering almost 100 peer-reviewed articles and 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; only a few were carried out in open water environments (16 percent). Shrimps were by far the dominating species group (76 percent), in combination with tilapia (29 percent) and milkfish (16 percent). Very few studies investigated integration in open waters (16 percent) and most of these included seaweeds. Although economic benefits were demonstrated in many cases, a few showed that the benefits from integration may not constitute a significant contribution to the farmer in terms of direct profits.

The author suggests that future expected increases in energy prices, costs for aquafeeds and the strengthening of environmental regulations should facilitate the implementation 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 through waste remediation or at a larger scale with respect to efficiency in resource utilization – such services should be internalized in order to benefit society as a whole (e.g. such as waste mitigation improving coastal ecosystem quality). 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. As Troell points out, only then it will be possible to estimate the true costs of any aquaculture production and make it more economically attractive by applying different mitigation measures (including integrated techniques, through for instance the "polluter pay principle").

Angel and Freeman (2009) deal with integrated aquaculture (INTAQ) as a way to implement an ecosystem approach to the aquaculture sector in an enclosed ecosystem, the Mediterranean Sea. This review does not provide extensive information on the current integrated practices (mostly inexistent) but focus on its feasibility and potential in an environment relatively poor in nutrients. Here the utilization of the additional nutrients provided by fed aquaculture is an added value of integrated aquaculture. However, Mediterranean Sea coastal zones in general have very high competing demand for tourism and mariculture practices are periodically challenged due to potential environmental impacts affecting tourism. In fact, the European Environmental Agency lists aquaculture as an important potential cause of environmental deterioration in the region if it is developed in unregulated and inappropriate modes. The authors mainly address four issues: to what extent INTAQ permits natural adjustments at the ecological level; how does INTAQ compare with alternative uses of the same environment; given the fact that there is intense competition for coastal and marine resources, where does INTAQ fit in terms of regional priorities; and what are the technical, production, investment, and regulatory challenges as well as opportunities for this practice in the Mediterranean Sea.

This review also emphasizes the practical constrains regarding legal frameworks of an ecosystem shared by several countries. In order to realize the potential of INTAQ, more information is needed on most aspects of the practice. Research and commercial scale experience is required. Information on the potential risks and returns to investment will be especially important in order to facilitate entry at the enterprise levels. The authors also underscore the urgent need to disseminate information on the environmental and broader social implications of INTAQ in order to counter prevail scepticism and negative attitudes toward mariculture in general and INTAQ in particular.

SUMMARY

Integrated marine aquaculture can cover a diverse range of co-culture/farming practices including IMTA to the more specialized integration of mangrove planting with aquaculture, called aquasilviculture. Clearly, integrated aquaculture has many benefits, where bioremediation is one of the most relevant and yet unvalued in its real social and economic potential. Reducing risks is another advantage and profitable aspect of farming multiple species: 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 a crop

All the authors highlight the need to develop modern integrated mariculture systems, which are bound to play a major role worldwide in sustainable expansions of aquaculture in the sea, within a balanced ecosystem thus responding to a global increase for seafood but with a new paradigm in the design of more efficient food production systems. Another important message from the three reviews is that a successful integrated mariculture operation must integrate all stakeholders into its development plan: government, industry, academia, the general public and environmental NGOs must work together and the role of integrated aquaculture within integrated coastal zone management plan must be clearly defined. The three reviews underscore the need to facilitate commercialization and promote effective legislation for the inclusion of integrated aquaculture through adequate incentives. This becomes particularly relevant when considering environmental costs of monoculture farming. Bioremediation of fed aquaculture impacts through integrated aquaculture is a core benefit but the increase of production, more diverse and secure business and larger profits should not be underestimated as additional advantages.

In many cases, more research is needed to further integrated aquaculture – particularly regarding the technical implementation of a farm. At this level, an important issue is to adopt adequate management practices that avoid or reduce the likelihood of disease transmission within and between aquaculture facilities or to the natural aquatic fauna. Also, careful consideration should be paid to the selection of species used in polyculture or integrated multitrophic aquaculture to reduce potential stress and suffering of culture individuals. Integrated aquaculture should be looked upon as a very important tool to facilitate the sustainable growth of marine aquaculture and its potential to promote sustainable development.

REFERENCES

Angel, D. & Freeman, S. 2009. Integrated aquaculture (INTAQ) as a tool for an ecosystem approach to the marine farming sector in the Mediterranean Sea. In D. Soto (ed.). Integrated mariculture: a global review. *FAO Fisheries and Aquaculture Technical Paper No. 529. Rome.* FAO. 2009. pp. 133-183.

Barrington, K., Chopin, T. & Robinson, S. 2009. Integrated multi-trophic aquaculture (IMTA) in marine temperate waters. In D. Soto (ed.). Integrated mariculture: a global review. *FAO Fisheries and Aquaculture Technical Paper.* No. 529, Rome. FAO. pp. 7–46.

Chopin, T. & Robinson, S. 2004. Defining the appropriate regulatory and policy framework for the development of integrated multi-trophic aquaculture practices: introduction to the workshop and positioning of the issues. *Bulletin of the Aquaculture Association of Canada* 104 (3): 4-10.

FAO/ICLARM/IIRR. 2001. Integrated agriculture-aquaculture: a primer. FAO Fisheries Technical Paper. No. 407. Rome, FAO. 2001. 149p.

FAO. 2008. FAO Aquaculture Glossary.

Halwart, M. & Gupta, M.V. (eds.) 2004. Culture of fish in rice fields. FAO and The WorldFish Center, 83p.

Little, D.C. & Edwards, P. 2003. *Integrated livestock-fish farming systems*. Inland Water Resources and Aquaculture Service/Animal Production Service, Food and Agriculture Organization of the United Nations (FAO), Rome 2003. 117p.

Soto, D., Aguilar-Manjarrez, J. & Hishamunda, N. 2008. Building an ecosystem approach to aquaculture. FAO/Universitat de les Illes Balears Expert Workshop. 7–11 May 2007, Palma de Mallorca, Spain. *FAO Fisheries and Aquaculture Proceedings*. No. 14. Rome, FAO. pp. 15–35.

Troell, M. 2009. Integrated marine and brackishwater aquaculture in tropical regions: research, implementation and prospects. In D. Soto (ed.). Integrated mariculture: a global review. *FAO Fisheries and Aquaculture Technical Paper No. 529*, Rome, FAO. pp. 47–131.

Integrated multi-trophic aquaculture (IMTA) in marine temperate waters

Kelly Barrington
University of New Brunswick, Department of Biology, PO Box 5050, Saint John, NB, E2L 4L5, Canada

Thierry Chopin
University of New Brunswick, Department of Biology, PO Box 5050, Saint John, NB, E2L 4L5, Canada
E-mail: tchopin@unbsj.ca

Shawn Robinson
Department of Fisheries and Oceans, St. Andrews Biological Station, 531 Brandy Cove Road, St. Andrews, NB, E5B 2L9, Canada

Barrington, K., Chopin, T. and Robinson, S. 2009. Integrated multi-trophic aquaculture (IMTA) in marine temperate waters. In D. Soto (ed.). Integrated mariculture: a global review. *FAO Fisheries and Aquaculture Technical Paper.* No. 529. Rome, FAO. pp. 7–46.

CONTENTS

Abstract	**8**
Background and objectives	**9**
Review of current IMTA systems	**14**
Major requirements for the expansion of IMTA	**28**
Conclusions and recommendations	**39**
References	**40**

ABSTRACT

This report covers the present situation and the potential for the practice of integrated multi-trophic aquaculture (IMTA) in the world's marine temperate waters.

IMTA is the practice which combines, in the appropriate proportions, the cultivation of fed aquaculture species (e.g. finfish/shrimp) with organic extractive aquaculture species (e.g. shellfish/herbivorous fish) and inorganic extractive aquaculture species (e.g. seaweed) to create balanced systems for environmental sustainability (biomitigation) economic stability (product diversification and risk reduction) and social acceptability (better management practices).

In summary,

- Canada, Chile, China, Ireland, South Africa, the United Kingdom of Great Britain and Northern Ireland (mostly Scotland) and the United States of America are the only countries to have IMTA systems near commercial scale, or at commercial scale, at present.
- France, Portugal and Spain have ongoing research projects related to the development of IMTA.
- The countries of Scandinavia, especially Norway, have made some individual groundwork toward the development of IMTA, despite possessing a large finfish aquaculture network.
- All countries discussed have enormous potential for IMTA growth and development.

Genera of particular interest and those with high potential for development in IMTA systems in marine temperate waters include:

- *Laminaria, Saccharina, Sacchoriza, Undaria, Alaria, Ecklonia, Lessonia, Durvillaea, Macrocystis, Gigartina, Sarcothalia, Chondracanthus, Callophyllis, Gracilaria, Gracilariopsis, Porphyra, Chondrus, Palmaria, Asparagopsis and Ulva* (seaweeds).
- *Haliotis, Crassostrea, Pecten, Argopecten, Placopecten, Mytilus, Choromytilus* and *Tapes* (molluscs).
- *Strongylocentrotus, Paracentrotus, Psammechinus, Loxechinus, Cucumaria, Holothuria, Stichopus, Parastichopus, Apostichopus* and *Athyonidium* (echinoderms).
- *Nereis, Arenicola, Glycera* and *Sabella* (polychaetes).
- *Penaeus* and *Homarus* (crustaceans).
- *Salmo, Oncorhynchus, Scophthalmus, Dicentrarchus, Gadus, Anoplopoma, Hippoglossus, Melanogrammus, Paralichthys, Pseudopleuronectes* and *Mugil* (fish).

These genera have been selected due to their established husbandry practices, habitat appropriateness, biomitigation ability and economic value.

In order to ensure the expansion of IMTA in these regions several steps should be taken where appropriate. These include:

- Establishing the economic and environmental value of IMTA systems and their co-products.
- Selecting the right species, appropriate to the habitat, available technologies, and the environmental and oceanographic conditions, complementary in their ecosystem functions, growing to a significant biomass for efficient biomitigation, and for which the commercialization will not generate insurmountable regulatory hurdles.
- Promoting effective government legislation/regulations and incentives to facilitate the development of IMTA practices and the commercialization of IMTA products.
- Recognizing the benefits of IMTA and educating stakeholders about this practice.
- Establishing the R&D&C continuum for IMTA.

Taking all these factors into account, IMTA can be used as a valuable tool towards building a sustainable aquaculture industry. IMTA systems can be environmentally responsible,

profitable and sources of employment in coastal regions for any country that develops them properly, especially when government, industry, academia, communities and environmental non-governmental organizations work in consultation with each other.

BACKGROUND AND OBJECTIVES

This report covers the present situation and the potential for the practice of integrated multi-trophic aquaculture (IMTA) in the world's marine temperate waters. The temperate zone of the globe generally refers to the region between latitudes 23.5° and 66.5° in both hemispheres (Milne, 1995). This includes oceanic waters in the temperature range of 7-25°C, although in winter the water temperature can dip to the near freezing point in higher latitudes (Levinton, 1995). This report considers countries in this range, particularly Canada, Chile, Finland, France, Ireland, Norway, Portugal, Spain, South Africa, Sweden, the United Kingdom (mostly Scotland) and the United States of America – all of which have active aquaculture industries and either have small scale IMTA systems already in practice or hold potential for the development of IMTA. The case of China is covered succinctly, as published information on IMTA in that country is difficult to find or accessed. The development of IMTA in China would deserve a review on its own and is beyond the scope of this review.

IMTA is a practice in which the by-products (wastes) from one species are recycled to become inputs (fertilizers, food and energy) for another. Fed aquaculture species (e.g. finfish/shrimps) are combined, in the appropriate proportions, with organic extractive aquaculture species (e.g. suspension feeders/deposit feeders/herbivorous fish) and inorganic extractive aquaculture species (e.g. seaweeds) (Figures 1 and 2), for a balanced ecosystem management approach that takes into consideration site specificity, operational limits, and food safety guidelines and regulations. The goals are to achieve environmental sustainability through biomitigation, economic stability through product diversification and risk reduction, and social acceptability through better management practices.

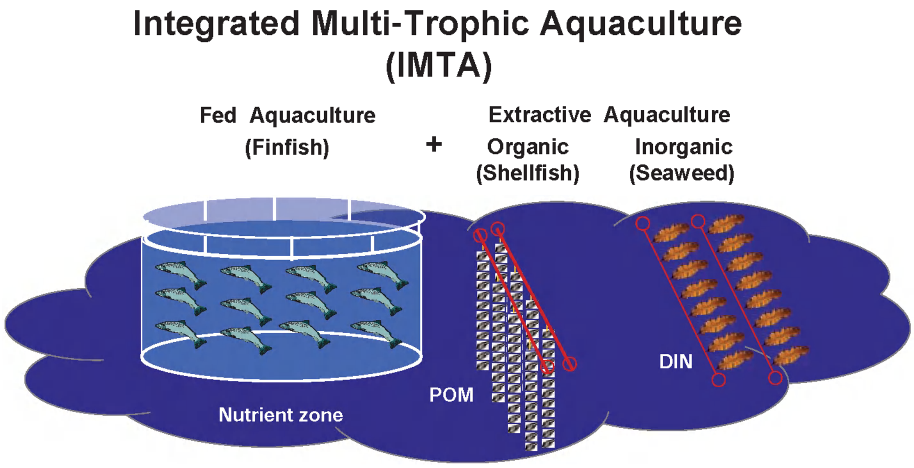
Multi-trophic refers to the incorporation of species from different trophic or nutritional levels in the same system (Chopin and Robinson, 2004; Chopin, 2006). This is one potential distinction from the age-old practice of aquatic polyculture, which could simply be the co-culture of different fish species from the same trophic level. In this case, these organisms may all share the same biological and chemical processes, with few synergistic benefits, which could potentially lead to significant shifts in the ecosystem. Some traditional polyculture systems may, in fact, incorporate a greater diversity of species, occupying several niches, as extensive cultures (low intensity, low management) within the same pond. The *integrated* in IMTA refers to the more intensive cultivation of the different species in proximity of each other (but not necessarily right at the same location), connected by nutrient and energy transfer through water.

Ideally, the biological and chemical processes in an IMTA system should balance. This is achieved through the appropriate selection and proportions of different species providing different ecosystem functions. The co-cultured species should be more than just biofilters; they should also be harvestable crops of commercial value (Chopin, 2006). A working IMTA system should result in greater production for the overall system, based on mutual benefits to the co-cultured species and improved ecosystem health, even if the individual production of some of the species is lower compared to what could be reached in monoculture practices over a short term period (Neori *et al.*, 2004).

Sometimes the more general term "integrated aquaculture" is used to describe the integration of monocultures through water transfer between organisms (Neori *et al.*, 2004). For all intents and purposes, however, the terms "IMTA" and "integrated aquaculture" differ primarily in their degree of descriptiveness. These terms are

FIGURE 1
Salmon (left), mussels (right foreground) and seaweeds (right background) integrated multi-trophic aquaculture (IMTA) in the Bay of Fundy, Canada

FIGURE 2
Conceptual diagram of an integrated multi-trophic aquaculture (IMTA) operation combining fed aquaculture (finfish) with organic extractive aquaculture (shellfish), taking advantage of the enrichment in particulate organic matter (POM), and inorganic extractive aquaculture (seaweeds), taking advantage of the enrichment in dissolved inorganic nutrients (DIN)



Source: Chopin (2006).

sometimes interchanged. Aquaponics, fractionated aquaculture, IAAS (integrated agriculture-aquaculture systems), IPUAS (integrated peri-urban aquaculture systems), and IFAS (integrated fisheries-aquaculture systems) may also be considered variations of the IMTA concept.

The IMTA concept is very flexible. IMTA systems can be land-based or open-water systems, marine or freshwater systems, and may comprise several species combinations (Neori *et al.*, 2004). Some IMTA systems have included such combinations as shellfish/shrimp, fish/seaweed/shellfish, fish/shrimp and seaweed/shrimp (Troell *et al.*, 2003).

What is important is that the appropriate organisms are chosen based on the functions they have in the ecosystem, their economic value or potential, and their acceptance by consumers. While IMTA likely occurs due to traditional or incidental, adjacent culture of dissimilar species in some coastal areas (Troell *et al.*, 2003), deliberately designed IMTA sites are, at present, less common. Moreover, they are presently simplified systems, like fish/seaweed/shellfish. In the future, more advanced systems with several other components for different functions, or similar functions but different size ranges of organic particles, will have to be designed (Chopin, 2006).

The aim is to increase long-term sustainability and profitability per cultivation unit (not per species in isolation as is done in monoculture), as the wastes of one crop (fed animals) are converted into fertilizer, food and energy for the other crops (extractive plants and animals), which can in turn be sold on the market. Feed is one of the core operational costs of finfish aquaculture operations. Through IMTA, some of the food, nutrients and energy considered lost in finfish monoculture are recaptured and converted into crops of commercial value, while biomitigation takes place. In this way all the cultivation components have an economic value, as well as a key role in services and recycling processes of the system, the harvesting of the three types of crops participating in the export of nutrients outside of the coastal ecosystem.

IMTA is considered more sustainable than the common monoculture systems – that is a system of aquaculture where only one species is cultured – in that fed monocultures tend to have an impact on their local environments due to their dependence of supplementation with an exogenous source of food and energy without mitigation (Chopin *et al.*, 2001). For some twenty years now, many authors have shown that this exogenous source of energy (e.g. fish food) can have a substantial impact on organic matter and nutrient loading in marine coastal areas (Gowen and Bradbury, 1987; Folke and Kautsky, 1989; Chopin *et al.*, 1999; Cromey, Nickell and Black, 2002), affecting the sediments beneath the culture sites and producing variations in the nutrient composition of the water column (Chopin *et al.*, 2001).

Integration of different species in one culture unit can reduce these impacts because the culture of the species that do not require exogenous feeding may balance the system outputs through energy conversion, whereby the waste of one species becomes the food for another (Chopin *et al.*, 2001). For example, the wastes given off from the culture of salmon, e.g. uneaten fish food, fish faeces and excreted nitrogen (N) and phosphorus (P), can be assimilated by shellfish (organic processors) and seaweed (inorganic processors), thereby reducing the amount of waste given off from a fish farm and turning it into fodder for another species which is also of commercial value.

This practice of IMTA can help reduce environmental impacts while also creating other economically viable products at the same time. It is this dual-benefit which should make IMTA attractive to fish farmers, while making the aquaculture system more acceptable to environmentalists and the general population.

Considering the potential for increased profitability, it is amazing to realize how very little the aquaculture sector has diversified in some countries or in significant producing regions. For example, the salmon aquaculture in Canada represents 68.2 percent of the tonnage of the aquaculture industry and 87.2 percent of its farmgate value (Chopin and Bastarache, 2004). In Norway, Scotland and Chile, the salmon aquaculture represents 88.8 percent, 93.3 percent and 81.9 percent of the tonnage of the aquaculture industry, and 87.3 percent, 90.9 percent and 95.5 percent of its farmgate value, respectively (Chopin *et al.*, 2008). Conversely, while Spain (Galicia), produces only 8 percent of salmon in tonnage (16 percent in farmgate value), it produces 81 percent of its tonnage in mussels (28 percent in farmgate value). Why should one think that the common old saying "Do not put all your eggs in one basket", which applies to agriculture and many other businesses, would not also apply to aquaculture? Having too much production concentrated in a single species leaves a business vulnerable to issues of sustainability because of low prices due to oversupply, and the possibility of catastrophic destruction of one's only crop (diseases, damaging weather conditions). Consequently, diversification of the aquaculture industry (especially at the local and regional levels) is imperative to reduce the economic risks and maintain its sustainability and competitiveness.

The traditional view of diversification often means producing another product along the same lines of the first, that would fit into the existing production and marketing systems. In finfish aquaculture in North America and Northern Europe, this has usually meant salmon, cod, haddock or halibut. However, from an ecological point of view, these are all "shades of the same colour". No synergies are created; rather, these situations compound the impacts on the system. True ecological diversification of aquaculture means farming at more than one trophic level, i.e. switching from another species of finfish to another group of organisms of lower trophic level (e.g. shellfish, seaweeds, echinoderms, polychaetes, bacteria, etc.), more resembling a natural ecosystem. Staying at the same ecological trophic level will not address some of the environmental issues because the system will remain unbalanced due to the non-stable distribution of energy and non-diversified resource needs and outcomes.

Product diversification should also mean looking at seafood from a different angle. Aquaculture products on the market today are very similar to those obtained from the traditional fishery resources, and are, thus, often in direct competition. While this may be part of the market forces at work, the opportunity exists to diversify from the fish filets, or mussels and oysters on a plate in a restaurant, to a large untapped array of bioactive compounds of marine origin (e.g. pharmaceuticals, nutraceuticals, functional foods, cosmeceuticals, botanicals, pigments, agrichemicals and biostimulants, and industry-relevant molecules). Consequently, research and development on alternative species should no longer be considered as R&D on alternative finfish species, but rather on alternative marine products. Moreover, diversification should be viewed as an investment portfolio, with short-term, long-term, high risk and low-risk components, and with long-term growth and stability as the main objectives.

There is a paradoxical situation when looking at current worldwide food production. In agriculture, 80 percent of the production is made up of plants and 20 percent of animal products (meat, milk, eggs, etc.), while in aquaculture, 80 percent of the production is animal biomass and 20 percent is plant biomass (Chopin and Reinertsen, 2003). Considering only mariculture, the worldwide production in 2004 was made up of 45.9 percent seaweeds, 43.0 percent molluscs, 8.9 percent finfish, 1.8 percent crustaceans, and 0.4 percent of varied other animals (FAO, 2006a). Consequently, in many parts of the world, aquaculture is not synonymous to finfish aquaculture, as so many people in affluent western countries believe. Based on the need for balancing the cultured species functions within the surrounding ecosystem functions, marine herbivores, carnivores and omnivores cannot be cultivated while neglecting marine plants – as efficient biofilters, a crop on their own, or a food component for other organisms – if we are to make the "Blue Revolution" (*sensu* Costa-Pierce, 2002) "greener". Several species of seaweeds cultivated under the right conditions, especially near sources of high levels of nitrogen as in proximity to finfish farms, can be excellent sources of proteins, important amino acids and unsaturated oils. We need to be aware of the other food production systems in the rest of the world if we want to understand our present prevailing system and correctly position it in perspective with other systems. Seaweeds and micro-algivores (e.g. filter feeding shellfish and herbivorous fish) represent 59 percent of the world aquaculture production, followed by the production of 30 percent of omnivores and detritivores. In tonnage, the three leading aquacultured species are the seaweed *Laminaria japonica*, and two micro-algivores, the Pacific cupped oyster, *Crassostrea gigas*, and the silver carp, *Hypophthalmichthys molitrix*. Vocal public opposition to aquaculture has been generated by "high value" salmonids and other carnivorous marine fish and shrimp, which, in fact, represent only 10.7 percent of the world mariculture production (but 40.8 percent of its value).

From the above numbers for mariculture, one may be inclined to think that at the world level, the two types of aquaculture, fed and extractive, are relatively balanced. However, because of the predominantly monoculture approach, these different types of aquaculture production are often geographically separate, and, consequently, rarely balance each other out on the local or regional scale. For example, in Eastern Canada, fed salmon aquaculture is primarily located in the Bay of Fundy in Southern New Brunswick and in Southern Newfoundland, while extractive mussel and oyster aquaculture is located in the Northumberland Strait and the Lower Gulf of St. Lawrence, along the coastlines of Prince Edward Island and Northeastern New Brunswick, and in Eastern Nova Scotia and Northeastern Newfoundland. In Japan, aquaculture is mostly carried out with various bays dedicated to either shellfish, seaweed or finfish aquaculture. There are, however, examples in China of bays managed according to the IMTA approach (Chopin and Sawhney, 2009).

While IMTA may seem like a new concept to western farmers, this approach to farming and aquaculture has long been in use in Asian countries. Japan and China have used this technique for the co-culture of rice and fish for millennia (Neori *et al.*, 2004). Even if the cultured species are different, why, then, is this common-sense solution not more widely implemented, especially in the western world? The reasons for this generally center around social customs and practices that we are already familiar with, even if common sense tells us that we should modify them. Human society does not change quickly unless there are compelling reasons to. The conservative nature of our marine food production industries is a good example of the relative slowness with which changes are adopted, especially when dealing with a complex aquatic environment, which we mostly see only the surface of, and have difficulty understanding the processes taking place beneath it over considerable distances and volumes.

Western countries are regularly reinventing the wheel. Research on integrated methods for treating wastes from modern mariculture systems was initiated in the 1970s (Ryther, DeBoer and Lapointe, 1978). After that period, the scientific interest in IMTA stagnated, and it was not until the late 1980s and early 1990s (Indergaard and Jensen, 1983; Buschmann, López and Medina, 1996; Kautsky, Troell and Folke, 1996; Chopin *et al.*, 1999) that a renewed interest emerged, based on the common-sense approach that the solution to nitrification is not dilution but conversion within an ecosystem-based management perspective. This interest has likely been an indirect result of the increased demand for aquaculture products. In 2004, aquaculture production from mariculture was 30.2 million tonnes, representing 50.9 percent of the global aquaculture (FAO, 2006a), which has steadily increased each year since the 1950s, at a rate of roughly 10 percent (FAO, 2006a). This increase has in turn, resulted in intensified cultures, decrease in available habitat (space available for cage sites/aquaculture leases), and increased environmental impacts on the immediate ecosystem. IMTA is a method whereby production can be intensified, diversified and yet remain environmentally responsible – thereby ensuring a sustainable aquaculture industry. Multi-trophic integration appears to be a logical next step in the evolution of aquaculture.

This trend in the global recognition of the need for more advanced ecosystem-based aquaculture systems has begun to show up in the scientific world through the aquaculture conference circuit. For example, in recognition of this growing interest, the Aquaculture Europe 2003 Conference in Trondheim, Norway, whose theme was "Beyond Monoculture", was the first large international meeting (389 participants from 41 countries) with IMTA as the main topic. In 2006, at the joint European Aquaculture Society and World Aquaculture Society Conference in Florence, Italy, IMTA was recognized as a serious research priority and option to consider for the future development of aquaculture practices.

The objectives of the present paper are:

- To review the current status (production systems and scales, environmental, economic and social benefits, etc.) and future potential of IMTA in regions situated in temperate marine waters, using the best published and personal contact information available.
- To outline the requirements for further expansion of IMTA in the world's marine temperate waters.

REVIEW OF CURRENT IMTA SYSTEMS

The IMTA concept is extremely flexible. It can be applied to open-water and land-based systems, and marine and freshwater systems (sometimes then called "aquaponics" or "partitioned aquaculture"). What is important is that the appropriate organisms are chosen based on the functions they have in the ecosystem and, moreover, for their economic value or potential. What is quite remarkable, in fact, is that IMTA is doing nothing other than recreating a simplified, cultivated ecosystem in balance with its surroundings instead of introducing a biomass of a certain type expecting this can be cultivated in isolation of everything else.

Moreover, IMTA goes beyond environmental sustainability; it provides economic diversification and reduces economic risk when the appropriate species are chosen, and it increases the acceptability of the overall aquaculture sector by using practices evaluated as responsible by the industry, the regulators and the general public.

Presently, the most advanced IMTA systems in open marine waters have three components (fish, suspension feeders such as shellfish, and seaweeds in cages and rafts), but they are admittedly simplified systems. More advanced systems will have several other components (e.g. crustaceans in mid-water reefs; deposit feeders such as sea cucumbers, sea urchins and polychaetes in bottom cages or suspended trays; and bottom-dwelling fish in bottom cages) for either different or similar functions but for different size brackets of particles, or selected for their presence at different times of the year, for example.

North America

Canada

In Canada, aquaculture of salmonids (salmon and trout), groundfish (cod and haddock), and shellfish (oysters, scallops and mussels) has been ongoing for many years. Canada produced, in 2004, 96 774 tonnes of salmonids and 37 925 tonnes of shellfish, with a respective value of US$298 056 000 and US$48 834 000 (Table 1). Most of the aquaculture systems in Canada are intensive monocultures. The blue mussel (*Mytilus edulis*) dominates the shellfish production with 60 percent of the volume, while oysters (*Crassostrea virginica* and *Crassostrea gigas*) make up 33 percent. Seaweeds (e.g. *Laminaria, Saccharina, Alaria, Ascophyllum, Fucus, Furcellaria, Palmaria* and *Chondrus*), although not cultivated in aquaculture systems, have been harvested as wild crops. The seaweeds are used primarily as sources of alginates, carrageenans, agrichemicals (biostimulants and fertilizers), animal feed supplements and ingredients, edible sea vegetables, nutraceuticals and botanicals for the health and beauty industries (DFO, 2001; Chopin and Bastarache, 2004). Acadian Seaplants Limited, based in Dartmouth, Nova Scotia, is a world leader in the development of land-based seawater tank cultivation of seaweeds (*Chondrus crispus*) with a unique commercial cultivation operation in Charlesville, Nova Scotia.

Within the past eight years, IMTA projects have been developed on both the Atlantic and Pacific coasts. On the Atlantic coast, in the Bay of Fundy, a project integrating the culture of salmon (*Salmo salar*), blue mussels (*Mytilus edulis*) and kelps (*Saccharina latissima*, previously described as *Laminaria saccharina*, and *Alaria esculenta*) has been ongoing since 2001 (Chopin and Robinson, 2004) and the results

TABLE 1
Quantity (in tonnes) and value (in US$ x 1000) of marine aquaculture products by country in 2004

Country	Aquatic plants		Crustaceans		Molluscs		Diadromous fishes		Marine fishes		Total	
	tonnes	US$	tonnes	US$	tonnes	US$	tonnes	US$	tonnes	US$	tonnes	US$
Canada	n/a	n/a	n/a	n/a	37 925	48 834	96 774	298 056	n/a	n/a	134 699	346 890
Chile	19 714	13 800	n/a	n/a	96 922	340 119	564 043	2 384 151	255	2 397	680 934	2 740 467
Finland	n/a	n/a	n/a	n/a	n/a	n/a	10 586	40 406	n/a	n/a	10 586	40 406
France	37	16	n/a	n/a	208 535	506 672	925	4 590	6 728	66 593	216 225	577 871
Ireland	n/a	n/a	n/a	n/a	43 092	53 423	14 349	64 727	25	280	57 466	118 430
Norway	n/a	n/a	21	395	3 796	2 746	627 581	1 656 146	5 404	21 997	636 802	1 681 283
Portugal	n/a	n/a	n/a	n/a	2 681	12 978	n/a	n/a	3 194	21 830	5 875	34 808
South Africa	2 845	1 252	30	419	1 680	26 477	n/a	n/a	n/a	n/a	4 555	28 148
Spain	n/a	n/a	46	666	236 708	97 346	158	462	23 294	144 512	260 206	242 986
Sweden	n/a	n/a	n/a	n/a	1 435	794	1 316	4 871	n/a	n/a	2 751	5 665
United Kingdom	n/a	n/a	n/a	n/a	32 500	64 278	159 879	479 985	440	3 888	192 819	548 151
United States	n/a	n/a	4 731	20 958	221 717	164 352	15 127	56 575	1 362	6 292	242 937	248 178
Total	22 596	15 068	4 828	22 438	886 991	1 318 019	1 490 738	4 989 969	40 702	267 789	2 445 855	6 613 283

Source: FAO (2006b).

support the establishment of IMTA systems in this region. Innovative kelp culture techniques have been developed and improved both in the laboratory and at the aquaculture sites. Increased growth rates of kelps (46 percent; Chopin *et al.*, 2004) and mussels (50 percent; Lander *et al.*, 2004) cultured in proximity to fish farms, compared to reference sites, reflect the increase in food availability and energy. Nutrient, biomass and oxygen levels are being monitored to estimate the biomitigation potential of an IMTA site. Salmonid solid and soluble nutrient loading is being modelled as the initial step towards the development of an overall flexible IMTA model. The extrapolation of a mass balance approach using bioenergetics is being juxtaposed with modern measures of ecosystem health such as exergy. Over eight years, none of the therapeutants used in salmon aquaculture have been detected in kelps and mussels collected from the IMTA sites; levels of heavy metals, arsenic, PCBs and pesticides have always been below Canadian Food Inspection Agency, USA Food and Drug Administration, and European Community Directive regulatory limits. A taste test at market size conducted on site grown versus reference mussels showed no discernable difference (Lander *et al.*, 2004). *Alexandrium fundyense*, the dinoflagellate responsible for producing paralytic shellfish poisoning (PSP) toxins, occurs annually in the Bay of Fundy and mussels can accumulate these toxins above regulatory limits in the summer/early fall. However, PSP toxins concentrations in mussels decreased readily as the blooms of *Alexandrium fundyense* diminished. Domoic acid, released by the diatom *Pseudo-nitzschia pseudodelicatissima*, was never above regulatory limits over the eight years. All of these results indicate that, with the proper monitoring and management, mussels and seaweeds from the IMTA operations can be safely harvested as seafood for human consumption (Haya *et al.*, 2004).

Two attitudinal studies towards salmon farming in general, and IMTA in particular, were conducted (Ridler *et al.*, 2007). The first survey found that the general public is more negative towards current monoculture practices and feels positive that IMTA would be successful (Robinson *et al.*, in press). The second attitudinal survey, a focus group study (Barrington *et al.*, 2008), showed that most participants felt that IMTA has the potential to reduce the environmental impacts of salmon farming (65 percent), improve waste management in aquaculture (100 percent), benefit community economies (96 percent) and employment opportunities (91 percent), and improve food production (100 percent), and the industry competitiveness (96 percent) and overall sustainability (73 percent). All felt that seafood produced in IMTA systems would be safe to eat and 50 percent were willing to pay 10 percent more for these products if labelled as such, which open the door to developing markets for differentiated premium IMTA products, either environmentally labelled or organically certified.

Preliminary data of a bio-economic model (Ridler *et al.*, 2007), in which net present value (NPV) calculations are conducted over 10 years to portray long-term variability, show that the addition of seaweed and mussel to salmon farming is more profitable and helps reduce risks through diversification. The project is now scaling up the experimental systems and working on an appropriate food safety regulatory and policy framework for the development of commercial scale IMTA operations with its two industrial partners, Cooke Aquaculture Inc. and Acadian Seaplants Limited. Presently, five amended salmon sites of Cooke Aquaculture Inc. are reaching commercial scale development for both seaweeds and mussels.

Site selection for the best compromise between site characteristics, species selection, and markets demands will be key to optimizing these IMTA operations. Further scaling-up of cultivation systems (seaweed and mussel rafts), species diversification, economic analysis and development of niche markets will be implemented. Scaling-up to commercial level will also allow the investigation into the impacts of IMTA on the carrying capacity of the coastal environment, water and benthos quality, potential for disease transfer, and animal and plant health at a realistically large scale to validate the early assumptions developed, and results obtained, through modelling with Monte Carlo simulations (Reid *et al.*, in press).

There have been concerns that co-cultured organisms, such as shellfish and seaweeds, could be "reservoirs" for diseases affecting fish. Interestingly, a recent study by Skar and Mortensen (2007) and our own unpublished data indicate that carefully chosen additional species in an IMTA setting have the potential for some disease control. Mussels (*Mytilus edulis*) are capable of reducing loads of the infectious salmon anaemia virus (ISAV) in the water. The mechanism is not yet completely elucidated; however, there is, consequently, the potential that appropriately placed mussels around salmon cages could act as a possible biofilter for disease reduction or prevention. All the possible interactions between co-cultured species have certainly not all been investigated, but what was initially perceived as a potentially problematic situation is now regarded as an unexpected positive interaction.

Concurrent with the positive results of the IMTA system on the east coast, a project concerning the feasibility of finfish-shellfish-seaweed culture has recently gotten underway on the west coast, in the waters of British Columbia (BC) off Vancouver Island (Cross, 2004a, b). Beginning in 2006, researchers plan to assess whether growing a range of species – including shellfish (mussels, oysters and scallops), kelps (*Saccharina latissima*), sea cucumbers, and sea urchins – can help reducing the environmental impacts of salmon and sablefish (or black cod, *Anoplopoma fimbria*) farming (S. Cross, pers. comm.). This work has been inspired by earlier preliminary investigations into the culture of Pacific oyster, *Crassostrea gigas*, with Chinook salmon, *Oncorhynchus tshawytscha*, on the BC coast. Jones and Iwama (1991) found that oysters grew three times the amount in shell height and growth rate when integrated with salmon farms than at reference sites. This increase in weight and growth of the co-cultured species is a positive side effect and holds obvious economic benefit for farmers.

The future of Canadian aquaculture is currently at a crossroad. Important to consider is Canada's historical dependence on traditional fisheries and the impact that the cod moratorium made on the cultural landscape, particularly in Newfoundland (Schrank, 2005). The East coast of Canada seems ripe for aquaculture development as the region struggles with high unemployment: 13.2 percent in Newfoundland and Labrador, 11.2 percent in Prince Edward Island, 8.0 percent in Nova Scotia and 7.2 percent in New Brunswick, whereas the national unemployment rate was at 5.9 percent in November 2007 (Statistics Canada, 2007). On the West coast of Canada, the salmon industry encounters environmental NGO's opposition (Hamouda *et al.*, 2005). The unique ability of IMTA systems to encourage sustainable aquaculture should be considered as a valuable tool when managing Canadian aquaculture. While aquaculture is developing on the East coast (particularly in Newfoundland), IMTA systems should be used to prevent potential environmental damage as this important employment area is growing; similarly, IMTA systems should be used on the West coast to mitigate environmental damage and to help quell public opposition.

Aquaculture can be a valuable socio-economic tool, particularly in the coastal communities of the provinces of New Brunswick, Nova Scotia, Prince Edward Island and Newfoundland and Labrador. These provinces have all been traditionally tied to the fishing industry. As wild capture fisheries are becoming less profitable and stocks dwindle, aquaculture can be a means by which people can maintain their cultural identities as folk who live off the sea. This industry has the potential to limit out-migration by providing jobs directly and indirectly related to the marine industry sector. A preliminary economic scenario for the New Brunswick side of the Bay of Fundy showed that IMTA could provide CDN$44.6 million in extra revenue and 207 new jobs in a sector presently worth CDN$223 million and already employing 1683 people directly and 1322 indirectly (Chopin and Bastarache, 2004; Chopin *et al.*, 2008).

United States of America

In 2004, the United States produced 221 717 tonnes of shellfish, 16 489 tonnes of fish and 4 731 tonnes of shrimp, with a respective value of US$164 352 000, US$62 867 000 and US$20 958 000 (Table 1). In the Northern United States, culture of mussels and salmon are common, while in the Southern United States culture of shrimp is more suited to the warmer climate. Like most aquaculture operations in North America, the majority of the culture units are intense monocultures.

Interest in IMTA has been primarily fuelled in the United States as a means of treating the wastewater from intensive culture of shrimp. Sandifer and Hopkins (1996) outlined a method of farming shrimp with herbivorous mullet and oyster, whereby the mullet and oyster feed on the wastewater of cultured shrimp, thereby acting as biofilters and recycling feeders. The researchers designed their IMTA system so that the solid removal from the shrimp effluent would be enhanced and deposition would also be reduced, while cultivating two other valuable species – oyster and mullet. Although this is currently a land based system, the authors have suggested that this system could be utilized in estuarine areas in the Southern United States (e.g. South Carolina to Texas). This model should be considered by shrimp farmers when managing their farm.

More recently, researchers in the American Northeast have been investigating the potential of the red alga *Porphyra* (also known as nori) to be used in integrated finfish-algal aquaculture system. Carmona, Kraemer and Yarish (2006) studied six species of *Porphyra* (*P. amplissima, P. purpurea, P. umbilicalis, P. haitanensis, P. katada* and *P. yezoensis*) and concluded that *P. amplissima, P. purpurea* and *P. umbilicalis* were excellent candidates as bioremediators in IMTA systems. These species are all native to coastal waters of the NE United States (e.g. Maine to Massachusetts) and should therefore be considered excellent candidates for integration with existing salmon or mussel farms or in land-based facilities with flounder or cod (project between the University of New Hampshire and Great Bay Aquaculture, LLC; C. Neefus, pers. comm.).

Chopin *et al.* (1999) stated that the culture of *Porphyra* in the Gulf of Maine and Bay of Fundy (the Atlantic Coast of the United States and Canada) may be limited by low levels of inorganic nutrients in the water. However, if this alga was grown in an integrated system with finfish for example, this problem may be mitigated. If the production of *Porphyra* is to expand from Asian waters to other countries such as Canada and the United States, IMTA systems may have to be employed in order to meet the biological demands of the seaweeds. This effort may be well rewarded if a niche can be found in the sushi-market, where profit returns can be high. Referring to Table 2, the value of the nori market was worth US$1.34 billion in 2004 (Chopin and Sawhney, 2009). The market for all edible seaweeds in North America is estimated at US$35 million.

The company Söliv International, a manufacturer of skin care products, has developed a land-based IMTA system in collaboration with the University of Washington in Seattle (Dr. Robert Waaland). Situated in Manchester, Washington State, they are cultivating the red alga *Chondracanthus exasperatus* (also known as Turkish towel) in tanks receiving seawater from Pacific halibut (*Hippoglossus stenolepsis*) and black cod (*Anoplopoma fimbria*) culture tanks. *Chondracanthus exasperatus*, with a maximal production of 725 kg wet weight per month, is used in formulations of cosmetic products.

Big Island Abalone Corporation, a tenant at the Natural Energy Laboratory of Hawaii Authority (NELHA), commercially produces Kona Coast Abalone™ (Japanese Northern Ezo abalone, *Haliotis discus hannai*) fed with patented red algae believed to be derived from a strain of Pacific dulse (*Palmaria mollis*). Each month, the 10-acre aquafarm grows, in large tanks, 70 tonnes wet weight of the red algae needed to produce 8 tonnes wet weight of abalone, which are shipped live to Japan, Hawaii and mainland United States. The Kona Coast of Hawaii's Big Island was chosen because

TABLE 2
Main components of the world's seaweed industry and their value (in US$) for 2004

Industry component	Raw material (wet tonnes)	Products (tonnes)	Value (US$)
Sea-vegetables	8.59 million	1.42 million	5.29 billion
Kombu (*Laminaria)*	4.52 million	1.08 million	2.75 billion
Nori (*Porphyra*)	1.40 million	141 556	1.34 billion
Wakame (*Undaria*)	2.52 million	166 320	1.02 billion
Phycocolloids	1.26 million	70 630	650 million
Carrageenans	528 000	33 000	300 million
Alginates	600 000	30 000	213 million
Agars	127 167	7 630	137 million
Phycosupplements	1.22 million	242 600	53 million
Soil additives	1.10 million	220 000	30 million
Agrichemicals (fertilizers, biostimulants)	20 000	2 000	10 million
Animal feeds (supplements, ingredients)	100 000	20 000	10 million
Pharmaceuticals, nutraceuticals, botanicals, cosmeceuticals, pigments, bioactive compounds, antiviral agents, brewing, etc.	3 000	600	3 million

Source: Chopin and Sawhney (2009).

it receives more sunlight per year than any other coastal location in the United States; secondly, through NELHA's deepwater pipe, Big Island Abalone Corporation has access to a constant supply of cold, nutrient-rich seawater, pumped from a depth of around 900 m in the Pacific Ocean. Lastly, Hawaii's location, midway between Asia and North America, enables the company to ship fresh, live abalone to markets on both continents.

Buttner and Leavitt (2003) reported an interesting study undertaken with lobster fishers along the Massachusetts coast, where lobster fishing was integrated with oyster cultivation. By modifying traditional lobster traps to incorporate trays for eastern oysters (*Crassostrea virginica*) the authors found that oysters could survive, grow, and augment the income of lobster fishers without affecting lobster captures rates. This pilot project promoted acceptance of aquaculture among commercial fishers, local communities, and regulatory agencies in the region. The authors also felt that this idea could easily be adapted to other bivalve species. This concept of lobster-bivalve co-culture is an interesting adaptation of the IMTA concept and illustrates the flexibility of the concept to suit particular communities' resources and needs, although, in this particular case, the nutrient capture and retention are minimal.

South America

Chile

The culture of salmon is widespread along the entire coastline of Chile's Region X and moving rapidly to Region XI. Chile is one of the world leaders in production of farmed salmon. In 2005, the value of exported farmed salmon was near US$ 2 million and production has nearly doubled since 2000 (FAO, 2006a). Chile ranks among the top ten aquaculture producers in the world, and produces 4 percent of the global aquaculture value (US$2.82 billion) (FAO, 2006a). In 2004, Chile produced 564 298 tonnes of fish, 96 922 tonnes of shellfish and 19 714 tonnes of seaweed, with a respective value of US$2 386 548 000, US$340 119 000 and US$13 800 000 (Table 1).

Species of finfish being commercially cultivated include *Salmo salar*, *Oncorhynchus mykiss*, *Oncorhynchus tschawytscha*, *Oncorhynchus masou*, *Oncorhynchus kisutch* and *Scophthalmus maximus* (Buschmann *et al.*, 1996). The three most economically important salmonids are *Salmo salar*, *Oncorhynchus kisutch* and *Oncorhynchus mykiss*. Besides the culture of salmon, monocultures of mussels (*Mytilus chilensis* and *Choromytilus chorus*), scallops (*Argopecten purpuratus*) and oysters (*Tiostrea chilensis* and *Crassostrea gigas*) are commonplace (Buschmann *et al.*, 1996).

There is much potential for a seaweed culture industry in Chile. The algae *Gracilaria chilensis*, *Gigartina skottsbergii*, *Sarcothalia crispata*, *Porphyra columbina*, *Callophyllis variegata*, *Chondracanthus chamissoi*, *Lessonia trabeculata*, *Lessonia nigrescens*, *Macrocystis pyrifera* and *Durvillaea antarctica* are commonly grown and collected in Chile (Buschmann *et al.*, 2001; 2005; 2006). To date, *Gracilaria chilensis* is the only species cultured on a commercial level (Buschmann *et al.*, 2005; 2006).

With the strong intensification trend of salmon aquaculture in Region X and further salmon sites expansion in Region XI, and following the tendencies in northern hemispheric countries, there have been increasing concerns about potential cumulative environmental impacts since the second half of the 1990's (Soto and Norambuena, 2004; Leon, 2006). Some authors have stressed the need to adopt integrated management measures to control these impacts, highlighting the relevance of maintaining a balance between further aquaculture development and environmental conservation through the development of IMTA systems (Buschmann *et al.*, 2006). The recent confirmation of the presence and spreading of the ISA virus in Chile should be seen as a warning signal for overstocked salmon monocultures.

IMTA started in the late 1980's in Chile, but is still fairly small. The first attempt considered the development of land-based intensive marine systems using pumped seawater to intensively culture trout (*Oncorhynchus mykiss*). The fish effluents were then used for the cultivation first of oyster (*Crassostrea gigas*) and second of the agar producing alga *Gracilaria chilensis*, which both were able to significantly reduce nitrogen and phosphorus. The first trials were successful and demonstrated that an IMTA approach was an additional way for developing a more sustainable aquaculture approach. It now consists of seaweed-finfish culture sites, where the algae *Gracilaria chilensis* and *Macrocystis pyrifera* are co-cultivated with salmon (Troell *et al.*, 1997). IMTA units are promising as thus far research has shown that biomass productivity of *Gracilaria chilensis* increased by 30 percent when grown with salmon, and it also has a higher agar quality (Buschmann *et al.*, 2005). Currently cultivated *Gracilaria* is used as feed for abalone and for the extraction of agar. Other algae that are economically valuable include *Ulva* and *Macrocystis*, from which organic fertilizers are being developed at a commercial level (Buschmann *et al.*, 2005). These species hold promise for further development and could also be used in IMTA systems due to their economic value (Table 3), established market niche, and suitability for growth in the climate.

TABLE 3
Profitability analysis using the net present value (NPV in US$) and internal rate of return (IRR in percent) of a culture system simulating three different net salmon productions (200, 400, 600 tonnes) and four different fish stocking densities (15, 30, 45, 60 kg/m³), in three scenarios: a) without internalizing the total environmental costs, b) considering the internalization of the total environmental costs, and c) considering the internalization of the total environmental costs reduced by the nutrient scrubbing capacity of *Gracilaria chilensis* and its conversion into another commercial marine crop (n.p. = no profit)

Fish net production (kg/m³)	Fish stocking density (tonnes)	NPV (US$)			IRR (%)		
		a	b	c	a	b	c
200	15	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.
	30	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.
	45	455 692	n.p.	39 982	24.1	n.p.	15.8
	60	685 939	n.p.	270 230	30.0	n.p.	20.8
400	15	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.
	30	814 852	n.p.	n.p.	21.9	n.p.	n.p.
	45	1 965 197	n.p.	1 133 772	34.3	n.p.	25.7
	60	2 498 356	339 186	1 666 931	42.2	19.2	32.2
600	15	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.
	30	2 065 330	n.p.	818 195	26.2	n.p.	19.4
	45	3 743 201	505 167	2 496 785	40.0	18.6	30.3
	60	4 569 269	1 330 517	3 322 135	47.8	25.4	37.5

Source: Chopin *et al.* (2001).

IMTA sites have remained at a small scale level, primarily because the explosive growth of salmon aquaculture prevented the adoption of alternative farming strategies, like IMTA, as the industry had no immediate incentive to modify a very successful financial story. It has not been easy to adopt an IMTA approach in Chile. Like oriental countries, Chile has a long tradition of shellfish and seaweed consumption; however, the price for these goods is very low, therefore, they cannot be suggested as an interesting business for investors. To encourage the farming of these organisms, novel uses of seaweeds are being developed (A. Buschmann, pers. comm.). Present licensing regulations also offer no incentives for the adoption of IMTA practices, especially as it does not encourage partnership between site owners involved in producing different crops, or their association within one site. It is unlikely that the owner of a large intensive salmon farm will invest and make the effort of growing seaweeds and mussels unless regulations would stipulate that the implementation of IMTA practices would allow to increase the number of fish being raised at the site or would lower penalties related to environmental effects levied by the authorities. Most parameters monitored for the environmental assessment of salmon farming focused on the state of the bottom under the cages and ignored issues encountered in the water column and watershed (e.g. nutrients), where IMTA could have a significant effect. If regulations were to address concerns of cumulative impacts and eutrophication at larger scale (fjords, channels, or whole bays), instead of focusing on local bottom effects, farmers would then become more inclined to adopt IMTA, especially if the implementation of such practices can be associated with recognition through certification systems or eco-labelling.

Other IMTA initiatives, both at freshwater and marine aquaculture sites, have been experimentally pursued. For example, the use of artificial reefs around and below salmon cages to enhance ecosystem restoration and to increase the production of crabs and other fish have been attempted (Soto and Mena, 1999; Soto and Jara, 2007).

An interesting situation has emerged in southern Chile with the recent development of mussel (*Mytilus chilensis*) cultivation. Mussel long lines can now be found between salmon cages in channels and fjords due to space limitations in the region. The decisions regarding the design and location of sites were, however, not based on scientific data for prevailing currents, suspended matter and nutrient circulation, oxygen availability, etc. and the IMTA concept was not explicitly considered, despite the fact that it has been documented that natural mussel beds near salmon farms can utilize these nutrients and particulate matter (Soto and Jara, 2007). Better pre-planning of these coastal zones, by inclusion of the IMTA principles, would represent much better management practices.

The development of abalone cultivation is presently emerging in Chile, adding an extra pressure on natural resources of seaweeds as a source of feed. A pilot scale farm (4-5 ha) is already producing the brown alga *Macrocystis pyrifera* and has demonstrated its technical and economic feasibility. Linking salmon aquaculture (the source of nutrients for seaweeds) with seaweed aquaculture (the source of food for abalone) and abalone aquaculture (the final recipient of the food and energy passed along) could represent another interesting IMTA system.

One potential problem with the integrated culture of seaweed-salmon farms is the spread of the invasive species *Codium fragile* ssp. *tomentosoides*. This invasive alga competes for nutrients with *Gracilaria* (Neill *et al.*, 2006), which could reduce biomass and agar quality. The spread of this alga needs to be monitored and controlled if possible to prevent losses to the industry.

The development of IMTA systems in Chile should be a high priority with the government and industry officials. Due to the high production volumes and rapid expansion of the salmon culture industry (FAO, 2006a), the risk of environmental degradation is high if salmon effluents are not managed and mitigated. IMTA systems can help prevent environmental degradation, while supporting an industry with high employment potential, which is an important socio-economic issue in a country that seeks to reduce unemployment. The possibility of allowing small shellfish and seaweed farmers to couple their efforts with large salmon farmers is an option which remains mostly unexplored, but which should help spreading the benefits of aquaculture to all stakeholders within a more ecosystemic perspective.

Europe

Spain and Portugal

In 2004, mariculture in Spain produced 236 708 tonnes of molluscs and 23 452 tonnes of fish, with a respective value of US$97 346 000 and US$144 974 000 (Table 1). Mariculture in Portugal produced 3 194 tonnes of fish and 2 681 tonnes of molluscs, with a respective value of US$21 830 000 and US$12 978 000 (Table 1).

IMTA research along the Atlantic coast of the Iberian Peninsula is primarily focussed on using algae (mainly Rhodophyta) with fish (mainly turbot, *Scophthalmus maximus*, and sea bass, *Dicentrarchus labrax*).

Of the seaweeds, much research is being done regarding the use of *Gracilaria bursa pastoris*, *Chondrus crispus*, *Palmaria palmata* (Matos *et al.*, 2006; Martínez *et al.*, 2006), *Porphyra dioica* (Pereira, Yarish and Sousa-Pinto, 2006), *Asparagopsis armata* (Mata *et al.*, 2006; Schuenhoff, Mata and Santos, 2006), *Gracilariopsis longissima* (Hernández *et al.*, 2006), *Ulva rotundata, Ulva intestinalis* and *Gracilaria gracilis* (Martínez-Aragon *et al.*, 2002; Hernández *et al.*, 2002) as biofilters for use in IMTA units.

All these authors show that many of these macroalgal species are excellent candidates for biofilters and wastewater effluent mitigation: all these species have excellent growth rates, photosynthetic rates and inorganic nutrient removal rates – all characteristics which make for good candidates in IMTA units – growth rates being important for biomass production and increased profit; photosynthetic rates being interesting for increasing the availability of oxygen at aquaculture sites; inorganic nutrient removal rates being important for effluent mitigation.

Using this knowledge, researchers have begun experimental studies where algae have been integrated with sea bass and turbot. Matos *et al.* (2006) found that of the three species tested (*Gracilaria bursa pastoris, Chondrus crispus* and *Palmaria palmata*) *Gracilaria bursa pastoris* had better yields and higher N uptake efficiency and was thus recommended as the best candidate for integration with sea bass or turbot. *Ulva rotundata*, *Ulva intestinalis* and *Gracilaria gracilis* have been co-cultivated with sea bass and found to be efficient biofilters of phosphates (PO_4^{3-}) (Martínez-Aragon *et al.*, 2002) and ammonium (NH_4^+) (Hernández *et al.*, 2002) from the wastewaters.

Borges *et al.* (2005) investigated a small scale IMTA unit of fish (sea bass, *Dicentrarchus labrax*, and turbot, *Scophthalmus maximus*), clams (*Tapes decussatus*) and three microalgal species (*Isochrysis galbana, Tetraselmis suecica* and *Phaeodactylum tricornutum*). Their purpose was to determine if the microalgal species could be efficiently reared from the effluents from the fish, which would be ultimately fed to clams in a shellfish culture unit. The authors found that all three algal species grew well in the effluent, and that the algae contributed to effluent purification while contributing to extra income at no increased cost. The microalgae all reduced the amount of NH_4^+, NO_{3-} and PO_4^{3-} from the effluent. The resulting microalgal production was designed to be either sold or fed to shellfish as supplemental feed. The study estimated that the algal system would produce enough food to feed 1 000 to 2 000 clams per day.

Once the algae are harvested, farmers have many options on how to use their additional product. One of the areas already mentioned is the use as food supplements for other cultured species such as fish and shellfish. Valente *et al.* (2006) investigated the potential for *Gracilaria bursa pastoris, Gracilaria cornea* and *Ulva rigida* as dietary ingredients for juvenile sea bass (*Dicentrarchus labrax*). The authors found that *Gracilaria bursa pastoris* and *Ulva rigida* could contribute up to 10 percent, and

Gracilaria cornea up to 5 percent, of the diet for juvenile sea bass, thus providing another use for macroalgae grown in IMTA systems in Portuguese waters.

France

In 2004, mariculture in France produced 208 535 tonnes of shellfish, 7 653 tonnes of fish and 37 tonnes of seaweeds, with respective values of US$506 672 000, US$71 183 000 and US$16 000 (Table 1). Most aquaculture units in France are intensive monocultures. The majority of the work on IMTA systems in France is concerned with the use of marine ponds to treat fish effluents, and all are at the experimental stage. More specifically, researchers (Pagand *et al.*, 2000; Metaxa *et al.*, 2006) are investigating the use of high rate algal ponds (HRAP) to treat sea bass (*Dicentrarchus labrax*) effluents and other researchers (Lefebvre, Barillé and Clerc, 2000) are investigating the use of oysters to treat sea bass effluent in a research initiative known as the European Genesis project.

Metaxa *et al.* (2006) found that when *Ulva* and *Cladophora* were used in HRAP the wastewater had significant reductions in the dissolved inorganic N and P. The authors also noted that the algae had no effect on fish growth. An important observation made by these researchers is that the uptake of N and P by the algae was greater in summer than winter; therefore farmers should consider seasonal effects on algal growth conditions and water effluent treatment in integrated units.

Pagand *et al.* (2000) found that when Ulva (as *Ulva* and *Enteromorpha*) was used in HRAP the wastewater effluent had higher levels of dissolved oxygen and lower concentrations of nutrients and suspended solids than the water in reference tanks. No toxic algae were observed, and, as in the previous study, the authors noticed a profound seasonal effect on algal growth and production.

Oysters are actively cultured in France, particularly in the Marennes-Oléron Bay. To assess the suitability of oysters to IMTA systems, Lefebvre, Barillé and Clerc (2000) investigated the ability of oyster (*Crassostrea gigas*) to clean sea bass (*Dicentrarchus labrax*) effluent. The authors found that *Crassostrea gigas* has the ability to feed on the detritus/waste of the fish farm effluent. This is one way that farmers can recapture the lost organic product of intensive fish farming, and grow another economically valuable species.

Although these studies are pond or tank based, they are all relevant to the marine-based aquaculture systems in coastal waters of France, specifically the aquaculture of sea bass. Therefore their importance to the development of IMTA systems, particularly the benefits of integrating macroalgae and oysters, in coastal waters should be justly noted.

United Kingdom of Great Britain and Ireland

Aquaculture in the United Kingdom (essentially Scotland's west coast) and Ireland primarily consists of monoculture units, with emphasis on salmonids and mussels. In Western Europe, the United Kingdom is second to Norway in aquaculture growth and makes up 17 percent of the region's salmon production (FAO, 2006a). In 2004, the United Kingdom produced 160 319 tonnes of fish and 32 500 tonnes of shellfish, with respective values of US$483 873 000 and US$64 278 000 (Table 1). Ireland produced 43 092 tonnes of shellfish and 14 374 tonnes of fish, with respective values of US$53 423 000 and US$65 007 000 (Table 1). There is some research on IMTA in Scottish and Irish waters.

The growth and production of mussels (*Mytilus edulis*) with salmon (*Salmo salar*) in Scottish sea lochs was investigated by Stirling and Okumuş (1995). They found that mussels integrated with salmon had higher growth rates and had less depleted tissue reserves over the winter than those grown without salmon. This study suggests that mussels can be integrated with salmon in Scottish waters for increased economic viability.

More recently, researchers at the Scottish Association for Marine Science (SAMS), in Oban, have been working with the salmon companies Loch Duart Limited and West Minch Salmon, as well as with the mussel producer Loch Beag, to initiate pilot projects investigating the potential for IMTA along Scotland's west coast (M. Kelly, pers. comm.). Currently, there are several projects underway. These include: integration of Atlantic salmon, *Salmo salar*, with the sea urchins, *Psammechinus miliaris* and *Paracentrotus lividus*, and the seaweeds, *Palmaria palmata, Laminaria digitata, Laminaria hyperborea, Saccharina latissima* and *Sacchoriza polyschides*; integration of organically farmed salmon with the oyster, *Crassostrea gigas*, and the king scallop *Pecten maximus*; and co-cultivation of the sea urchin *Paracentrotus lividus* and the mussel *Mytilus edulis* (M. Kelly, pers. comm.). Results thus far are encouraging. Both sea urchin species are growing well next to salmon, and seaweed performance is positive, but varies according to species and site hydrography (M. Kelly, pers. comm.). Research using stable isotopes with *Palmaria palmata* shows that this species can utilise dissolved nitrogen of salmon farm origin. The current challenges facing IMTA in Scotland are primarily economical, as new market routes for the co-products (e.g. sea urchins) remain to be established (M. Kelly, pers. comm.). However, with the full support of industry and co-operative efforts of academic researchers and government, these hurdles should soon be overcome. The regulatory framework, as it relates to IMTA, also remains to be tested in Scotland.

Aquaculture, both mono-specific and integrated, is currently underway in Ireland. Irish farmers have taken advantage of the abundance of commercially viable seaweed. Kraan and Barrington (2005) report on the success of a commercially viable farm that cultivates *Asparagopsis armata* in County Galway. As shown by Schuenhoff, Mata and Santos (2006), *Asparagopsis armata* is an excellent biofilter of fish farm effluent and it also has high economic value when harvested for the antibiotic and cosmetic industry (Santos, 2006). Therefore, *Asparagopsis armata* should be considered an excellent species for integration with fish farms in the United Kingdom and Ireland.

Besides the commercial cultivation of *Asparagopsis armata*, there are three other seaweeds currently being farmed in Ireland: *Palmaria palmata, Alaria esculenta* and *Chondrus crispus*. There are also monoculture sites growing cod (*Gadus morhua*), salmon (*Salmo salar*), oysters (*Crassostrea gigas*) and mussels (*Mytilus edulis*), which, due to the intensity of the operations, are nearing carrying capacity at their current locations (S. Kraan, pers. comm.). Moreover, some of these species (e.g. mussels and seaweeds) are already being cultured, albeit independently, in the same bay (Roaring Water Bay, County Cork). Consequently, Ireland seems ready for IMTA and it should only be a small step to integrate these existing systems, once consensus is reached between industry officials and state agencies (S. Kraan, pers. comm.). Researchers at the Irish Seaweed Centre (ISC) at the National University of Ireland, Galway, have recently been meeting with fishers' groups in County Kerry. Since the banning of salmon drift net fishing in 2007, the fishers have been looking to supplement their income. In consultation with the ISC, they were planning on establishing an IMTA operation incorporating seaweed with mussel and scallop farms in Bantry Bay and Brandon Bay, Co. Kerry, in 2007, with the possibility of expanding into cod and sea bass operations in 2008.

The ISC, in conjunction with 2 commercial companies and a state agency are currently planning a large project in Bantry Bay, which was scheduled to start in late 2007 (S. Kraan, pers. comm.). This IMTA system will integrate 4 different species on 3 different trophic levels (2 algal species, shellfish and finfish). *Laminaria digitata* will be integrated into a salmon farm. This kelp will then be used as feed for an abalone farm in which *Porphyra* sp. will be grown with the abalone effluent. *Porphyra* will be used as a back up supply for feeding abalone when access to the kelp farm is restricted due to weather conditions. Excess *Porphyra* will be used for other commercial purposes and for experimental feed design for farmed finfish, possibly salmon in the proposed IMTA system. In this integrated-looped system, the macroalgae are internalized food sources for shellfish and finfish, while simultaneously acting as effluent biomitigators, increasing the sustainability of the entire operation.

Norway, Sweden and Finland

Much like in the United Kingdom, aquaculture in the Scandinavian countries of Norway, Sweden and Finland is largely focussed on monocultures of salmonids and mussels. A review of the existing literature shows that there are no commercial harvests of cultured seaweed in these countries, nor are there any commercial IMTA systems.

Norway is by far the leader in salmon aquaculture in Europe, producing 71 percent of the region's Atlantic salmon (FAO, 2006a). The Norwegian aquaculture industry produces large amounts of salmon and rainbow trout, to a lesser extent cod, halibut, turbot and eel, and shellfish – mussels, oysters and scallops (Maroni, 2000). In 2004, Norway produced 632 985 tonnes of fish and 3 796 tonnes of shellfish, with a respective value of US$1 678 143 000 and US$2 746 000 (Table 1).

The Swedish and Finnish aquaculture industries are substantially smaller than that of Norway. The Swedish aquaculture industry produces rainbow trout, salmon, eel, arctic char, blue mussel and crayfish (Ackefors, 2000). The Finnish aquaculture industry produces primarily rainbow trout and salmon (Varjopuro *et al.*, 2000). In 2004, Sweden produced 1 435 tonnes of shellfish and 1 316 tonnes of fish, with a respective value of US$794 000 and US$4 871 000 (Table 1). Finland produced 10 586 tonnes of fish, with a value of US$40 406 000 (Table 1).

These countries, especially Norway, experienced a large boom in salmon and trout monoculture in the late 1980's and throughout the 1990's (Maroni, 2000). As a result of this rapid and largely unchecked expansion, disease and parasite outbreaks were common. To help control this situation the government began to strictly control the salmon culture industry and as a result have some of the most detailed records of farm activity in the world (Maroni, 2000). Licence applications have strict outlines and environmental monitoring programs are in place.

With such stringent industry control on environmental monitoring, and the large volume of monocultured fish, Norway could be an excellent candidate for IMTA systems. The biofiltration ability of seaweeds, along with the presently cultured shellfish species, would aid in meeting the government mandate towards environmentally sustainable farming. While Norway has a long history of seaweed harvesting (especially of kelps for alginates), there is no commercial seaweed culture in Norway. Many economically valuable species exist in Scandinavian waters (e.g. *Laminaria, Saccharina, Porphyra, Gracilaria, Palmaria, Chondrus*, etc.) and it would be interesting to integrate these species with salmon farms to help aquaculture become more sustainable.

The availability of resources for fish feed, suitable locations in the coastal zone, pathogen control and environmental impacts have all been regarded as possible constraints for the continued growth of the Norwegian salmon aquaculture industry (K. Reitan, pers. comm.). While Norway has aimed to produce 2.5 million tonnes of farmed salmon by 2030, researchers and industry are aware that these constraints must be addressed in order for their industry to maintain a high level of production and quality.

To help deal with these constraints, Norwegian researchers have initiated two projects. The first project is currently investigating possible pathogen transfer between blue mussels and salmon (Skar and Mortensen, 2007). The second project is a 5-year (2006-2010) pilot IMTA project. In this project, researchers are investigating which technologies are best used to determine site and species appropriateness, as well as which apparatus are best for the growth and harvest of alternate species. Currently, researchers have integrated blue mussels at salmon farms, and are planning to expand into seaweeds such as *Laminaria* and *Gracilaria* at these sites (K. Reitan, pers. comm.).

Investigators have highlighted two main points that require improvement to ensure the success of IMTA in this region: the adaptation of technology for growth of the alternate species (i.e. mussels and seaweeds), and the reduction of labour intensive activities, particularly during harvesting (K. Reitan, pers. comm). Improvements in both these areas will ensure economic efficiency of IMTA. Although at this point in time there is no commercial scale IMTA in Norway, it may only be a few years (after 2010) until researchers have developed the appropriate technology and systems to bring this practice to commercial scale. Regulations regarding distances between farms and types of organisms will also have to be revisited for their appropriateness vis à vis IMTA.

Southern Africa

South Africa

In 2004, South Africa produced 2 845 tonnes of seaweeds and 1 680 tonnes of shellfish, with respective values of US$1 252 000 and US$6 477 000 (Table 1). South African mariculture is focused on the abalone industry, particularly the Midas ear abalone, *Haliotis midae* (Bolton *et al.*, 2006), as well as on the Pacific oyster (*Crassostrea gigas*) in the Knysna region of the Cape and the Mediterranean mussel (*Mytilus galloprovincialis*) in the Saldahna Bay area. This industry has grown rapidly over the past ten years, expanding from Port Nolloth to Port Elizabeth along the west coast of the region where suitable rocky habitat exists (Troell *et al.*, 2006). However, a bottleneck for this rapidly expanding industry has been the availability of a consistent and convenient food source. Over 6 000 tonnes of kelp, *Ecklonia maxima*, are harvested annually on the South African west coast for abalone feed, and some kelp beds are now reaching sustainable limits of exploitation. As a result, *Ecklonia maxima* has been the subject of a parallel aquaculture industry with many systems now developed as integrated abalone-kelp culture units (Troell *et al.*, 2006). This kelp is grown alongside the abalone and is harvested as a food source for the molluscs. This on-land integrated culture unit, with shallow raceways, is widely viewed as the preferred method of production for the abalone industry, and the way of the future for the industry (Bolton *et al.*, 2006). A growing body of evidence suggests that a mixed diet of kelps and other seaweeds can induce growth rates at least as good as with artificial feed, can improve abalone quality and reduce parasite loads. Seaweeds grown in abalone wastewater have an increased nitrogen content, resulting in value-added seaweeds with over 40 percent protein dry weight content and, hence, of excellent quality to feed abalone.

According to Bolton *et al.* (2006), besides *Ecklonia maxima*, *Ulva* has also been grown in integrated culture units with abalone. However, when the abalones were fed a diet of *Ulva*, an off-taste and sulphur-like smell was observed in the canned abalone, thus decreasing market value. It is known that *Ulva* can increase the levels of dimethyl sulphide in abalone; therefore it is not the preferred feed choice. This off taste in abalone has not been observed in *Ecklonia maxima* fed abalone. Farmers should thus consider the effects of taste the various seaweed species may have on their final shellfish products to avoid product depreciation.

Besides *Ulva* and *Ecklonia*, the seaweeds *Gelidium* and *Gracilaria* are both harvested from wild populations along the coast of South Africa (Troell *et al.*, 2006). These seaweeds could also be used as candidates for IMTA systems. The integrated cultivation of *Gracilaria* with salmon, and its economic value, have already been demonstrated in Chile (Buschmann *et al.*, 2001; 2005; 2006), making it an obvious choice for IMTA in any country where it exists naturally.

The general benefit from IMTA, i.e. reduction of nutrient release to the environment, is also true for integrated seaweed-abalone culture. Furthermore, as seaweeds remove ammonium from the seawater and add oxygen, the abalone wastewater passing through seaweed ponds can be partially re-circulated back to the abalone tanks, thus potentially reducing pumping costs. The ability to operate in re-circulation mode is important as red tides occasionally occur along the South African coast. Moreover, some coastal areas experience heavy traffic of tanker boats, which represent potential risks for oil spills. It has been shown that a farm can operate successfully at 50 percent re-circulation, and even higher recirculation (up to 100 percent) can be sustained for shorter periods. This can, of course, be optimized, depending on what the main objective is with re-circulation. The re-circulation through seaweed tanks/ponds also has the potential to raise water temperature, which can stimulate abalone growth in areas of cold coastal waters. Compared to many other aquaculture operations, there is currently no real environmental pressure from abalone wastewater release in South Africa. Wastes from abalone operations are different from those of fish, with significantly lower concentrations of both nitrogen and phosphorus. This implies that the seawater in the seaweed tanks needs to be fertilized to sustain seaweed growth. This additional input of nutrients would not be needed if seawater from fish tanks were to be used (this has been tested with success). The development of IMTA in South Africa has, in fact, been driven by other incentives, such as future limitation of wild kelp harvesting and the proven economic benefits from improved abalone growth and quality with seaweed diets.

There is also strong socio-economic pressure on the South African government to create more jobs in the area, which has high unemployment and poverty levels (Troell *et al.*, 2006). The further expansion and permanent job creation potential of this industry, as well as indirect related jobs, in remote coastal communities, is very attractive. Thus there is much support for this practice of co-cultivating kelp with abalone, from government, industry and the general population.

There may also be incentives to move IMTA concepts into the mussel growing industry in Saldahna Bay. Studies have shown that the large mussel culture rafts are impacting the benthos in the Bay, suggesting that stocking densities are too high for natural assimilation of the organic load to the bottom (Stenton-Dozey, Probyn and Busby, 2001).

Asia

China

The level of IMTA development in the marine temperate waters of China is not easy to apprehend, as published information on IMTA in that country is difficult to find or access. Describing the development of IMTA in China is really beyond the scope of this review; it would, however, deserve a review on its own, written by Chinese authors or by people with a rare and prolonged insight in the history of aquaculture in that vast country.

IMTA in China will be covered succinctly below by reporting on two examples of variations on this practice approach: suspended multi-species aquaculture, generally in shallow nearshore waters, and multi-species large scale sea ranching in more offshore and deeper waters (J. Fang, pers. comm.). The reader should note the large scale of these enterprises.

An example of suspended multi-species aquaculture is what is being developed in Sungo Bay, in the East of the Shandong Peninsula. Scallops (*Chlamys farreri*, 2 100 tonnes fresh weight in 2005) and oysters (*Crassostrea gigas*, 110 000 tonnes fresh weight) are cultivated, on the same long line system, with the kelp, *Laminaria japonica* (80 000 tonnes fresh weight). The cultivation zone extends to 8 km offshore with a water depth of around 20-30 m. The co-cultivation of abalone (*Haliotis discus hannai*, 1 000 tonnes fresh weight) with *L. japonica* is also being developed, with abalones kept in lantern nets hanging vertically from the long lines, while kelps are grown on ropes maintained horizontally between long lines so that the abalones can feed on the kelps by manual feeding. Once the kelps have been harvested, the abalones are fed with dried kelps.

An example of multi-species large scale sea ranching is taking place near Zhangzidao Island, 40 miles offshore in the northern Yellow Sea (water depth from 10 to 40 m). Sea ranching is usually practised for the enhancement of natural stocks, but the scale and intensity at which it is practised in some Chinese waters means, in fact, that one is really talking about aquaculture on natural substrates. The Zhangzidao Fishery Group Co., Ltd., is authorized to farm up to approximately 40 000 ha, and presently cultivates 26 500 ha of the scallop, *Patinopecten yessoensis*, 10 000 ha of the arkshell, *Scapharca broughtonii*, 660 ha of the sea cucumber, *Apostichopus japonicus*, and 100 ha of the abalone *Haliotis discus hannai.* The company has been in existence for more than 10 years. The total harvest in 2005 reached 28 000 tonnes, valued at more than US$60 million (US$18 million in net profit). To improve ecological conditions and the sustainability of the operation, the company is now thinking of developing seaweed cultivation and the construction of artificial reefs in more offshore environments. To date, about 13 300 ha have been optimized in this way.

MAJOR REQUIREMENTS FOR THE EXPANSION OF IMTA

In order to ensure the further development of IMTA systems in marine temperate waters, several steps should be taken to move IMTA from the experimental concept to the full commercial scale.

Establishing the economic value of IMTA systems and their co-products

One such requirement would be to ensure that the added elements (e.g. seaweeds, shellfish, echinoderms and polychaetes) to an already existing monoculture unit (e.g. fish farm) make the systems at least as profitable or even more. Several projects in different parts of the world, like those presented above, have now accumulated enough data and information to support the biological demonstration of the IMTA concept. The next step is the scaling up of the experimental systems to make the biological demonstration at a commercial scale, and to document the economic and social advantages of the concept, which will be key to convincing practitioners of mono-specific aquaculture to move towards IMTA practices.

IMTA farms should be planned and engineered as complete systems, rather than as clusters of different crops, to maximize the benefits of the complementing ecological functions of the different species toward the profitability of the entire operations. Economic analyses need to be inserted in the overall modelling of IMTA systems as they get closer to commercial scale and their economic impacts on coastal communities are better understood. It will, then, be possible to add profitability and economic impacts to the comparison of the environmental impacts between IMTA and monoculture settings. These models will need to be sensitized for the most volatile parameters and explicit assumptions so as to develop models for IMTA systems with built-in flexibility to be tailored to the environmental, economic and social particulars of the regions where they will be installed. They could be modified to estimate the impact of organic and other eco-labels, the value of biomitigation services, the savings due to multi-trophic conversion of feed and energy which would otherwise be lost, the reduction of risks by crop diversification and the increase in social acceptability of aquaculture (including food safety, food security and consumer attitudes towards buying sustainable seafood products).

An indirect effect of establishing the economic value of IMTA systems to a community will result in the increase stewardship of the coastal zone. Because the system has to work as a whole, there will be direct economic benefits flowing to the community for keeping the ecosystem healthy. In a practical sense, this means reviewing infrastructure projects from an environmental point of view will be important to the town's finances. The increased cost of monitoring and management should be more than made up by the returns from the local IMTA industry with their increased value in food quality and safety.

Developing bio-economic models for IMTA systems

Chopin *et al.* (2001) demonstrated how integrating seaweeds (*Gracilaria*) with salmon farms can help increase profits while internalizing environmental costs. Assuming an average price for salmon of US$4.8 kg, Table 3 shows how salmon farm profits (at different production levels and stocking densities, based on Chilean fish farms) increase without internalizing the total environmental costs (scenario a) and present situation throughout the world). Assuming the costs of effluent mitigation are US$6.4 to 12.8/kg for nitrogen and US$2.6 to 3.8/kg for phosphorus (based on treatment costs in Swedish sewage treatment plants), scenario b) of Table 3 shows that, if laws or regulations were implemented to have aquaculture operations responsibly internalizing their environmental costs, a significant reduction of their profitability would occur. Scenario c) of Table 3 shows that by integrating the culture of the nutrient scrubber and commercial crop *Gracilaria* (at a conservative price of US$1 per kg [dry]), the environmental costs of waste discharges are significantly reduced and profitability is significantly increased. Although profitability in Table 4 is not as high as in Table 5 in the short term, it gains stability and sustainability for the culture system and reduced environmental and economic risk in the long term, which should make financing easier to obtain (Brzeski and Newkirk, 1997).

Another economic model using integrated salmon-mussel farms was developed by Whitmarsh, Cook and Black (2006) using base line data from farms on the west coast of Scotland. Table 5 shows that the NPV of a salmon-mussel IMTA system is greater than the combined NPV of salmon and mussel monoculture, assuming 20 percent greater production rate of mussels due to proximity to fish cages and a discount rate of 8 percent. Enhanced mussel productivity translates into a measurable financial benefit,

TABLE 4

Scenarios for salmon monoculture versus kelp/mussel/salmon IMTA in the Bay of Fundy, Canada. Ten year run NPV discounted at 5 percent and 10 percent (in US$)

Operation	Discount rate	Scenario 1 (optimistic)	Scenario 2 (worst case)	Scenario 3 (intermediate)
Salmon monoculture	NPV at 5 %	8 146 477	50 848	2 664 112
IMTA	NPV at 5 %	8 906 435	674 850	3 296 037
Salmon monoculture	NPV at 10 %	6 885 181	-228 345	2 391 135
IMTA	NPV at 10 %	7 508 913	403 579	3 014 866

Source: Ridler *et al.* (2007).

TABLE 5

Financial performance (in UK£) of salmon and mussel aquaculture, considered independently or in an IMTA system

Indicator	Salmon monoculture	Mussel monoculture	IMTA	Integration benefits
Normal production (tonnes per annum)	600	77	-	15.4
Price (UK£ per tonne)	1 900	1 100	-	-
Annualized equivalent cost (UK£ per tonne)	1 723	583	-	-
NPV (UK£)	922 114	353 328	1 425 685	150 243

Source: Whitmarsh, Cook and Black (2006).

TABLE 6
Net present value (NPV in UK£) of salmon/mussel IMTA investment: sensitivity to variations in mussel productivity enhancement and salmon price trends

Mussel productivity enhancement (percent)	Integration benefits (UK£)	Constant salmon price (UK£)	Salmon price falls at 1 % per annum (UK£)	Salmon price falls at 2 % per annum (UK£)
0	0	1 275 442	477 455	-242 795
10	75 121	1 350 564	552 577	-167 673
20	150 243	1 425 685	627 698	-92 552
30	225 364	1 500 807	702 820	-17 430

Source: Whitmarsh, Cook and Black (2006).

which can be recognized as a genuine "economy of integration". Table 6 describes the sensitivity of the NPV of IMTA under three different assumptions about salmon prices. Integration is economically profitable if the price of salmon remains constant or drops by 1 percent per annum; however, a drop of 2 percent per annum would result in a negative NPV for IMTA, making it a financially unattractive investment. It should be noted, however, that the non-viability of the aquaculture operation was due to the salmon prices rather than the value of the associated species, in this case mussels.

The IMTA project in the Bay of Fundy, Canada, is presently developing a bio-economic model (Ridler *et al.*, 2007). Economic estimates (with risk scenarios) have been undertaken comparing the profitability of a kelp/mussel/salmon IMTA system with salmon monoculture. Initially a capital budgeting model was designed for a hypothetical salmon monoculture cage operation using parameters for the Bay of Fundy. To this were added fixed and operating costs of mussel and kelp cultivation, and potential additional revenues from these two species. Profitability (NPV) was estimated by projections over ten years using discount rates of 5 percent and 10 percent. To take risk into consideration, three scenarios were run, and each scenario was given a probability of occurrence. The best scenario, Scenario 1, has salmon harvested every second year, with a mortality rate of 11 percent. This would give a total of five successful harvests in the ten year span with a probability of occurrence of 20 percent. The worst scenario was Scenario 2. It followed the same rules as the first, except it had only four successful harvests, because in one harvest all fish were assumed destroyed. This scenario is plausible because of infectious salmon anaemia or winter chill. This scenario was assigned a 40 percent probability. Scenario 3 was intermediate between 1 and 2. It had four successful harvests and one harvest in which only 30 percent of the fish survived. This scenario was also given a 40 percent probability. The NPV for these scenarios are shown in Table 4. Additional revenues from mussels and seaweeds more than compensate for additional costs with a resulting higher NPV for IMTA than for salmon monoculture. The increase in NPV is significant at 24 percent. As one would expect with diversification, IMTA results in higher NPV. Mussels and seaweeds provide alternative uncorrelated sources of income, thereby softening the damaging effect of salmon losses. Even under the worst case scenario (2), IMTA provided a positive NPV at both discount rates. Just one bad harvest can have a negative impact on the entire 10 year run of a monoculture salmon farm, whereas IMTA effectively reduces the risk. The natural factors that affect salmon mortality may not necessarily affect mussels and kelps. For instance, salmon experience winter chill at -0.8°C, while mussels and kelps can survive much colder temperatures (e.g. mussels live in the intertidal zone that can experience drops to -40°C); similarly, kelps are temperate cold water organisms and, in fact, most of kelp growth occurs from winter to late spring). Therefore, the addition of these co-products can reduce risk (it is unlikely that all three species will be affected simultaneously) and maintain profitability.

These economic models (Chopin *et al.*, 2001; Whitmarsh, Cook and Black, 2006; Ridler *et al.*, 2007), all based on different IMTA operations (using data from Chile and Sweden, Scotland, and Canada), indicate that integrating mussels and seaweeds with existing salmon monocultures can increase the profits of salmon farmers while remaining environmentally responsible. Also, this increase in profitability is compounded over time, grows with increased production and stocking densities, and is using only conservative estimates for seaweed market value. Assuming no major market changes or die-offs, the outlook for IMTA is certainly promising.

Exploring additional economic value for IMTA coproducts

Besides the commonly cultured finfish, shrimps and bivalves, the economic value of seaweeds, echinoderms, crustaceans and polychaetes should also be considered for IMTA.

Aquatic plants represent 23.4 percent of the tonnage and 9.7 percent of the value of the global (marine, brackishwater and freshwater) aquaculture production, estimated at 59.4 million tonnes and US$70.3 billion in 2004. Considering only mariculture (50.9 percent of the global aquaculture, estimated at 30.2 million tonnes and US$28.1 billion), aquatic plants represent 45.9 percent of the tonnage and 24.2 percent of the value. Molluscs represent 43.0 percent, fish 8.9 percent, crustaceans 1.8 percent, and other aquatic animals 0.4 percent (FAO, 2006a). The seaweed aquaculture production (92 percent of the world seaweed supplies) is estimated at 11.2 million tonnes and US$ 5.7 billion (99.7 percent being provided by Asian countries). Approximately 220 species of algae are cultivated; however, 6 genera are providing 94.8 percent of the seaweed aquaculture production (*Laminaria* [kombu; 40.1 percent], *Undaria* [wakame; 22.3 percent], *Porphyra* [nori; 12.4 percent], *Eucheuma/Kappaphycus* [11.6 percent] and *Gracilaria* [8.4 percent]), and 4 genera are providing 95.6 percent of its value (*Laminaria* [47.9 percent], *Porphyra* [23.3 percent], *Undaria* (17.7 percent) and *Gracilaria* [6.7 percent]).

According to Santos (2006), until recently, the most commonly used seaweeds for biofiltration in Europe belonged to the genera *Ulva* and *Gracilaria*. Although their husbandry is well established, their market value is low, as they are used primarily as feed or fertilizer. Therefore alternative species of seaweeds with higher market value are being explored. For example, *Asparagopsis armata* has a high value due to its ability to concentrate halogenated organic metabolites, which can be used for fungicides, antibiotics and skin cosmetics, with the possibility of patents (Lognone *et al.*, 2003). Therefore to ensure further expansion of IMTA, further research into alternative species must continue or be initiated. As well, new markets for these products should be sought out to further safe guard economic reward.

As shown in Table 2, seaweeds can be highly profitable, assuming growing conditions are optimal and market niches have been established. While there exists a wide range in seaweed use (e.g. from fertilizer to human consumption), the value and quality of the product also have a wide range. These points are important to consider when determining product value.

Other species in an IMTA system, invertebrates and herbivores in general, also have high economic value. As shown in Table 1, molluscs (particularly bivalves) have well established market value. Other mid-trophic animals such as echinoderms, crustaceans and polychaetes are also economically valuable. Ross, Thorpe and Brand (2004) showed how sea urchins and crabs can be grown with scallops to prevent biofouling on nets, which in turn help reduce maintenance costs and improve growth rates of scallops. These co-products can also be sold. For example, sea urchin gonad (“roe” or “uni”) is popular in Asian sushi restaurants where it can demand prices in the range of US$6 to US$200 per kilogram, depending on quality (Robinson, Castell and Kennedy, 2002; Robinson, 2004). Therefore to ensure maximal gonad growth and quality, the stage of gametogenesis (among other factors) must be considered before harvesting (Robinson, Castell and Kennedy, 2002). However, as wild stocks of sea urchins are in decline, and the demand from Japanese markets still exists, aquaculture of sea urchins is viewed in a positive light and research into sea urchin (particularly that of the green sea urchin, *Strongylocentrotus droebachiensis*) growth and husbandry is ongoing (Pearce, Daggett and Robinson, 2004; Robinson, 2004; Daggett, Pearce and Robinson, 2006). There is much room for growth in the sea urchin aquaculture industry. In 2004, the global fishery for sea urchins (*Strongylocentrotus* spp. and *Paracentrotus lividus*) was 32 606 tonnes, while commercial aquaculture that same year was reported at only 7 495 tonnes (FAO, 2006b). This occurred in Asia (7 491 tonnes of *Strongylocentrotus* spp. worth US$22 473 000) and Europe (4 tonnes of *Paracentrotus lividus* worth US$47 000) (FAO, 2006b). In Chile, the sea urchin *Loxechinus albus* has been overexploited for domestic and export markets (Moreno *et al.*, 2007). The largest harvest was recorded in 2002 (60 000 tonnes). It declined to 37 000 tonnes in 2005, with an export of 3 000 tonnes worth US$61 000 000 (FAO, 2006b). There are presently several efforts to develop sea urchin aquaculture in Chile due to the imminent collapse of the fishery in all regions but the 12th; however, farmed sea urchins remain more expensive than wild harvested ones.

Another echinoderm that has strong market demand from Asian markets is the sea cucumber. Sea cucumbers, particularly the species *Holothuria scabra* and *Stichopus japonicus*, have been heavily exploited by the traditional fisheries, and as a result of strong market demand, sea cucumber aquaculture is on the rise (Hamel and Mercier, 1997; Purcell, Blockmans and Agudo, 2006; Purcell, Patrois and Fraisse, 2006). In 2004, Asia produced 53 315 tonnes of cultured *Stichopus japonicus* worth US$159 943 000 (FAO, 2006b). Although commercial scale sea cucumber aquaculture is currently restricted to Asia, there is a pilot project underway on the Pacific coast of Canada culturing *Parastichopus californicus*. Traditional fisheries are located globally, capturing a total of 23 439 tonnes, with 4 973 tonnes from North America and 15 470 tonnes from Asia (FAO, 2006b). Sea cucumbers are naturally found in temperate waters, and with a high market demand and value, are excellent candidate species for IMTA. In Chile, there are pilot projects to cultivate *Athyonidium chilensis* and *Apostichopus japonicus* for export markets.

Traditional lobster and crab fisheries are also highly lucrative. In 2004, globally, 232 922 tonnes of wild lobster were caught in traditional capture fisheries (FAO, 2006b). Commercial aquaculture of the spiny lobster that same year was reported at only 39 tonnes (FAO, 2006b). This occurred in North America (1 tonne worth US$5 000) and Asia (38 tonnes worth US$655 000) (FAO, 2006b). If these animals could be integrated with existing fed-aquaculture operations, it could not only provide profit for the farmers, but it could also relieve pressure on dwindling wild populations and help clean the benthic environment of the aquaculture sites. While much research is being done on the culture of the spiny and rock lobsters, *Panulirus* sp. and *Janus* sp. (common in tropical waters; Phillips and Liddy, 2003; Phillips, Smith and Maguire, 2004), there is much work yet to be done on the culture of the temperate water lobsters, *Homarus americanus* and *Homarus gammarus* (Nicosia and Lavalli, 1999; Tlusty, Fiore and Goldstein, 2005) and their integration in IMTA systems. In the Bay of Fundy, Canada, it is common to see lobster boats setting their traps at the periphery of salmon aquaculture sites. In the majority of cases, there is a good relationship between the farmers and the fishers and the divers that service aquaculture sites will often retrieve lobster traps that have become entangled in the mooring lines and give them back to the fishers (S. Robinson, pers. comm.).

Polychaetes are another invertebrate group that can play a key role in IMTA. These worms are often found in benthic regions under aquaculture sites, and can play an important role in organic sediment bioremediation (Lu and Wu, 1998). Polychaetes (*Sabella spallanzanii*) have been successfully co-cultured with the alga *Cladophora prolifera* as bioremediators for aquaculture wastewater treatment in the Mediterranean

Sea (Pierri, Fanelli and Giangrande, 2006). In a review on polychaete aquaculture, Olive (1999) recommended the potential for polychaetes to be used as feed for fish brood stock. Olive (1999) also drew attention to the niche that polychaetes have in the recreational fishing industry. Interestingly, some polychaetes (*Nereis* spp. "ragworms" and *Arenicola* spp. "lugworms") have high value as bait in the sea angling sport and leisure industry. These marine worms are commonly sold in bait shops in the United Kingdom, Ireland and the Netherlands. Olive (1999) reported that the European baitworm industry is worth about €200 million (US$262 million), and according to FAO (2006b), while no commercial harvest of cultured polychaetes was reported in 2004, there was a wild harvest of 500 tonnes of polychaetes. With a high value as fishing bait, the potential as a food supply for fish brood stock, and their role as a sediment bioremediator (Tsutsumi *et al.*, 2005), polychaetes integrated with existing aquaculture operations could be beneficial for fish farmers. Moreover, the haemoglobin of *Arenicola marina* has been reported as a potential substitute for human red cells (Zal, Lallier and Toulmond, 2002), and could be a promising alternative at a time of worldwide blood shortage.

Besides uses as bioremediators, biofouling agents, bait, fishmeal and human consumption, invertebrates and herbivorous fishes can also be used to meet the market demand for aquaria and laboratory specimens. In 2001, the global export value of ornamentals was US$350 million (Hardy, 2003). Although marine ornamentals only consisted of 4 percent of the volume, they were worth 20 percent of the value (Chapman *et al.*, 1997). While most ornamentals are captured in the wild or grown in aquaria, the potential for co-culturing ornamentals with other aquaculture species could hold lucrative economic benefits for farmers, if they chose to exploit this market niche.

It will also be important to assemble interdisciplinary and complementary teams combining the expertise of cultivating and providing marine biomass (of different and consistent composition and quality through IMTA practices) with the expertise of identifying and characterizing bioactive compounds. This will position differentiated IMTA products for high added-value applications in promising niche market opportunities, and, consequently, make the whole IMTA approach even more attractive and profitable.

Selecting the right species

When establishing which species to use in an IMTA system, one must carefully consider the suitability of the species in a particular habitat/culture unit. In order to ensure successful growth and economic value, farmers should:

- Use local species that are well within their normal geographic range and for which technology is available. This will help to prevent the risk of invasive species causing harm to the local environment, and potentially harming other economic activities. These species have also evolved to be well adapted to the local conditions.
- Use species that will complement each other on different trophic levels. For example species must be able to feed on the other species' waste in order for the newly integrated species to improve the quality of the water and grow efficiently. Not all species can be grown together efficiently. Particulate organic matter and dissolved inorganic nutrients should be both considered, as well as the size range of particles, when selecting a farm site.
- Use species that are capable of growing to a significant biomass. This feature is important if the organisms are to act as a biofilter that captures many of the excess nutrients and that can be harvested from the water. The other alternative is to have a species with a very high value, in which case lesser volumes can be grown. However, with the latter, the biomitigating role is reduced.
- Use species that have an established or perceived market value. Farmers must be able to sell the alternative species in order to increase their economic input. Therefore, they should establish buyers in markets before investing too heavily.

- Use species for which regulators and policy makers will facilitate the exploration of new markets, not impose new regulatory impediments to commercialization.

Understanding habitat specificity

Each farm site has its own unique oceanographic and biological characteristics. These factors will affect the performance of the species being grown. Therefore, when establishing aquaculture leases, site managers should know the flushing rates, nutrients and oxygen levels, temperature and salinity ranges, ice conditions, etc., for each site. The addition of infrastructures to cultivate different species can alter the oceanographic and biological conditions of a habitat to a certain extent. Therefore site managers should be mindful of the changes in oxygen levels, flow rates, particulate organic matter and dissolved inorganic nutrient levels, etc. when species are added or removed from an IMTA system. For example, the addition of seaweeds and shellfish can alter the O_2 and CO_2 concentrations for short periods of time at an aquaculture site that is naturally limited in O_2 at different times of the year (e.g. the fall in the Bay of Fundy, Canada). Using GIS tools could facilitate the identification of sites amenable to IMTA practices by offering the best compromise of characteristics which will be acceptable to different species with different requirements.

Promoting effective government legislation/regulations and incentives to facilitate the development of IMTA practices and the commercialization of IMTA products

Establishing effluent regulations conducive to the development of IMTA

The development and adoption of technology often depends highly on the level of legislative pressure from a nation's government, itself reacting to pressures from consumers, ENGOs and the public at large. If environmental legislation remains low priority with government, then little progress toward the use of biofilters (as a means of effluent mitigation) will occur. The only motivator will be profit obtained from additional product growth and regulatory incentives. Therefore, if government puts legislative pressure on the proper management of wastewater effluent, openly supports the use of biomitigation for effluent management, and put in place the appropriate corresponding financial tools (funding for IMTA R&D, outreach and technology transfer and tax incentives), the development of IMTA will be encouraged.

It is also important to note that present aquaculture business models do not consider and recognize the economic value of the biomitigation services provided by biofilters, as there is no cost associated with aquaculture discharges/effluents in open seawater-based systems. Regulatory and financial incentives may therefore be required to clearly recognize the benefits of the extractive components of IMTA systems (shellfish and seaweeds). A better estimate of the overall cost/benefits to nature and society of aquaculture waste and its mitigation would create powerful financial and regulatory incentives to governments and the industry to jointly invest in the IMTA approach. For example, Denmark, after the initial development of finfish aquaculture in the 1970-80's, is now reconsidering more finfish aquaculture development, but the condition for that to occur is proper planning for biomitigation and the recommended use of biofilters, such as seaweeds and shellfish, is being considered. This means that the use of extractive species would become part of the license requirements to operate in Denmark, and that the nutrient reduction services provided by these organisms would finally be recognized and valued for their ecosystem functions. These services need to be quantified; for example, in Denmark, the remediation costs for one kilogram of nitrogen is estimated at €33 (Holdt, Moehlenberg and Dahl-Madsen, 2006). If laws or regulations were implemented to have aquaculture operations responsibly internalize their environmental costs, a significant reduction of their profitability would occur. As previously mentioned, a study in Chile showed that by integrating the culture of the algal nutrient biofilter *Gracilaria*, environmental costs of waste discharges are significantly reduced and profitability is significantly increased (Chopin *et al.*, 2001). The introduction of a nutrient tax, or its exemption through the implementation of biomitigative practices, would make the economic demonstration of the validity of the IMTA approach even more obvious. Moreover, by implementing better management practices, the aquaculture industry should increase its social acceptability, a variable to which it is very difficult to give a monetary value, but an imperative condition for the development of its full potential. Reducing environmental and economic risk in the long term should also make financing easier to obtain.

Lifting fish farm moratoria on the condition that biomitigative practices such as IMTA are implemented

Many countries (e.g. Norway, Sweden and South Africa) have moratoria on the further expansion of fish farms. This could limit the immediate development of IMTA. However, as the positive benefits of this type of culture system become further known from the work of academic and industry pioneers in this field (e.g. Canada), it is likely those other countries will also adopt this practice. The adoption of IMTA may allow the further expansion of aquaculture farms and economic opportunities in coastal regions due to the sustainability and ecological balancing of this type of production system. Therefore, to ensure further expansion of aquaculture, countries could consider lifting the moratoria on fish farms, on the condition that they show initiative towards sustainable development, through biomitigation, as is already the case in Sweden (Lindahl *et al.*, 2005).

Putting in place enabling legislation for commercialization of IMTA products

For IMTA to develop to a commercial scale, appropriate regulatory and policy frameworks need to be put in place. Present aquaculture regulations and policies are often inherited from previous fishery frameworks and reasoning, which have shown their limitations. To develop the aquaculture of tomorrow, the present aquaculture regulations and policies need to be revisited. Adaptive regulations need to be developed by regulators with flexible and innovative minds, who are not afraid of putting in place mechanisms that allow the testing of innovative practices at the R&D level, and, if deemed promising, mechanisms that will take these practices all the way to C (commercialization). As the IMTA concept continues to evolve, it is important that all sectors of the industry be aware of the implications of the changes involved so that they can adapt in a timely and organized manner. To move research from the "pilot" scale to the "scale up" stage, some current regulations and policies may need to be changed or they will be seen as impediments by industrial partners who will see no incentive in developing IMTA. For example, an earlier version of the Canadian Shellfish Sanitation Program (CSSP) prevented the development of IMTA because of a clause that specified that shellfish could not be grown closer than 125 m of finfish net-pens. This paragraph was never written with IMTA in mind, but it impinged seriously its development. After four years (2004-2008), it has finally been amended so that IMTA practices can legally develop to commercial scale based on recent, reliable and relevant data and information provided by the IMTA project in the Bay of Fundy and similar projects in other parts of the world. While four years may appear to be a long period of time for some, it is a relatively short delay when one recognizes the regulations and legislations that needed to be reviewed and considered through such governmental type processes involving several federal and provincial departments. However, when developing a new aquaculture practice in a particular country, regulatory issues should be addressed right from the beginning to avoid delays when new products are ready to go to market.

Recognizing the benefits of IMTA and educating stakeholders about this practice

Once government, industry and the general population will become aware of the positive impacts of IMTA, they are likely to be more inclined to encourage the establishment of these culture systems.

The benefits of IMTA include:

- The mitigation of effluents through the use of biofilters (e.g. seaweeds and invertebrates), which are suited to the ecological niche of the farm. → *Effluent biomitigation.*
- Prevention or reduction of disease among farmed fish can be provided by certain seaweeds due to their antibacterial activity against fish pathogenic bacteria (Bansemir *et al.*, 2006), or by shellfish reducing the virulence of ISAV (Skar and Mortensen, 2007; S. Robinson, pers. comm.). → *Disease control.*
- Increased overall economic value of an operation from the commercial by-products that are cultivated and sold. → *Increased profits through diversification.*
- Potential for differentiation of the IMTA products through eco-labelling or organic certification programmes. → *Increased profits through obtaining premium prices.*
- Economic growth through employment (both direct and indirect) and product processing and distribution. → *Improving local economy.*
- Product diversification may offer financial protection and decrease economic risks when price fluctuations occur, or if one of the crops is lost to disease or inclement weather. → *Form of 'natural' crop insurance.*

To help spread the word on the positive impacts of IMTA:

- Researchers should not only publish their work on IMTA in peer reviewed journals, but also in magazines geared toward the general public and industry professionals. It is very important to get the biological, economic and social results out as soon as possible as many institutions, agencies, industries and various organizations are taking a "wait and see" approach, which creates inertia for the development of IMTA systems.
- Government/industry/academia could launch public awareness campaigns (via media outlets, e.g. newspapers, TV and radio documentaries, pamphlets, websites; and information on IMTA seafood products available in the marketplace, through pamphlets, labels or stickers) to highlight the benefits of IMTA so that the general public could be reached and educated about this practice and the quality of its products.
- Academia/government/industry/general public should hold regular meetings to discuss progress, stumbling blocks, new directions, etc. so that the IMTA concept becomes better known, and progresses from better to best management practice (BMP).
- International exchanges between personnel working on IMTA could be established to exchange knowledge (e.g. conferences, workshops, student/researcher exchanges).
- A website database on IMTA could also be established to more easily share knowledge.

There is still a large amount of education and outreach required to bring society into the mindset of incorporating IMTA into their suite of social values. Some of the social surveys conducted in Canada (DFO, 2005; Barrington *et al.*, 2008) indicate that the general public is in favour of practices based on the "recycling concept". Whether this will translate into a greater appreciation of the sustainable ecological value of the concept, a willingness to support it tangibly with their shopping money, and demands to their elected representatives will be the ultimate test. The degree to which researchers and extension people become creatively involved with this educational component will be vital to the success of IMTA practices.

The determination to develop IMTA systems will, however, only come about if there are some visionary changes in political, social, and economic reasoning. This will be accomplished by seeking sustainability, long-term profitability and responsible management of coastal waters. It will also necessitate a change in the attitude of consumers towards eating products cultured in the marine environment in the same way that they accept eating products from recycling and organic production systems on land, for which they are willing to pay a higher price. IMTA systems, under their various forms, have existed for centuries in Asian countries, through trial and error and experimentation. Consequently, the Asian culture is accustomed to the concept of considering wastes from farming practices as resources for other crops rather than pollutants. However, this attitude still has a long way to progress in the western world where aquaculture is a more recent development. At the present time, several western organizations are trying to modify seafood consumption trends by incorporating such concepts into food safety, and environmental and social sustainability.

Governments have a role to play. One of the key roles for government agencies, from the municipal to the federal levels, is to understand the basic concept of IMTA and to evaluate their current and future policies. If they agree with the concept of IMTA, then they should try and promote protocols through their policies that will encourage the marine production sectors to follow those tenets. This could be done in the form of incentives or penalties similar to economic policies that are currently used to regulate environmental behaviour of people in land-based systems (i.e. fuel or cigarette taxes, better premiums for good behaviour on life insurance policies, incentives for identifying and recognizing the values of environmental services as in a few countries such as the Netherlands, Denmark and Sweden).

The aquaculture industry also has to play its role and be ready to help in the development of IMTA so that we take it along the continuum of R&D&C (C for commercialization). A closer association between natural, engineering and socio-economic scientists and industrial partners is necessary and, in fact, is very rewarding when it works. Scientists have to come down from their ivory tower and stop disparaging applied science, and industrial partners have to understand that answers do not always come from short-term projects and are not always black and white.

Academic institutions need to get involved. IMTA is truly interdisciplinary in nature. A lot of people talk about the interdisciplinary approach to problem solving, but very few practice interdisciplinarity and very few train students to be interdisciplinary minded. Academic institutions continue to teach along the classical disciplinary lines at both the undergraduate and graduate levels, which prevents cross-fertilization of minds and the development of appropriate minds for tackling interdisciplinary projects. Very few candidates for postdoctoral fellowships are presently ready for conducting interdisciplinary research. Academics need to develop curricula/programs to train the needed interdisciplinary scientists of tomorrow.

The international community of IMTA scientists and practitioners should coordinate its effort. It would be an understatement to say that gaining a working understanding of the essential functions of the ecosystem is a complex, but essential task. Reasonable estimates of the cause and effect relationships will have to be defined and this will take significant amounts of research time and funding. Although this knowledge will be needed for various ecological zones, these zones are often shared between various countries. For example, similar ecological processes are likely involved in temperate areas that are currently used to grow salmonids in sea pens in diverse countries such as Norway, Scotland, Chile, Canada and the United States of America. Therefore, it makes sense that these countries should collaborate in their efforts to understand how the ecological processes operate in their respective areas. Not only would a concerted effort allow for a sooner understanding of the principles involved so that all associated areas could benefit, it would also raise the public consciousness of the new paradigm on a global level.

Establishing the R&D&C continuum for IMTA

The maintenance of productive R&D programs is vital for any industry, particularly one as dynamic as today's aquaculture industry. As pointed out by Troell *et al.* (2003), several areas of R&D are especially important for IMTA:

- A thorough understanding of the biological, biochemical, hydrographic, oceanographic, seasonal and climatic processes, and their interactions, experienced at each IMTA site by the selected species/strains is crucial for management.
- To be useful, such R&D programs into these advanced aquaculture technologies should be conducted at scales relevant to commercial implementation or suitable for extrapolation, while still not being irreversible. They should address the biology, engineering, operational protocol and economics of these technologies.
- Models should be developed to estimate the appropriate biological and economic ratios between fed organisms, organic extractive organisms and inorganic extractive organisms at the aquaculture sites. If general models can be developed, they have to remain flexible and site manager friendly enough so that they can be tailored and adjusted to the specifics of a particular site.
- Adaptation and development of new technologies is very important to improve the efficiency of aquaculture operations. For example, what role does fallowing have in the functioning of an IMTA site? Is it necessary to fallow all organisms or just salmon?
- Engineers, statisticians, economists and marketing people play an important role in site design and operation, and in product distribution. Biologists, farm managers and stakeholders in general, should consult with these experts.
- The roles and functions of IMTA systems for improved environmental, economic and social acceptability should be analysed within the broader perspective of integrated coastal zone management and ecosystem carrying/assimilative capacity. The appropriate variables to measure, as proxies for describing the health of the system, often remain to be identified.
- Appropriate food safety regulatory and policy frameworks will have to be developed and harmonized among countries to enable the development of commercial scale IMTA operations in a more universal fashion.
- Educational, training and financial incentive approaches have to be developed to facilitate the outreach and transfer of these novel, and somewhat complex, IMTA technologies from the scientists to the industry, the different levels of government and the public at large.

As always, when large projects involve different parties, their timetables and objectives are not always aligned. The research is conducted under academic timelines in synchrony with grant schedules. Business runs on shorter timelines than science and has to be more flexible. Timelines for changing business plans only start once there are enough data to convince industry to start; but once they do, things will happen quickly. So, there is a need for harmonizing needs and deadlines by parties understanding that they operate under different constrains and objectives/goals.

The successful development of IMTA will require a clear commitment from the different players (the aquaculturists, the scientists, the government departments, the funding agencies, the ENGOs and the public at large), associated with a clear respect and appreciation of their respective contributions, while recognizing their specificities. The role and mission of R&D should be clearly understood. One has to realize that the order of the letters has its significance: it is R&D, not D&R (the horses before the carriage!). R&D should be conducted in a scientific manner to obtain and keep credibility and validity. If not properly carried out, it could lead to questionable data, unfounded speculations and biased conclusions. Consequently, one has to recognize that R&D is a full component of any economic development plan. One should also not forget that R&D is only justified if a "C" (commercialisation) comes next; unfortunately, there is frequently a major gap between R&D and C, often because the appropriate funding structures and incentives are not in place to take a R&D project to a C reality.

One must also understand that the performance evaluation of IMTA systems requires a different approach from the typical linear growth models used for monoculture over the last decades, without consideration of the environmental and social costs. Five-year profitability models, with the goal of reaching maximal performance for each cultured species in isolation, should be replaced by optimized, long-term and sustainable bio-economic models in which the yield per unit resource input is evaluated.

Finally, let us not forget that we are still in the infancy of modern intensive aquaculture and that some agricultural practices have taken centuries to develop into better, not yet best, management practices.

CONCLUSIONS AND RECOMMENDATIONS

The aquaculture ecological, engineering, economic and social challenges remaining to be solved are for some maybe daunting. However, the goal is to develop modern IMTA systems, which are bound to play a major role worldwide in sustainable expansions of the aquaculture operations of tomorrow, within a balanced ecosystem approach, to respond to a worldwide increasing seafood demand with a new paradigm in the design of the most efficient food production systems.

Most of the countries with coastlines in temperate regions of the globe have some level of aquaculture ongoing, although very few, with the exception of Canada, Chile, South Africa, the United Kingdom, Ireland, the United States of America and China, have ongoing IMTA systems near or at commercial scale. IMTA has enormous potential for growth in all the countries discussed. Several countries have active research programs gaining knowledge about their regions potential for development of IMTA, while other countries have made no direct groundwork toward the development of IMTA.

Genera of particular interest and those with high potential for development in IMTA systems in marine temperate waters include:

- *Laminaria, Saccharina, Sacchoriza, Undaria, Alaria, Ecklonia, Lessonia, Durvillaea, Macrocystis, Gigartina, Sarcothalia, Chondracanthus, Callophyllis, Gracilaria, Gracilariopsis, Porphyra, Chondrus, Palmaria, Asparagopsis* and *Ulva* (seaweeds),
- *Haliotis, Crassostrea, Pecten, Argopecten, Placopecten, Mytilus, Choromytilus* and *Tapes* (molluscs),
- *Strongylocentrotus, Paracentrotus, Psammechinus, Loxechinus, Cucumaria, Holothuria, Stichopus, Parastichopus, Apostichopus* and *Athyonidium* (echinoderms),
- *Nereis, Arenicola, Glycera* and *Sabella* (polychaetes),
- *Penaeus* and *Homarus* (crustaceans), and
- *Salmo, Oncorhynchus, Scophthalmus, Dicentrarchus, Gadus, Anoplopoma, Hippoglossus, Melanogrammus, Paralichthys, Pseudopleuronectes* and *Mugil* (fish).

This is based on established husbandry practices, habitat appropriateness, biomitigation ability and the economic value of these species.

In order to ensure the expansion of IMTA in these regions several steps should be taken where appropriate. These include:

1) Establishing the economic and environmental value of IMTA systems and their co-products – seaweeds and invertebrates can be very profitable cultured species, not only for their services as effluent biomitigators, but also as differentiated premium cash crops diversifying the aquaculture sector and reducing risks.

2) Selecting species appropriate to the habitat and available technologies – native species should be used, to avoid problems with invasive, and potentially harmful, species.
3) Selecting species according to the environmental and oceanographic conditions of the sites proposed for IMTA development, and also according to their complementary ecosystem functions.
4) Selecting species that are capable of growing to a significant biomass in order to capture many of the excess nutrients and remove them efficiently at harvesting time.
5) Selecting species that have an established or perceived market value and for which the commercialization will not generate insurmountable regulatory hurdles.
6) Promoting effective government legislation/regulations and incentives to facilitate the development of IMTA practices and the commercialization of IMTA products.
7) Educating government/industry/academia and the general public about the benefits of IMTA. This can be done by disseminating knowledge through diverse media supports targeting diverse audiences.
8) Establishing the R&D&C continuum to ensure success in the long term for IMTA to become a widespread reality.

Taking all these factors into account, IMTA can be used as a valuable tool towards the establishment of a more sustainable aquaculture sector. IMTA systems can be environmentally responsible, profitable and sources of employment in coastal regions for any country that develops them properly, especially when government, industry, academia, communities and ENGOs work in consultation with each other. It is highly recommended that IMTA systems be utilized wherever possible, and ultimately replace monoculture operations in regions where they can be developed.

The reasons for this aquaculture system replacement have been made clear in this report. IMTA is the best option for a sustainable aquaculture industry. It is environmentally responsible, economically profitable and more socially acceptable. The IMTA project established in the Bay of Fundy, Canada, has provided solid examples concerning all these issues (environmental, economical and social) and can be referred to as a base model for temperate water IMTA. Indeed, several other countries in temperate waters have begun to establish their own IMTA systems, although much more R&D&C is needed.

Overall, the keystone of IMTA is integration. As pointed out during a workshop on IMTA in Saint John, New Brunswick, Canada, in March 2004 (Robinson and Chopin, 2004), a successful IMTA operation must integrate all stakeholders into its development plan. Government, industry, academia, the general public and ENGOs must work together. The role of IMTA in an integrated coastal zone management plan must be clearly defined. Beyond selecting the appropriate species for growth at a particular site, economics and social acceptability must also play a key role. Once these are established, a focused R&D&C programme will ensure efficiency and long-term sustainability for the aquaculture sector.

REFERENCES

Ackefors, H. 2000. Review of Swedish regulation and monitoring of aquaculture. *Journal of Applied Ichthyology* 16: 214-223.

Bansemir, A., Blume, M., Schröeder, S. & Lindequist, U. 2006. Screening of cultivated seaweeds for antibacterial activity against fish pathogenic bacteria. *Aquaculture* 252: 79-84.

Barrington, K., Ridler, N., Chopin, T., Robinson, S. & Robinson, B. 2008. Social aspects of the sustainability of integrated multi-trophic aquaculture. *Aquaculture International* DOI 10.1007/s10499-008-9236-0.

Bolton, J.J., Robertson-Andersson, D.M., Troell, M. & Halling, C. 2006. Integrated systems incorporate seaweeds in South African abalone culture. *Global Aquaculture Advocate* 9: 54-55.

Borges, M.T., Silva, P., Moreira, L. & Soares, R. 2005. Integration of consumer-targeted microalgal production with marine fish effluent biofiltration – a strategy for mariculture sustainability. *Journal of Applied Phycology* 17: 187-197.

Brzeski, V. & Newkirk, G. 1997. Integrated coastal food production systems – a review of current literature. *Ocean and Coastal Management* 34: 55-71.

Buschmann, A.H., López, D.A. & Medina, A. 1996. A review of the environmental effects and alternative production strategies of marine aquaculture in Chile. *Aquacultural Engineering* 15: 397-421.

Buschmann, A.H., Troell, M., Kautsky, N. & Kautsky, L. 1996. Integrated tank cultivation of salmonids and *Gracilaria chilensis* (Gracilariales, Rhodophyta) *Hydrobiologia* 326/327: 75-82.

Buschmann, A.H., Correa, J.A., Westermeier, R., Paredes, M.A., Adeo, D., Potin, P., Aroca, G., Beltrán, J., & Hernández-González, M.C. 2001. Cultivation of *Gigartina skottsbergii* (Gigartinales, Rhodophyta): recent advances and challenges for the future. *Journal of Applied Phycology* 13: 255-266.

Buschmann, A.H., Hernández-González, M.C., Astudillo, C., de la Fuente, L., Gutierrez, A. & Aroca, G. 2005. Seaweed cultivation, product development and integrated aquaculture studies in Chile. *World Aquaculture* 36: 51-53.

Buschmann, A.H., Riquelme, V.A., Hernández-González, M.C., Varela, D., Jiménez, J.E., Henríquez, L.A., Vergara, P.A., Guíñez, R. & Filún, L. 2006. A review of the impacts of salmonid farming on marine coastal ecosystems in the southeast Pacific. *ICES Journal of Marine Science* 63: 1338-1345.

Buttner, J. & Leavitt, D. 2003. Augmenting the lobster catch: Oyster aquaculture in modified lobster traps. *Journal of Shellfish Research* 22: 290-291.

Carmona, R., Kraemer, G.P. & Yarish, C. 2006. Exploring Northeast American and Asian species of *Porphyra* for use in an integrated finfish-algal aquaculture system. *Aquaculture* 252: 54-65.

Chapman, F.A., Fitz-Coy, S.A., Thunberg, E.M. & Adams, C.M. 1997. United States of America trade in ornamental fish. *Journal of the World Aquaculture Society* 28: 1-10.

Chopin, T. 2006. Integrated Multi-Trophic Aquaculture. What it is and why you should care… and don't confuse it with polyculture. *Northern Aquaculture* 12 (4): 4.

Chopin, T., Yarish, C., Wilkes, R., Belyea, E., Lu, S. & Mathieson, A. 1999. Developing *Porphyra*/salmon integrated aquaculture for bioremediation and diversification of the aquaculture industry. *Journal of Applied Phycology* 11: 463-472.

Chopin, T., Buschmann, A.H., Halling, C., Troell, M., Kautsky, N., Neori, A., Kraemer, G.P., Zertuche-Gonzalez, J.A., Yarish, C. & Neefus, C. 2001. Integrating seaweeds into marine aquaculture systems: a key towards sustainability. *Journal of Phycology* 37: 975-986.

Chopin, T. & Reinertsen, H. 2003. Aquaculture Europe 2003 – Beyond Monoculture. Summary document. European Aquaculture Society. 36 p.

Chopin, T. & Bastarache, S. 2004. Mariculture in Canada: finfish, shellfish and seaweed. *World Aquaculture* 35: 37-41.

Chopin, T. & Robinson, S. 2004. Defining the appropriate regulatory and policy framework for the development of integrated multi-trophic aquaculture practices: introduction to the workshop and positioning of the issues. *Bulletin of the Aquaculture Association of Canada* 104 (3): 4-10.

Chopin, T., Robinson, S., Sawhney, M., Bastarache, S., Belyea, E., Shea, R., Armstrong, W., Stewart, I. & Fitzgerald, P. 2004. The AquaNet integrated multi-trophic aquaculture project: rationale of the project and development of kelp cultivation as the inorganic extractive component of the system. *Bulletin of the Aquaculture Association of Canada* 104 (3): 11-18.

Chopin, T., Robinson, S.M.C., Troell, M., Neori, A., Buschmann, A.H. & Fang, J. 2008. Multi-trophic integration for sustainable marine aquaculture, pp. 2463-2475. In: *The Encyclopedia of Ecology. Ecological Engineering* (Vol. 3). S.E. Jørgensen and B.D. Fath (eds.). Elsevier, Oxford.

Chopin, T. & Sawhney, M. 2009. Seaweeds and their mariculture, pp. 4477-4487. In: *The Encyclopedia of Ocean Sciences*. J.H. Steele, S.A. Thorpe & K.K. Turekian (eds). Elsevier, Oxford.

Costa-Pierce, B.A. 2002. *Ecological Aquaculture: The Evolution of the Blue Revolution*. Blackwell Science, Oxford, 382 p.

Cromey, C.J., Nickell, T.D & Black, K.D. 2002. DEPOMOD-modelling the deposition and biological effects of waste solids from marine cage farms. *Aquaculture* 214: 211-239.

Cross, S.F. 2004a. Finfish-shellfish integrated aquaculture: water quality interactions and the implication for integrated multi-trophic aquaculture policy development. *Bulletin of the Aquaculture Association of Canada* 104 (3): 44-55.

Cross, S.F. 2004b. Marine finfish and suspended shellfish aquaculture – water quality interactions and the potential for integrated aquaculture. PhD thesis, University of Stirling, United Kingdom, 360 p.

Daggett, T.L., Pearce, C.M. & Robinson, S.M.C. 2006. A comparison of three land-based containment systems for use in culturing green sea urchins, *Strongylocentrotus droebachiensis* (Müller) (Echinodermata: Echinoidea). *Aquaculture Research* 37: 339-350.

DFO Canada. 2001. Impact of harvesting on marine plants, Margaree – Grandy Sound Area. Department of Fisheries and Oceans, Government of Newfoundland and Labrador. Fisheries Diversification Program, FDP project no. 311.

DFO Canada. 2005. Qualitative research exploring Canadians' perceptions, attitudes and concerns toward aquaculture. Prepared for Department of Fisheries and Oceans Strategic Communications Branch. Ottawa. 188 p.

FAO. 2006a. State of world aquaculture, 2006. Food and Agriculture Organization of the United Nations, FAO Fisheries Technical Paper 500, Rome.

FAO. 2006b. Fisheries Global Information System (FIGIS) website. www.fao.org/figis/servlet/TabLandArea?tb_ds=Aquaculture&tb_mode=TABLE&tb_act=SELECT&tb_grp=COUNTRY

Folke, C. & Kautsky, N. 1989. The role of ecosystems for a sustainable development of aquaculture. *Ambio* 18: 234-243.

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

Hamel, J.F. & Mercier, A. 1997. Sea cucumbers: current fishery and prospects for aquaculture. *Aquaculture Magazine* 23: 42-53.

Hamouda, L., Hipel, K.W., Kilgour, D.M., Noakes, D.J., Fang, L. & McDaniels T. 2005. The salmon aquaculture conflict in British Columbia: a graph model analysis. *Ocean & Coastal Management* 48: 571-587.

Hardy, R. 2003. Introduction to the special issue on ornamental fish. *Aquaculture Research* 34: 903.

Haya, K., Sephton, D.H., Martin, J.L. & Chopin, T. 2004. Monitoring of therapeutants and phycotoxins in kelps and mussels co-cultured with Atlantic salmon in an integrated multi-trophic aquaculture system. *Bulletin of the Aquaculture Association of Canada* 104 (3): 29-34.

Hernández, I., Martínez-Aragon, J.F., Tovar, A., Pérez-Lloréns, J.L. & Vergara, J.J. 2002. Biofiltering efficiency in removal of dissolved nutrients by three species of estuarine macroalgae cultivated with sea bass (*Dicentrarchus labrax*) waste waters 2. Ammonium. *Journal of Applied Phycology* 14: 375-384.

Hernández, I., Pérez-Pastor, A., Vergara, J., Martínez-Aragon, J., Fernández-Engo, M.Á. & Pérez-Lloréns, J. 2006. Studies on the biofiltration capacity of *Gracilariopsis longissima*: from microscale to macroscale. *Aquaculture* 252: 43-53.

Holdt, S., Moehlenberg, F. & Dahl-Madsen, K.I. 2006. Polyculture in Denmark: status, feasibility and future. World Aquaculture Society Conference, Florence, Italy, 9-13 May 2006. *Book of Abstracts*: 390.

Indergaard, M. & Jensen, A. 1983. Seaweed biomass production and fish farming. In: *Energy from biomass. Proc. 2nd EC conference on biomass, Berlin, September 1982*. A. Strub, P. Chartier, & G. Schleser (eds). Applied Science Publishers, London.

Jones, T.O. & Iwama, G.K. 1991. Polyculture of the Pacific oyster, *Crassostrea gigas* (Thunberg), with Chinook salmon, *Oncorhynchus tshawytscha*. *Aquaculture* 92: 313-322.

Kautsky, N., Troell, M. & Folke, C. 1996. Ecological engineering for increased production and environmental improvement in open sea aquaculture. In: *Ecological engineering for waste water treatment*. C. Etnier & B. Guterstam (eds). Lewis Publishers, Boca Raton.

Kraan, S. & Barrington, K.A. 2005. Commercial farming of *Asparagopsis armata* (Bonnemaisoniaceae, Rhodophyta) in Ireland, maintenance of an introduced species? *Journal of Applied Phycology* 17: 103-110.

Lander, T.R., Barrington, K.A., Robinson, S.M.C., MacDonald, B.A. & Martin, J.D. 2004. Dynamics of the blue mussel as an extractive organism in an integrated multi-trophic aquaculture system. *Bulletin of the Aquaculture Association of Canada* 104 (3): 19-28.

Lefebvre, S., Barillé, L. & Clerc, M. 2000. Pacific oyster (*Crassostrea gigas*) feeding responses to a fish-farm effluent. *Aquaculture* 187: 185-198.

Leon, J. 2006. Synopsis of salmon farming impacts and environmental management in Chile. *Technical Report to the World Wild Life Fund Chile*, 46 p.

Levinton, J.S. 1995. *Marine Biology: function, biodiversity and ecology*. Oxford University Press, New York.

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

Lognone, V., Patrick, D., Lüning, K., Santos, R., Mata, L., Bansemir, A., Schuenhoff, A. & Lindequivist, U. 2003. Procédé de production à terre des algues rouges de la famille des Bonnemaisoniacées. Submission no. 0308717. Institut National de la Propriété Industrielle, Paris, France.

Lu, L. & Wu, R.S.S. 1998. Recolonization and succession of marine macrobenthos in organic enriched sediment deposited from fish farms. *Environmental Bulletin* 101: 241-251.

Maroni, K. 2000. Monitoring and regulation of marine aquaculture in Norway. *Journal of Applied Ichthyology* 16: 192-195.

Martínez-Aragon, J.F., Hernández, I., Pérez-Lloréns, J.L., Vásquez, R. & Vergara, J.J. 2002. Biofiltering efficiency in removal of dissolved nutrients by three species of estuarine macroalgae cultivated with sea bass (*Dicentrarchus labrax*) waste waters. 1. Phosphate. *Journal of Applied Phycology* 14: 365-374.

Martínez, B., Viejo, R.M., Rico, J.M., Rødde, R.H., Faes, V.A., Oliveros, J. & Álvarez, D. 2006. Open sea cultivation of *Palmaria palmata* (Rhodophyta) on the northern Spanish coast. *Aquaculture* 254: 376-387.

Mata, L., Silva, J., Schuenoff, A. & Santos, R. 2006. The effects of light and temperature on the photosynthesis of the *Asparagopsis armata* tetrasporophyte (*Falkenbergia rufolanosa*), cultivated in tanks. *Aquaculture* 252: 12-19.

Matos, J., Costa, S., Rodrigues, A., Pereira, R. & Sousa-Pinto, I. 2006. Experimental integrated aquaculture of fish and red seaweeds in Northern Portugal. *Aquaculture* 252: 31-42.

Metaxa, E., Deviller, G., Pagand, P., Alliaume, C., Casellas, C. & Blancheton, J.P. 2006. High rate algal pond treatment for water reuse in a marine fish recirculation system: water purification and fish health. *Aquaculture* 252: 92-101.

Milne, D.H. 1995. *Marine Life and the Sea*. Wadsworth Publishing Co., Belmont, CA.

Moreno, C.A., Barahona, N., Molinet, C., (Lobo) Orensanz, J.M., Parma, A.M. & Zuleta, A. 2007. From crisis to institutional sustainability in the Chilean sea urchin fishery. In: *Fisheries Management: Progress Toward Sustainability*: 43-67. T. McClanahan & J.C. Castilla (eds). Blackwell Publishing Limited, Oxford.

Neill, P.E., Alcade, O., Faugeron, S., Navarrete, S.A. & Correa, J.A. 2006. Invasion of *Codium fragile* ssp. *tomentosoides* in northern Chile: a new threat for *Gracilaria* farming. *Aquaculture* 259: 202-210.

Neori, A., Chopin, T., Troell, M., Buschmann, A.H., Kraemer, G.P., Halling, C., Shpigel, M. & Yarish, C. 2004. Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. *Aquaculture* 231: 361-391.

Nicosia, F. & Lavalli, K. 1999. Homarid lobster hatcheries: their history and role in research, management, and aquaculture. *Marine Fisheries Review* 61(2): 1-57.

Olive, P.J.W. 1999. Polychaete aquaculture and polychaete science: a mutual synergism. *Hydrobiologia* 402: 175-183.

Pagand, P., Blancheton, J.P., Lemoalle, J. & Casellas, C. 2000. The use of high rate algal ponds for the treatment of marine effluent from a recirculating fish rearing system. *Aquaculture Research* 31: 729-736.

Pearce, C. M., Daggett, T.L. & Robinson, S.M.C. 2004. Effect of urchin size and diet on gonad yield and quality in the green sea urchin (*Strongylocentrotus droebachiensis*). *Aquaculture* 233: 337-367.

Pereira, R., Yarish, C. & Sousa-Pinto, I. 2006. The influence of stocking density, light and temperature on the growth, production and nutrient removal capacity of *Porphyra dioica* (Bangiales, Rhodophyta). *Aquaculture* 252: 66-78.

Phillips, B.F. & Liddy, G.C. 2003. Recent developments in spiny lobster aquaculture. Proceedings of the Third World Fisheries Congress: Feeding the World with Fish in the Next Millenium – the Balance Between Production and Environment. *American Fisheries Society Symposium* 38: 43-57.

Phillips, B.F., Smith, R.M. & Maguire, G.B. 2004. Western rock lobster: Potential for enhancement and aquaculture. *Journal of Shellfish Research* 23: 307.

Pierri, C., Fanelli, G. & Giangrande, A. 2006. Experimental co-culture of low food-chain organisms, *Sabella spallanzanii* (Polychaeta, Sabellidae) and *Cladophora prolifera* (Chlorophyta, Cladophorales), in Porto Cesaro area (Mediterranean Sea). *Aquaculture Research* 37: 966-974.

Purcell, S.W., Blockmans, B.F. & Agudo, N.N.S. 2006. Transportation methods for restocking of juvenile sea cucumber, *Holothuria scabra*. *Aquaculture* 251: 238-244.

Purcell, S.W., Patrois, J. & Fraisse, N. 2006. Experimental evaluation of co-culture of juvenile sea cucumbers, *Holothuria scabra* (Jaeger), with juvenile blue shrimp, *Litopenaeus stylirostris* (Stimpson). *Aquaculture Research* 37: 515-522.

Reid, G., Robinson, S.M.C., Chopin, T., Mullen, J., Lander, T., Sawhney, M., MacDonald, B., Haya, K., Burridge, L., Page, F., Ridler, N., Boyne-Travis, S., Sewuster, J., Marvin, R., Szemerda, M. & Powell, F. Recent development and challenges for open-water, integrated multi-trophic aquaculture (IMTA) in the Bay of Fundy, Canada. In: *Aquaculture Canada 2007. Proceedings of Contributed Papers*. C. Couturier, E. Boucher & A. Vickerson (eds). Aquaculture Association of Canada Special Publication No. 13 (in press).

Ridler, N., Wowchuk, M., Robinson, B., Barrington, K., Chopin, T., Robinson, S., Page, F., Reid, G., Szemerda, M., Sewuster, J. & Boyne-Travis, S. 2007. Integrated multi-trophic aquaculture (IMTA): a potential strategic choice for farmers. *Aquaculture Economics and Management* 11: 99-110.

Robinson, B., Wowchuk, M., Ridler, N., Chopin, T., Robinson, S., Page, F., Haya, K. & MacDonald, B. The socio-economics of integrated multi-trophic aquaculture (IMTA): a case study of the Bay of Fundy. In: *Ocean Management*. N. Catto (ed.). OMRN, Volume 1 (in press).

Robinson, S.M.C., Castell, J.D. & Kennedy, E.J. 2002. Developing suitable colour in the gonads of cultured green sea urchins (*Strongylocentrotus droebachiensis*). *Aquaculture* 206: 289-303.

Robinson, S.M.C. 2004. The evolving role of aquaculture in the global production of sea urchins. In: *Sea Urchins – Fisheries and Ecology: Proceedings of the International Conference on Sea Urchin Fisheries and Aquaculture, Puerto Varas, Chile, March 25-27, 2003*: 343-358. J.D. Lawrence (ed.). DEStech Publications Inc., Lancaster.

Robinson, S.M.C. & Chopin, T. 2004. Defining the appropriate regulatory and policy framework for the development of integrated multi-trophic aquaculture practices: summary of the workshop and issues for the future. *Bulletin of the Aquaculture Association of Canada* 104 (3): 73-84.

Ross, K.A., Thorpe, J.P. & Brand, A.R. 2004. Biological control of fouling in suspended scallop cultivation. *Aquaculture* 229: 99-116.

Ryther, J.H., DeBoer, J.A. & Lapointe, B.E. 1978. Cultivation of seaweeds for hydrocolloids, waste treatment and biomass for energy conversion. *Proc. Int. Seaweed Symp.* 9: 1-16.

Sandifer, P.A. & Hopkins, J.S. 1996. Conceptual design of a sustainable pond-based shrimp culture system. *Aquacultural Engineering* 15: 41-52.

Santos, R. 2006. Special issue opening comments: seaweed-based integrated mariculture. *Aquaculture* 252: 1-2.

Schrank, W.E. 2005. The Newfoundland fishery: ten years after the moratorium. *Marine Policy* 29: 407-420.

Schuenhoff, A., Mata, L. & Santos, R. 2006. The tetrasporophyte of *Asparagopsis armata* as a novel seaweed biofilter. *Aquaculture* 252: 3-11.

Skar, C.K. & Mortensen, S. 2007. Fate of infectious salmon anaemia virus (ISAV) in experimentally challenged blue mussels *Mytilus edulis*. *Diseases of Aquatic Organisms* 74: 1-6.

Soto, D. & Mena, G.P. 1999. Filter feeding by the freshwater mussel *Diplodon chilensis* as a biocontrol of salmon farming eutrophication. *Aquaculture* 171: 65-81.

Soto, D. & Norambuena, F. 2004. Evaluating salmon farming nutrient input effects in Southern Chile inland seas: a large scale mensurative experiment. *Journal of Applied Ichthyology* 20: 1-9.

Soto, D. & Jara, F. 2007. Using natural ecosystem services to diminish salmon-farming footprints in Southern Chile. In: *Ecological and Genetic Implications of Aquaculture Activities*: 459-475. T.M. Bert (Ed.). Springer Publications, New York.

Statistics Canada. 2007. Latest release from the Labour Force Survey. Friday, December 7, 2007. www.statcan.ca/english/Subjects/Labour/LFS/lfs-en.htm

Stenton-Dozey, J., Probyn, T. & Busby, A. 2001. Impact of mussels (*Mytilus galloprovincialis*) raft culture on benthic macrofauna, *in situ* oxygen uptake, and nutrient fluxes in Saldanha Bay, South Africa. *Canadian Journal of Fisheries and Aquatic Sciences* 58: 1021-1031.

Stirling, H.P. & Okumuş, İ. 1995. Growth and production of mussels (*Mytilus edulis* L.) suspended at salmon cages and shellfish farms in two Scottish sea lochs. *Aquaculture* 134: 193-210.

Tlusty, M.F., Fiore, D.R. & Goldstein, J.S. 2005. Use of formulated diets as replacements for *Artemia* in the rearing of juvenile American lobsters (*Homarus americanus*). *Aquaculture* 250: 781-795.

Troell, M., Halling, C., Nilsson, A., Buschmann, A.H., Kautsky, N. & Kautsky, L. 1997. Integrated marine cultivation of *Gracilaria chilensis* (Gracilariales, Rhodophyta) and salmon cages for reduced environmental impact and increased economic output. *Aquaculture* 156: 45-61.

Troell, M., Halling, C., Neori, A., Chopin, T., Buschmann, A.H., Kautsky, N. & Yarish, C. 2003. Integrated mariculture: asking the right questions. *Aquaculture* 226: 69-90.

Troell, M., Robertson-Andersson, D., Anderson, R.J., Bolton, J.J., Maneveldt, G., Halling, C. & Probyn, T. 2006. Abalone farming in South Africa: an overview with perspectives on kelp resources, abalone feed, potential for on-farm seaweed production and socio-economic importance. *Aquaculture* 257: 266-281.

Tsutsumi, H., Kinoshita, K., Srithongouthai, S., Sato, A., Nagata, S., Inoue, A., Yoshioka, M., Ohwada, K. & Hama, D. 2005. Treatment of the organically enriched sediment below the fish farm with the biological activities of artificially mass-cultured colonies of a small deposit feeding polychaete, *Capitella* sp. 1. *Benthos Research* 60 (1): 25-37.

Valente, L.M.P., Gouveia, A., Rema, P., Matos, J., Gomes, E.F. & Sousa-Pinto, I. 2006. Evaluation of three seaweeds *Gracilaria bursa-pastoris*, *Ulva rigida* and *Gracilaria cornea* as dietary ingredients in European sea bass (*Dicentrarchus labrax*) juveniles. *Aquaculture* 252: 85-91.

Varjopuro, R., Sahivirta, E., Mäkinen, T. & Helminen, H. 2000. Regulation and monitoring of marine aquaculture in Finland. *Journal of Applied Ichthyology* 16: 148-156.

Whitmarsh, D.J., Cook, E.J. & Black, K.D. 2006. Searching for sustainability in aquaculture: an investigation into the economic prospects for an integrated salmon-mussel production system. *Marine Policy* 30: 293-298.

Zal, F., Lallier, F. & Toulmond, A. 2002. Utilisation comme substitut sanguin d'une hémoglobine extracellulaire de poids moléculaire élevé. French Patent No. 00 07031, granted August 2, 2002.

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

Troell, M. 2009. Integrated marine and brackishwater aquaculture in tropical regions: research, implementation and prospects. In D. Soto (ed.). Integrated mariculture: a global review. *FAO Fisheries and Aquaculture Technical Paper.* No. 529. Rome, FAO. pp. 47–131.

CONTENTS

Abstract 48
Introduction 49
Objectives and methodologies 51
Aquaculture development 52
  Tropical marine and brackishwater aquaculture 53
  Integrated aquaculture 54
Integrated tropical mariculture – an overview 57
  Systems classification 57
  Research 58
  Practices 59
Development, incentives and constraints 89
Conclusions 92
Acknowledgements 93
References 93
Appendix 1. Sources 115
Appendix 2. Research matrix: integrated tropical mariculture 116

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 Aquaculture[1]), 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 discuses 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.

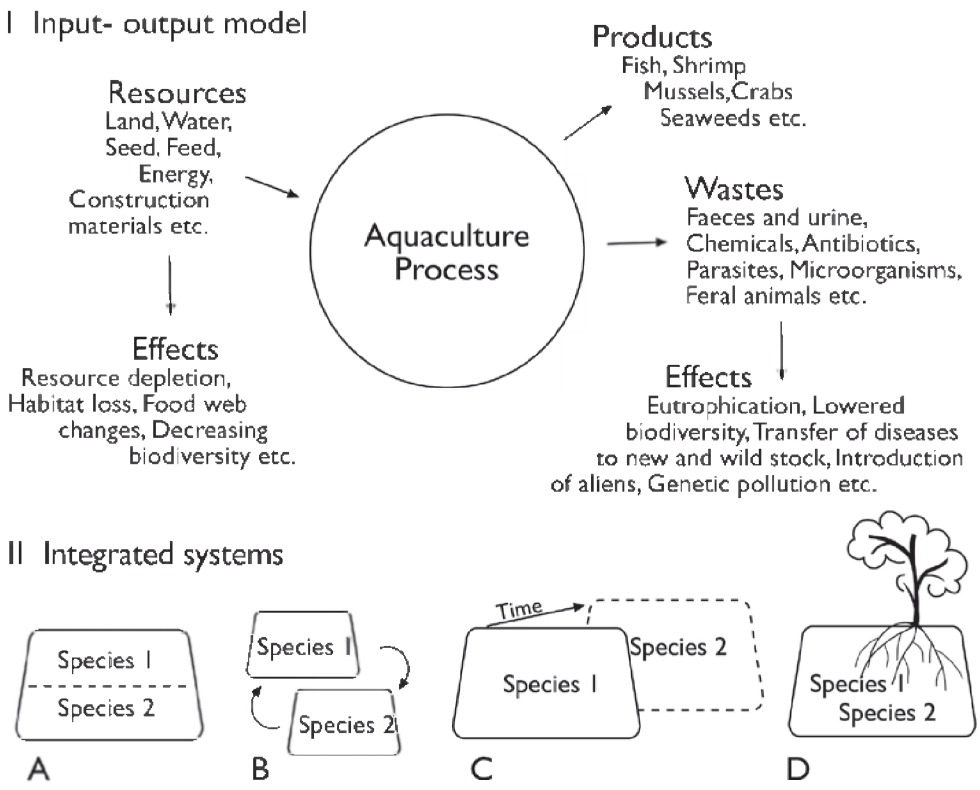
AQUACULTURE DEVELOPMENT

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 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

FIGURE 1

I. Diagram illustrating the use of resources by aquaculture, generation of wastes, and direct and indirect environmental effects; II. Main models of integrated aquaculture in marine or brackish waters



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, Mullets Drums, Amberjack, Croaker, pompano, Siganids, 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 (Hanain 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
Inproving 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 , 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).

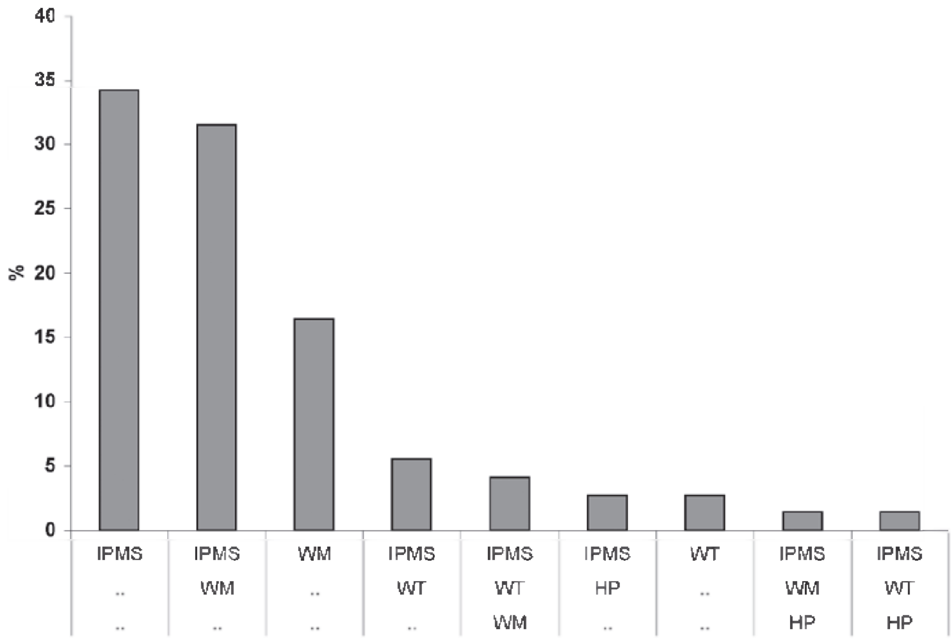
Other types of integration that have been omitted because they mostly encompass freshwater aquaculture includes: bacteria as biofilters, different halophytes, aquaponic systems, wetlands (i.e. cattail and reed, although mangroves have been included), microalgae (with the exception of "green water" and occasional studies), *Macrobrachium* spp. farmed in brackishwater environments, species from same feeding niches (like mixes of two carnivorous fish), artemia cultivation, AquamatsTM, 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.

FIGURE 2
Frequency of most common objectives in integrated aquaculture practices: IPMS – Increased profits multiple species; WM – Waste release mitigation; WT – Treating culture water + culture environment: HP – Habitat preservation



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, Poespitasari 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 m^{-2}) 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 (Barraclough 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 incorporing 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 Martinez-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.

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 brasiliana*) 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 (*Graciliaria* 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.

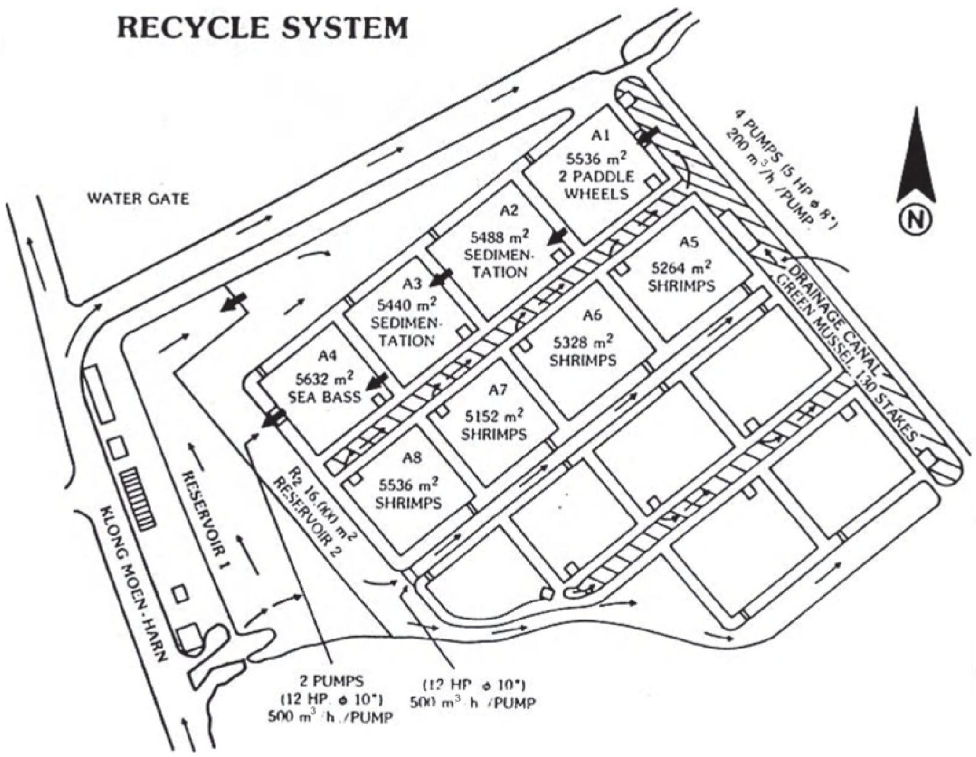
Work along these lines has also been carried out by the Department of Fisheries in Bangkok, Thailand, where green mussels and seaweeds have been used for treatment of waste-water intensive shrimp ponds (Darooncho, 1991; DOF, 1992; Chaiyakam and Tunvilai, 1989; Chaiyakam and Tunvilai, 1992). One important 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/m^2 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 (se references in Chien and Liao [2001]). These projects

FIGURE 3

Closed large-scale recycle system for shrimp (*Penaeus monodon*) developed by Charoen Pokphand Group (CP) during the 1990s. The system consisted of 4–10 x 0.5 ha shrimp ponds, and 4 x 0.5 ha treatment ponds used for herbivorous and omnivorous species



Source: From Anonymous (1996d) in Fast and Menasveta (2000).

involved integration of shrimp (*P. monodon*) with mud clam (*Meretrix lusoria*), seaweed (*Gracilaria* sp.) and milkfish (*Chanos chanos*), longneck purple clam (*Sanguinolaria rostata* 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)

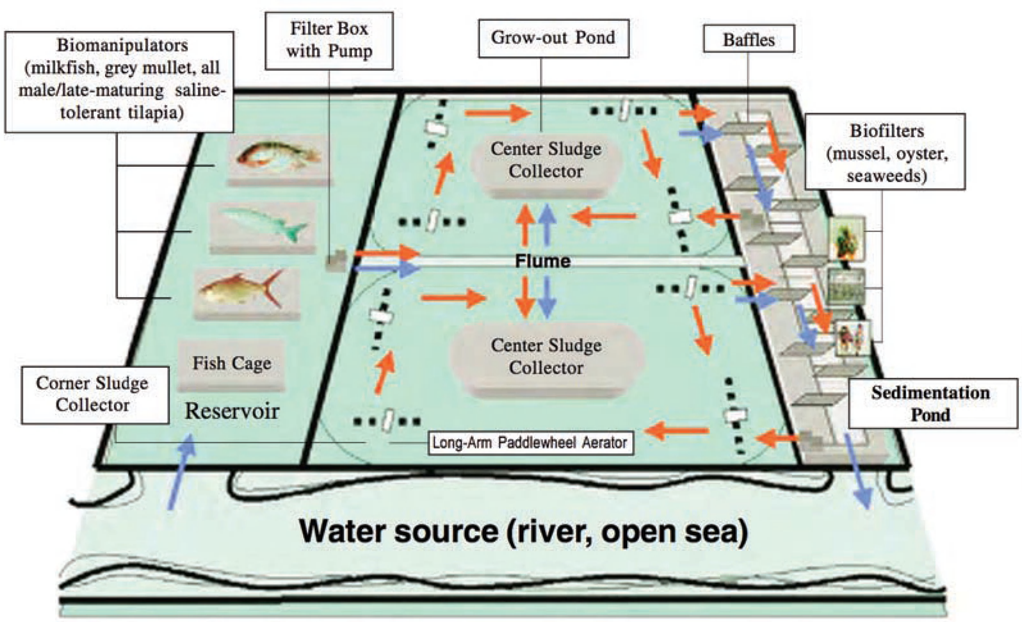
	Harvest survival (%)	Harvest size/weight	Production (kg ha^{-1})
Monoculture			
Shrimp	92,1	20.8**	11 517
Integration			
Shrimp	83.5	21.3**	10 649
Clams	53.4	25.7***	7.050
Oyster*	95	53.1***	7.020

* 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/m^2 of cage area (Tachanavarong, 1988).

FIGURE 4
Pond lay-out of a low-discharge/re-circulating shrimp farm in the Philippines



Source: from Baliao and Tookwinas (2002).

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 costal 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

PHOTO: JOFFRE OLIVIER

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 *khazans* 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 gehrs 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 ± 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 ± 0.4	49.7 ± 18.6	204.5 ± 62.6	5 600	6 391
Medium	6.1 ±1.0	37.1 ± 2.1	155.9 ± 10.6	5 632	4 315
Large	54.2 ± 36.9	17.6 ± 9.6	83.5 ± 48.5	5 673	82

*Value of shrimp plus those of finfishes, other shrimps and mud crab
Source: From Islam *et al.* (2005)

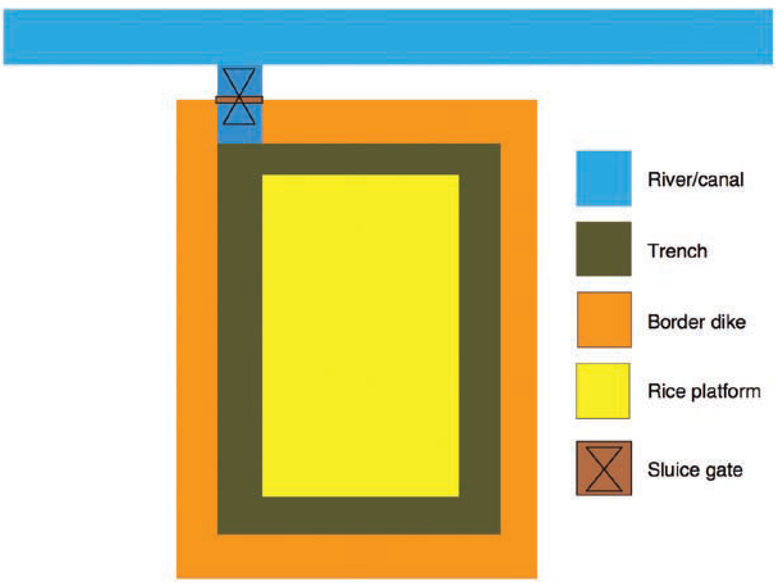
Viet Nam

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 merguiensis, 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

FIGURE 5

General outline for a rice-shrimp farm in the coastal Mekong Delta. Ponds have a shallow central platform area (approx. 80 percent of the total pond area, 20 cm deep) and a trench (1 m deep) around the perimeter of the platform



Source: from Preston *et al.* (2003).

Rice-shrimp ponds in Mekong Delta, Viet Nam.

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 desalinized 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* systems[2] 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 Tuerner, 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 Menatsveta [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.

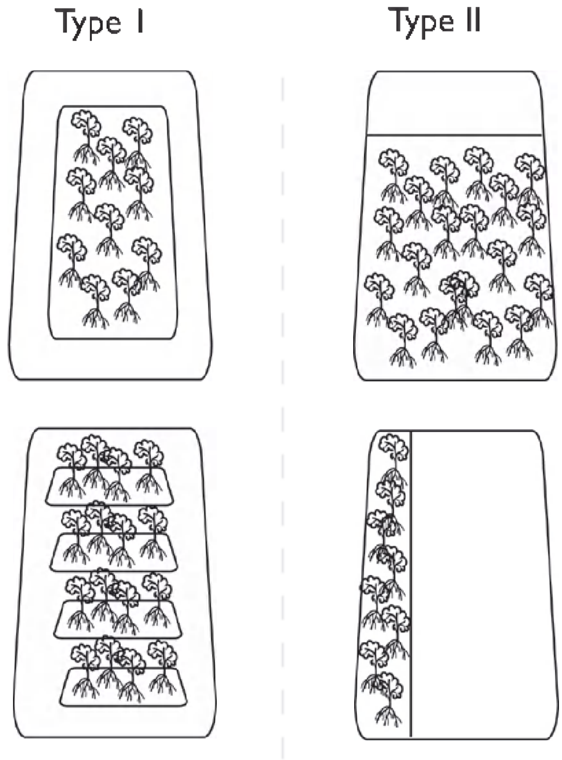
Silvifisheries – aquasilviculture

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 residules from agriculture and housholds) (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 leafs), 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

FIGURE 6
Silvofisheries models with aquaculture (ponds/canals) and mangrove areas integrated (Type I) or separate (Type II)



Source: From FitzGerald (1997).

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 Baconguis, 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 ovarall 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 exists 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

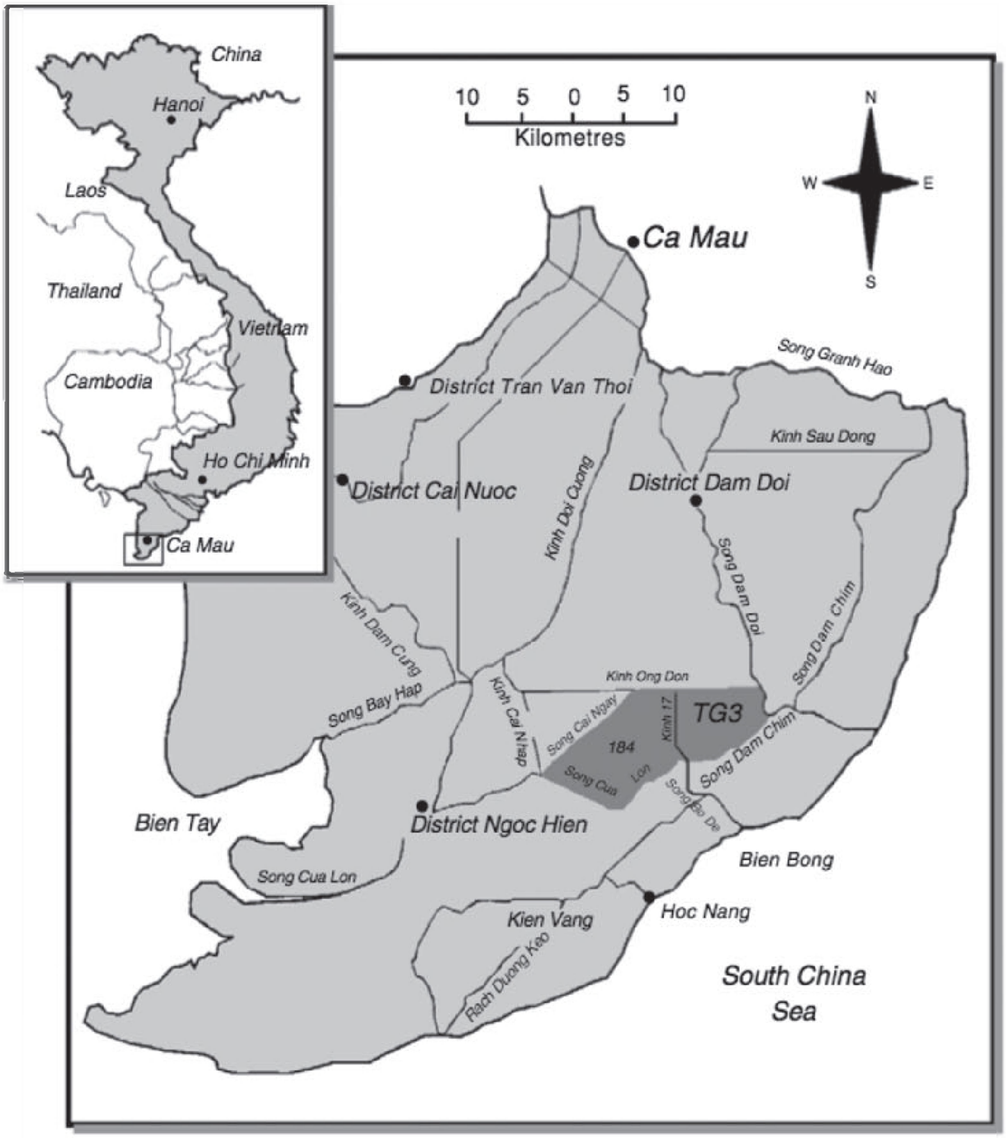
Mixed shrimp-mangrove ponds in Viet Nam have been primarily extensive integrated systems but improved extensive and semi-intensive ponds have been increasing (Beukeboom, Lai and Otsuka, 1993; Binh and Lin, 1995; Binh, Phillips and Demaine, 1997; Minh, Yakupitiyage, and Macintosh, 2001; Joffre, in press). 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 charachteristics 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			
Technology and source, year started	traditional gei wai; (mid-1940s)	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	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 (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	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 *Avicennia*, *Kandelia candel*	natural & planted *Avicennia*, *Rhizophora*	planted Rhizophora	planted *Rhizophora*	natural, planted	logged over, planted *Rhizophora*
Aquaculture	wild shrimp, fish, natural food species: *P. monodon*, *P. merguiensis*, *P. penicillatus*, *metapenaeus ensis*, *M. affinis*, *M. burkenroadi*, *Macrobrachium nipponense*, *Palemon orientalis*, tilapia, mullet, seabream, seabass, carp	stocked milkfish, wild fish, shrimp; natural food	stocked milkfish, wild fish, shrimp; natural food, supplem. 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, supplem. 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	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			200-400 kg ha-1 yr-1; US$ 280- 1200 ha-1 yr-1		
Owner structure	government	small-scale farmers	small scale-medium farmers	family	family, villages	
Trends	Managed more or less as bird sanctuary, *Phragmites* replacing mangroves			Intensification, conflicts owner structure		

FIGURE 7
Map showing the location of two main Fishery-Forestry Enterprises – TG3 and SFFE 184, Ngoc Hien District, Ca Mau Province, focusing on aquasilviculture practices



Source: from Preston *et al.* (2003).

The two aquasilviculture systems in Ca Mau province are 1) mixed system and 2) separate system (Johnston *et al.*, 1999a; Clough *et al.*, 2002). The mixed system has channels dug through the mangroves with vegetated dikes or levees, whereas in the separate system the mangroves are grown separately next to the pond and levees are bare (Johnston *et al.*, 1999a). The systems can be classified into four different types, reflecting intensity and species focus, as follows: (1) the traditional mixed mangrove farming system relying on natural stocking (mainly *Metapenaeus ensis* and *M. lysianassa* and to some extent also *Penaeus indicus*). Secondary fisheries products in this system consist of fish (barramundi, mullet) and mud crabs. (2) Natural stocking and also hatchery reared shrimps. (3) Both hatchery reared shrimps and mangrove crabs (*Scylla serrata*). (4) Blood cockles (*Anadara granosa*) are added to the shrimps and the crabs (Minh, Yakupitiyage and Macintosh, 2001; FitzGerald 2002). In addition to the pond production and forest production, secondary cash crops are cultivated along the pond dikes (e.g. bananas, taro, pineapples, cherries, etc.). The natural food, developing from

Mixed shrimp-mangrove culture in Ca Mau, Viet Nam.

mangrove litter and materials and species being transported into the pond with the tides, is not sufficient to support higher stocking densities of hatchery reared larvae. To support additional stocking farmers add either fertilizers or supplemental feeds. However, the increased inputs can result in degradation of water quality and pond environment (i.e. increased organic matter and ammonia) (Johnston *et al.*, 1999a). A higher production increases accumulation of solids in the ponds and channels, which have to be removed. Dumping the solids onto the vegetated flats and dikes leads to poor growth of mangroves from elevated farm area and to decreased tidal flushing (Primavera, 2000). In many areas of the Mekong Delta using such practices, has shrimp yields per unit area have declined (de Graaf and Xuan, 1998; Johnston *et al.*, 2000a). Low quality and quantity of seed may be resulting from poor pond management, overexploitation of wild stock, and disease outbreaks (Binh, Phillips and Demaine, 1997; Johnston *et al.*, 1999a: 2000a).

The production from different types of aquasilviculture systems in Ca Mau is presented in Table 7. Production is low for all systems, averaging some hundred kilograms per year, and even if accounting for the multiple products of fish and crustaceans they fall short when comparing with production per unit area from intensive culture of e.g. shrimps or fish. Johnston (2000b) showed that yields were significantly higher from extensive aquasilviculture farms compared to traditional farms, and that secondary integrated products, such as fish and mud crabs, increased total farm income by 14 percent. Binh, Phillips, and Demaine (1997) demonstrated that integrated mangrove– shrimp farms with a mangrove cover of 30–50 percent of the pond area had higher economic returns compared to farms where mangrove had been cleared. This comparison included only farms depending on natural productivity.

Even when production of various land crops and yields from the mangrove forest are included, both production and profits are still relatively low. However, mixed mangrove-aquaculture systems have been sustainable for a long time (FitzGeralds, 2002); while semi- and intensive shrimp pond farming have had limited lifetime due to their environmental impacts (Kautsky *et al.,* 2000). Further, clearance of mangroves, and degradation of the coastal environment involved with more intensive shrimp pond-farming in the intertidal zone leads to loss of various goods and services from the coastal zone (Rönnbäck, 2001), something that impacts negatively on other people

TABLE 7
Production from different mixed mangrove-aquaculture systems in Ca Mau, Viet Nam. Kg/ha/year

Production	Traditional	Hatchery reared shrimp	Hatchery reared shrimp/crab	Hatchery reared shrimp/crab and cockle
P. monodon		72 ± 85	107 ± 99	107 ± 99
Shrimps[a]	290-400	333 ± 111	425 ± 102	425 ± 102
Crabs[b]		24 ± 13	62 ± 50	62 ± 50
Cockle[c]				1.300
Fish[d]				
Mangroves[e]				

a) *Metapenaeus ensis* and *M. lysianassa* and to some extent also *P. indicus*
b) *Scylla sp.*
c) *Anadara granosa*
d) Fish mainly for household consumption
e) Contributing only with about 1 % of household selling

Sources: from Minh *et al.* (2001), Johnston *et al.* (1999a).

living within and from the coastal or adjacent inter-linked ecosystems (i.e. in the seascape). Hambrey (1996b) calculated that, due to low investment requirements, traditional activities such as mud crab fisheries and charcoal or pole production have a higher profit margin than any form of aquaculture developed in mangrove areas. Crop diversification on a farm also reduces the risks from income and food loss, something that is especially important for subsistence farmers. More intensive shrimp aquaculture depends on high capital investment and is susceptible to diseases (Clough *et al.*, 2002), which for most farmers imply high risks.

Aquasilviculture in Viet Nam has been developing towards maximizing production of higher valued species per unit area by means of increased inputs (feed and seed) (Clough *et al.,* 2002). In addition to shrimps, the mangrove crab is increasingly being farmed. This is not specific for Viet Nam but it is seen in other countries as well. The mangrove crab has been shown to be a good species for polyculture, particularly with finfish species (milkfish and tilapia) and seaweeds (*Gracilaria*). Crabs for grow-out are either stocked directly in the culture pond or in pens situated in the mangroves. The latter is being practised in the Philippines and Sarawak, East Malaysia (Primavera, 2000) (see below).

The development of intensive aquasilviculture practices in e.g. Ca Mau province may generate short-term benefits but results in the eventual loss of productive land (Clough *et al.,* 2002). This would indicate the need for proper land use planning and implementation of incentives for sustainable farming practices (i.e. enabling mangrove conservation) (Clough *et al.,* 2002). However, the question remains, what practices meet the sustainability criteria in a broader sense? The National Consortium for Forest and Nature Conservation in Indonesia reviewed five mixed mangrove – aquaculture systems, ranging from traditional to more intensive, and concluded that a single sustainability model could not be identified for all locations, since such models are highly site specific as well as subject to other local conditions that influence a system's sustainability (Anonymous, 1996b).

Case study 2 – Mud crab farming in the Philippines

Mud crab farming is argued to be environment-friendly, particularly to mangroves (Primavera, 2005). The culture of mud crabs *Scylla* sp. in mangrove pens can be conducted in such a way that mangroves are preserved both within and out-side the net pens. Feed usually consists of low-value fish, which may be questionable from a sustainability perspective in those cases where such fish constitute affordable and needed protein source for poor people. The interaction between mangroves and mud crab farming, both with respect to benefits from integration, and potential negative impacts on the mangrove ecosystem have not been sufficiently evaluated. Primavera *et al.*,

Mudcrab aquasilviculture, Aklan, Philippines.

TABLE 8

Summary of survival and production of wild *Scylla olivacea* with different feeding treatments in 200 m² mangrove pens in Zarraga, Iloilo

		No feeding	1 month supplem. feed	Fish	Pellets
BW (g)	Initial	65.9 ± 4.5	68.2 ± 6.9	65.1 ± 4.0	58.2 ± 2.7
	Final	114.5 ± 5.2	119.6 ± 5.2	129.3 ± 4.6	121.2 ± 4.6
Survival rate (%)		15.2	19.2	21.8	15.9
Total prod. (kg)		8.6	11.4	14	9.6

Source: from Primavera *et al*., (in revision).

(in revision) studied how mud crabs pen systems (mixed of *Scylla olivacea*, *S. serrata*, and *S. tranquebarica*, stocked at 0.5–0.8/m² in 400/m² net pens) can benefit from mangrove production by comparing performance of different feed alternatives. The study also quantified impacts on mangrove macroflora from pen crab farming in the Aklan province, central Philippines. The different feeding treatments included no feeding (natural productivity), no feeding for 1 month + supplementary feeding, fish, low-cost pellets (2 percent fishmeal), and pellets + fish. Not surprisingly the crabs being fed fish had the highest production, but the difference in survival rates was not significant between the treatments (Table 8). The study showed that growth rates among different treatments, including crabs with no feeding, were similar during the two first months of cultivation. A sensitivity analysis, comparing fish with pellets + fish, showed improved economic performance for the latter.

The crab cultures did not affect mangrove trees, although it reduced species diversity and also numbers and biomass of seedlings and saplings (Primavera *et al.*, in revision). The authors recommended mud crab pen culture in mangroves with mature trees, but not in newly planted or newly colonized (wild) areas, and suggested that development of low-cost pellets can reduce dependence on local fish.

Mangroves as nutrient filters for shrimp pond effluents

Studies on aquasilviculture systems have mainly focused on production, and less on water nutrient quality (e.g. Johnston *et al.*, 2002; Primavera *et al.*, 2007). However, information about the role of mangroves for nutrient sequestration does exist, mainly in association with pond culture of shrimps (and sewage treatment). Thus another way to integrate aquaculture and mangroves is to discharge pond effluents into natural or planted mangrove forests. This approach is different from extensive aquasilviculture, and in addition to mangrove conservation it also aims at limiting the risk of eutrophication of adjacent open waters (Twilley, Chen, and Hargis, 1992; Robertson and Phillips, 1995; Massault, 1999; Rivera-Monroy *et al.*, 1999). The function of mangroves to act as nutrient sinks has been emphasized (Nedwell, 1975; Tam and Wong, 1993; 1995; 1996; Corredor and Morell, 1994; Wong *et al.*, 1995; Alongi, 1996; Tam, Yang and Wong, 2006). Specific processes studied were sedimentation, decomposition, nutrient uptake by plants and bacteria, nitrification-denitrification, and soil absorption of nutrients (Nedwell, 1975; Robertson and Phillips, 1995; Boyd and Tucker, 1998; Rivera-Monroy *et al.*, 1999). The use of mangroves as filters for absorbing effluents of intensive shrimp culture ponds is being recommended in countries like the Philippines (Primavera, 2000; Baliao and Tookwinas, 2002).

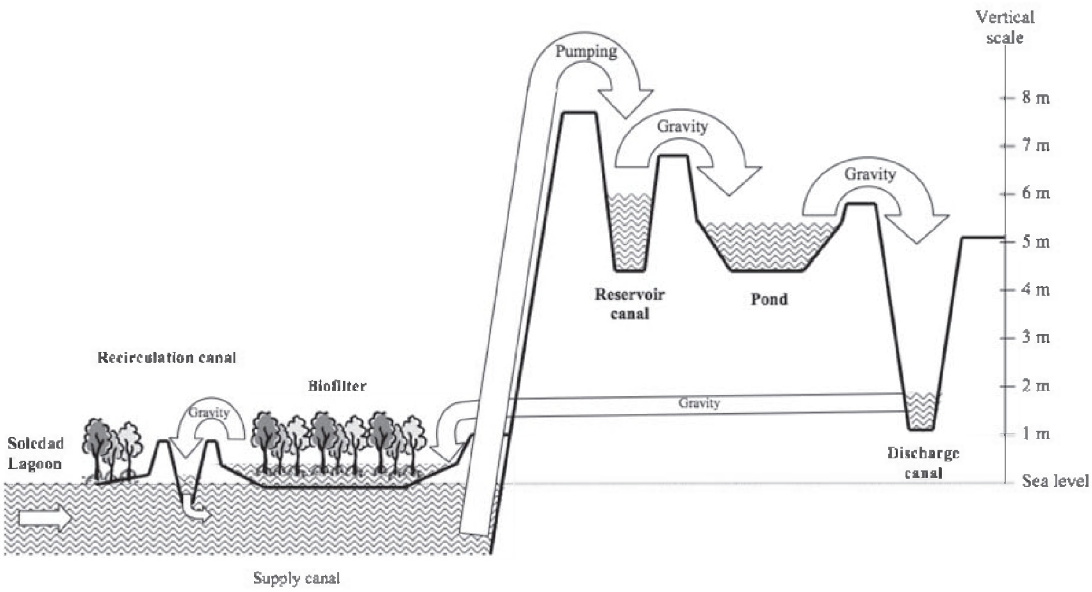
The discharge of aquaculture wastewater to the sea through mangroves is likely to benefit coastal fisheries and mangrove growth, and minimize coastal contamination (and thereby providing a higher-quality water supply for coastal aquaculture in general) (Boyd, 1997; Primavera *et al.*, 2007). There are, however, only a limited number of studies investigating how aquaculture farm effluent impacts mangrove nutrient absorption/transfer efficiency and productivity in the mangrove food web (Sansanayuth *et al.*, 1996; Massaut, 1999; Rivera-Monroy *et al.*, 1999; Rivera-Monroy, Twilley and Castañeda, 2001; Gautier, Amador and Newmark, 2001; Gautier, 2002; Valderrama and Engle, 2002; Primavera *et al.*, 2007). This is, however not surprising as measuring nutrient fluxes in coastal wetlands proved to be difficult (e.g. Boto and Robertson, 1990; Wattayakom, Wolanski and Kjerfve, 1990). Theoretical calculations show that 2–22 ha of mangrove wetlands are required to remove nutrients produced by 1 ha of semi-intensive shrimp pond (Robertson and Phillips, 1995) (Table 9). However, this calculation was based on uptake by the mangrove vegetation and did not take into account nutrient loss through denitrification, sedimentation, and soil absorption (Boyd and Tucker, 1998; Rivera-Monroy *et al.*, 1999). Theoretical calculations based especially on vegetation uptake data are complemented by actual trials using both natural mangroves (Boonsong and Eliumnoh, 1995; Gautier, 2002; Primavera *et al.*, 2007) and constructed or planted mangroves (Sansanayuth *et al.*, 1996; Ahmad, 2000) to treat shrimp pond wastes.

Based only on plant uptake Rivera-Monroy *et al.* (1999) found that 0.5–1.8 ha of Colombian mangroves were needed to remove dissolved inorganic nitrogen produced by 1 ha of semi-intensive shrimp pond. This ration dropped to only 0.04–0.12, once the denitrification capacity of the mangroves was also considered. Even though it is difficult to extrapolate to other areas due to large variability and complexity of mangrove systems, these findings suggest that some, but not all, mangroves can effectively treat aquaculture wastes. Denitrification was of only minor importance (< 1 percent of the total N budget) in a pristine mangrove forest comprised of *Rhizophora*

TABLE 9
Comparison of published ratios of mangrove: shrimp pond area, illustrating the areas of mangroves that are needed for total removal of nutrients released in shrimp pond effluents

Reference	System	Mangrove: pond ratio (area)	
		N	P
Boonsong and Eiumnoh, 1995	Intensive	9:1	8:1
Robertson and Phillips, 1995	Intensive	7:1	22:1
	Semi-int.	2:1	3
Kautsky *et al.*, 1997	Semi-int.	6:1	6:1
Primavera, 2005	Intensive	3-7:1	
	Semi-int.	2:1	

FIGURE 8
Construction and flows through a mangrove biofilter in Colombia. Water directed by concrete structures and several exits, allowing for controlling water residence time before being released into adjacent lagoon



Source: From Gautier (2002).

(Kristensen, 1997). Mangroves (a mix of planted and natural) only partially biofiltered shrimp wastes in an integrated semi-intensive system (*Litopenaeus vannamei*) and mangroves (dominated by *Rhizophora mangle*) Gautier (2002). Water flow through the 120 ha mangrove forest, which was surrounded by levees, was directed by concrete structures and several exits (allowed for controlling water residence time) within the mangrove unit before the water entered the adjacent lagoon (Figure 8). The mangroves decreased the suspended solid concentration, but concentrations of dissolved nutrients (SRP, TAN, and NO_3) increased after passing through the mangrove biofilter; this latter phenomenon being explained by production of guano by a large bird community.

The authors concluded that mangrove growth and regeneration constituted an important factor for nutrient storage, but that nutrient cycling within the mangrove system was still poorly understood and needed to be further investigated. The study did not examine sediment biogeochemistry or fauna within the mangroves. As no water exchange was allowed from the lagoon into the mangrove biofilter, the mangroves function as nursery and feeding ground was lost. This could have negative consequences for coastal fishery production in the area.

Valderrama and Engle (2002) used own data and results from Rivera-Monroy *et al.* (1999) and Rivera-Monroy, Twilley and Castañeda (2001) to estimate the potential nitrogen and phosphorus treatment capacity for mangrove forests receiving effluents from shrimp aquaculture ponds in Honduras. The largest mangrove area calculated was for total nitrogen removal (45 percent of farm) and this was in accordance to Rivera-Monroy, Twilley and Castañeda (2001).

Valderrama and Engle (2002) also calculated net returns for different Better Management Practices (BMPs) options and could show that natural and artificial mangrove biofilters involved the highest costs (Table 10). Construction of both settling basins and mangrove wetlands drastically reduced profit margins. The authors concluded that sophisticated mangrove biofilters could not be recommended for small farms in Honduras, and that financial incentives are required for farmers to adopt such practice. Valderrama and Engel (2002) (referring to work by Gautier (2002)) pointed out that such integrated system can result in significant savings if an effluent tax is

TABLE 10
Annual enterprise budget for an 85-ha shrimp cooperative in Nicaragua based on 2001 prices and costs. Two production cycles per year were assumed

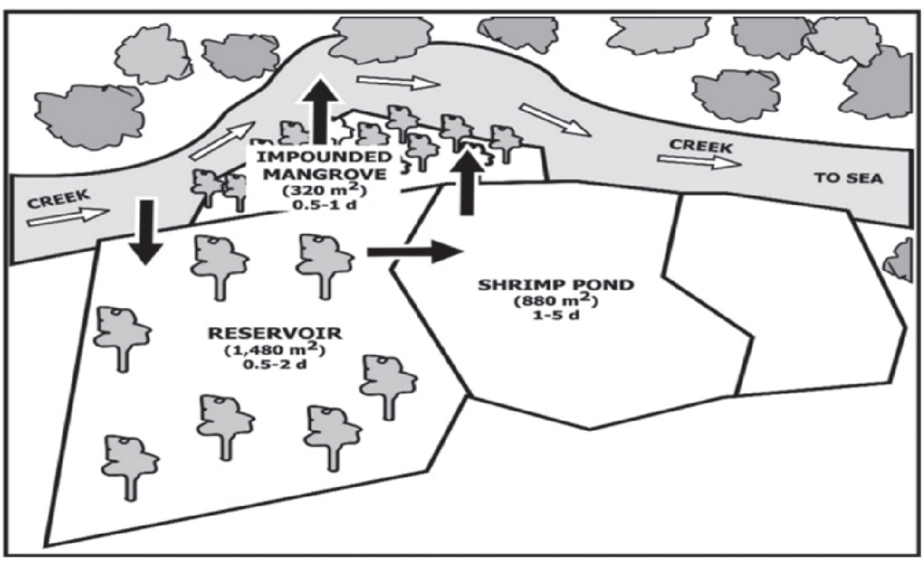
MBP	Net returns/ha in baseline scenario	Net returns/ha in BMP scenario (US$/ha)	Change	Description of change
Reduction in water exchange rates from 10-11% to 5%	483	648	34%	Total diesel cost decreased from US$7,701 to US$3,618
Application of entire ration of feed on feed trays	483	751	55%	Total feed cost decreased from US$24,753 to US$18,147
Combined BMP: reduced water exchange rates and use of feed trays	483	916	89%	Changes as above
Settling basin installation	483	244	-50%	Fixed costs increased by US$240/ha (annual amortized cost of basin)
Construction of mangrove biofilter – Natural forest	483	333	-31%	Fixed costs increased by US$150/ha (annual amortized cost of biofilter)
Construction of mangrove biofilter – Artificial forest	483	-442	-192%	Fixed costs increased by US$925/ha (annual amortized cost of biofilter)

Source: From Valderrama and Engle (2002).

practised. This, together with the fact that mangrove biofilters allow for partial or complete recirculation of effluent-waters, could be seen as something positive for a farmer.

In another study, Primavera *et al.* (2007) estimated that 2.2 and 4.4 ha of mangrove area were required to process nitrogen wastes from one ha of semi-intensive and intensive shrimp pond (*P. monodon* with milkfish being separated by a net pen), respectively. In Table 9 this ratio is being compared to ratios obtained in other studies (theoretical and actual experiments). Differently from the study by Gautier (2002) the mangrove filter studied by Primavera *et al.* (2007) allowed incoming tides into the experimental ponds. This facilitated the entrance of wild organisms which could utilize the mangrove area and could then return to adjacent waters (Figure 9). Thus, mangroves used in such way retained some of their natural functions. Generally, brackishwater

FIGURE 9
Schematic outline of aquasilviculture experiment conducted in the Philippines



Source: From Primavera (in revision).

pond aquaculture and mangroves are mutually exclusive since most fish and shrimps, require a permanent water column. In contrast, the growth and survival of mangrove trees, the dominant components of the ecosystem, require periodical water drainage by low tides. Therefore only a few animal taxa – mainly epifauna and infauna such as crabs and bivalves that bury in the substrate can be integrated in hydrologically-intact mangrove habitats (Primavera, 2000; Williams and Primavera, 2001). None of the above-mentioned studies were, however, conducted over a longer time period, and because the "mangrove filter" functions as a sedimentation pond, the long-term impact of effluents on mangrove ecosystem has yet to be assessed (Gautier, 2002).

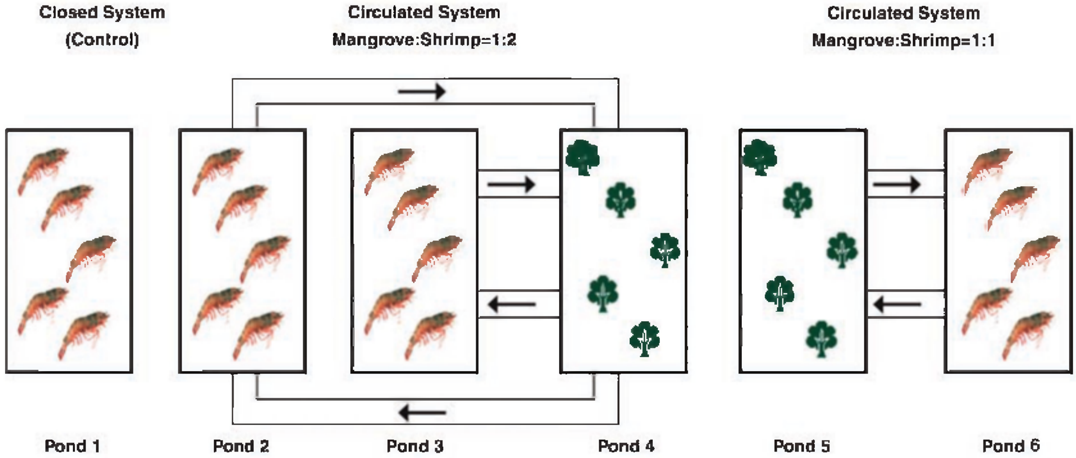
The use of constructed mangrove ponds (*Rhizophora mucronata*) to purify shrimp (*Penaeus monodon*) pond waste-water has been studied as part of a sustainable aquaculture research collaboration between the Faculty of Fisheries, Kasetsart University, Thailand, and Japan International Research Center for Agricultural Sciences (JIRCAS) (Fujioka, 2005; Fujioka *et al.*, 2006; 2007). This effort was part of the research project "Studies on sustainable production systems of aquatic animals in brackish mangrove". Fieldwork at Samut Songkhram Fisheries Research Station, optimized mangrove pond and shrimp pond ratios (Figure 10), and measured the role of benthic organisms and shrimp production in mangroves receiving shrimp wastewater (Fujioka *et al.*, 2006). It was concluded that the mangrove system was overloaded if receiving shrimp wastes from shrimp farm area twice the size of the mangrove area. However, if areas allocated to shrimp and to mangrove were of similar size, bentic organisms were positively effected which also resulted in improved shrimp production (Fujioka *et al.*, 2006). There was no significant difference in nutrient concentrations between water in mangrove-shrimp ponds and single shrimp ponds (Fujioka *et al.*, 2006) Biogeochemical processes were, however, not studied in greate detail in these studies.

In Indonesia, Ahmad (2000) and Ahmad, Tjaronge and Suryati (2003) used natural mangroves in a "reservoir pond" to treat shrimp pond effluents. Water nutrient concentrations were lower in the mangroves than in the shrimp pond, but nutrient levels (particularly ammonia) slowly built up in both ponds. It was difficult to say anything about nutrient removal efficiency from the experiment as no controls were used. A separate tank experiment, to isolate nutrient uptake and water quality

PHOTO: YOSHIMI FUJIOKA

Integrated mangrove-aquaculture at Samut Songkhram Fisheries Research Station, Kasetsart University, Thailand.

FIGURE 10
Set-up of mangrove ponds (*Rhizophora mucronata*) to treat shrimp pond effluents (*Penaeus monodon*) in recirculation systems



Source: From Fujioka *et al.* (2006).

(i.e. microorganisms activity processes), did not result in any better understanding about efficiency. The potential benefits from mangrove production of bioactive compounds, acting as bactericides, was indicated by the findings that *Vibrio* spp. were always found to be lower in the mangrove reservoir water. However, the benefits to the shrimps from such reduction need to be studied in more detail, as shrimp are bottom dwellers and get exposed to bacteria populations in the sediments.

Special cases of integration

Farming herbivorous fish as feed for carnivore fish in polyculture

Polyculture where piscivorous fish species are used to control free spawning of targeted cultured fish species have been common practice in many tropical countries (i.e. for tilapia culture) (Guerrero, 1982; Mair and Little, 1991). Such practice reduces the risk of over-population and thereby increases economic performance. Variants of the practice include using larger predatory fish to control herbivorous fish in seaweed cultures (described earlier in text). Appendix 2 includes studies testing farming sea urchin on oyster ropes to control epiphytes (Lodeiros and Garcia, 2004), and Siganidae fish in cages with oysters to control epiphytes.

Poor Asian fish farmers often cannot afford good quality artificial feeds, necessary to farm higher valued fish species. A polyculture technique, where low valued inputs are transformed into high valued fish through intermediate production of low valued fish, has been applied by some farmers. Example of this practice can be seen in the Thai Ban Pho and Bang Pakong districts, were some farmers polyculture barramundi and tilapia in 0.6–1.6 ha ponds (personal observations, and personal communication Anocha Kiriyakit, AIT). The practice has been implemented in larger ponds in other districts. Water depth in such ponds is about 2–3 meters and they are prepared before stocking by draining, use of cyanide to get rid of snakehead fish (Channidae), and then dried for 3–4 days. Clean water is then pumped into the pond and chicken manure is applied 5–7 days before stocking takes place. Tilapia is stocked first, at about 40 000 fingerlings per hectare, and 3-4 months later 4 000 barramundi per hectare are added. The fish (i.e. mainly the tilapia) are then fed once a day with by-products (e.g. waste of soybean, waste from fish and chicken factory, rice bran, etc.). The type of feed added depends on availability and price. The carnivorous barramundis depend mainly on juvenile tilapias that are readily available from free spawning in the pond. The salinity of culture water depends on the seasons, and it is around 20 ppt during January to April, and then gradually decreases to 0 ppt in July. The harvesting of barramundi in polyculture usually takes place after about 10–12 months, mainly around August when demand and price of barramundi is at its maximum. Price of tilapia is more stable throughout the year. Yearly harvest per hectare of polyculture pond is around 2.1–4.2 tons of tilapia and 0.3–0.42 tons of barramundi.

Green water systems

"Biomanipulators" (e.g. all-male tilapia, milkfish, grouper, etc.) have been increasingly used, especially in shrimp farming polyculture (or practised as sequential integration) to "treat" the water (Wang *et al.,* 1998; Baliao, 2000; Yap, 2000; Corre, 2000; Fitzsimmons, 2001; Paclibare *et al.,* 2002; Lio-Po *et al.,* 2005; Tendencia, de la Peña and Choresca, 2006; Martinez-Cordero, Duncan and Fitzsimmons, 2004; Yi and Fitzsimmons, 2004; Yi *et al.,* 2004; Cruz *et al.,* 2007). Tilapia is often co-cultured with shrimps, in a wide range of salinity levels (from 0 to 30 percent), where the system either utilizes water from separate tilapia culture ponds and reservoirs, or tilapia are being stocked in cages inside shrimp pond or even mixed in the same ponds (Akiyama and Anggawati, 1999; Lio-Po *et al.,* 2005; Yi and Fitzsimmons, 2004). The excretion of nutrients from co-cultured species stimulates phytoplankton blooms, It is not exactly known what creates the positive qualities of the water (Leaño *et al.,* 2005), but for shrimp farming this methodology may tackle disease problems in multiple ways: 1) the treated water may be beneficial to the shrimps by reducing light intensity and thereby decreasing stress at the bottom where the shrimps stay most of the time, 2) by preventing the growth of benthic algae, 3) by helping oxygenate the water during the day, 4) by stabilizing water temperature, 5) by promoting the development of a favorable microbial community composition, 6) by removing potentially toxic faecal wastes and metabolites, and 7) by promoting enzyme enhancement (Martinez-Cordero, Duncan and Fitzsimmons, 2004; Izquierdo *et al.,* 2006). The "greening" effect of the culture environment can, however, also be achieved by other means than adding co-cultured species (Izquierdo *et al*., 2006).

Tilapia production in former shrimp ponds (with and without shrimp) has increased rapidly in many countries including Thailand, the Philippines, Honduras, Mexico, Peru and the inland desert of Arizona (Yap, 2000; Fitzsimmons *et al.,* 2003). Results from a survey carried out in twelve Provinces in Thailand (Yi and Fitzsimmons, 2004) indicated that 42.6 percent of the farms used a simultaneous tilapia-shrimp polyculture system, and 16.4 percent used shrimp monoculture water from reservoir stocked with fish. Among the farmers practising mixed farming, 76.9 percent released tilapia directly into shrimp ponds, and 23.1 percent stocked tilapias in cages suspended in shrimp ponds. Farmers practicing green water technology with fish stocked in a larger reservoir will have to reduce the shrimp pond area to fit within the culture site. Income losses from reducing shrimp production area can be compensated by the sales of fish raised in the reservoir, and a more stable water quality will result in higher shrimp production per area (from suppression of growth of pathogenic *Vibrio*).

In the Philippines a 1:1 ratio of shrimp culture to reservoir area is being recommended. The reservoir is stocked with fish (e.g. tilapia) at 3–3.5 tons/ha. This maintains blooms of beneficial microalgae like *Chlorella*, having a suppressive effect on *V. harveyi* (Corre *et al.,* 1999). The fish are also stocked in a cage inside the shrimp pond (Guerrero, 2006; Guerrero and Guerrero, 2006). In shrimp-milkfish polyculture, practised in areas where shrimp farming is no longer viable, the recommended area ratio has been 3:1 (Tendencia, de la Peña and Choresca, 2006).

Although today, fish are mainly being considered as a promoter of beneficial effects on water quality, in the future, alternative species groups such as seaweeds may function similarly. Seaweeds have been shown to inhibit aquaculture pathogenic bacteria (Nagahama and Hirata, 1990; He *et al.*, 1990; Pang, Xiao and Bao, 2006) and viruses (Tsutsui *et al.*, 2007).

Development, incentives and constraints

Biological methods for water treatment based on integration with non-microbial organisms have been investigated and implemented in many tropical countries. Several approaches and designs removed both particulate and dissolved wastes, and at the same time also generated additional aquaculture crops and benefited physiologically the main cultivated species (see Appendix 2). However, the systems that have actually been implemented by farmers have generally belonged to the "simpler" polyculture practices, either traditional or based on more recent scientific findings. The question is then why new practices and technologies, for example sequential farming techniques, both on land and in open waters, have not become implemented at any larger scale in tropical countries (or elsewhere). The answer is probably related to the greater skills required for multi-unit multi-species culture, as different species and different units require different culture conditions and protocols. This is different from polyculture, where organisms share and must tolerate the quality of a common culture unit. Polyculture is thus simpler, even though of course it limits the species that can be farmed together, considering competition for feed, oxygen, and space (Lutz, 2003).

In small-scale experiments it may be easier to show the efficient biofiltering capacity and growth of co-cultured species, but when the technology is adjusted to larger scale operations it may prove difficult to match the different species requirements and maximize their exposure to the wastes in question. This will involve issues like water movements and retention times, particle and nutrient densities, water temperature and salinity, etc. Bivalves, for example, may be sensitive to salinity fluctuations, which may cause problems during some parts of the year. Oyster growth may be depressed if cultured too close to the bottom dominated by particles with low nutritional value (Lin, Ruamthaveesub, and Wanuchsoontorn, 1993; Soletchnik, Lambert and Costil, 2005). Another aspect with respect to filter-feeders is the production of faeces and pseudo-faeces that can add to the sediment load in the system (Troell and Norberg, 1998; Smith, 1999). Further, the scaling up from small scale experiments may reveal unknown effects with respect to performance at commercial scale (Troell *et al.*, 2003).

This can be illustrated by preliminary experiments on polyculture of shrimps with sea cucumbers. Combining juveniles in culture tanks of 500–1 000 L the integration was successful suggesting that such integration was possible (Pitt *et al.*, 2004; Purcell *et al.*, 2006). However, when the integration was tested in ponds using shrimps and sea cucumbers of sizes likely to be reared together during commercial operations, the survival and growth of the latter were poor (Bell *et al.*, 2007).

A review of the potential of seaweeds for the removal of nutrients from intensive mariculture, focusing especially on possibilities within tropical aquaculture in general and shrimp aquaculture in particular, Troell *et al.* (1999), concluded that there was a lack of information on the feasibility of the approach. Even though more studies have been conducted since then there still seems to be a lack of knowledge or/and interest in what intuitively seems to be a straightforward environmentally benign practice. Briggs and Funge-Smith (1993) reviewed the possibilities of culturing seaweeds together with shrimps. Data on growth, physiological properties, economic values, etc., led them to conclude that seaweeds could favorably be used as biofilters in shrimp ponds, being cultured either as polyculture or in an adjacent sedimentation pond (of about 30 percent of the shrimp pond area in size). The measured benefits of the seaweeds were nutrient removal, and lessening of blooms and crashes of phytoplankton. The authors, however, pointed out the need for larger-scale experiments. Some seaweed species can be sensitive to salinity fluctuations, and can also suffer from light limitation in turbid and eutrophic pond effluents, as well as smothering by sediment and epiphytic microbial growth (Smith, 1999; Troell *et al.*, 1999). Indeed, poor seaweed growth in shrimp ponds has been linked to high epiphytic load and high water turbidity (Phang *et al.*, 1996; Nelson *et al.*, 2001; Marinho-Soriano, Morales and Moriera, 2002).

Integrated practices in open culture systems, characterized by a continuous exchange of water, which makes waste disposal difficult to control, have been rarely investigated in the tropics (Troell *et al.*, 1999; Troell *et al.*, 2003). The expansion of coastal cage farming (which is open by nature) in many tropical countries should provide opportunities to develop and study integrated practices, building upon experiences from temperate regions (China, Japan and Canada).

Issues related to sanitation, food safety, and environmental quality need to be considered in integrated aquaculture systems (Taylor, 2004). The predominance of regulatory regimes and instruments in aquaculture are relevant to monocultures much more than to integrated systems (Walrut, 2003). This implies that species produced in mixed cultures will be subject to the same regulations as those from monocultures, i.e. following regulations and standards specific for each individual species included in the culture, while positive or negative implications of the integration may be overlooked. From a European perspective, however, it is not likely that deployment of biofilter organisms should hinder development where a farm would be authorised under all other criteria (White and Pickering, 2003). Nevertheless, it has been argued that in many instances the development of multiple species culture may be subjected to further regulatory requirements in the future (White and Pickering, 2003). This will probably also be the case for integrated aquaculture in the tropics. Potential transmission of pathogens (or chemicals) from one species to another (Taylor, 2004; Etienne *et al.*, 2006), not only within the farm practicing integration, but also spreading to neighbour farms may occur. A federal regulation in Canada restricted the harvesting of shellfish within 125 m of a source of organic waste. However, IMTA research demonstrating that fish-farm waste does not constitute the same health issues as human wastes, has changed this regulation (Taylor, 2004). However, there is a need for more research on this topic in e.g. the tropics, in light of promising results about these isssues from integrated systems in other climates (see refs in Neori *et al.* [2007]).

It is also important to recognize that one practice, developed for a specific system or place, may need to be tested before being transferred and implemented in a different region or locality. For example, the ability of biofiltering systems to improve water quality may vary depending on initial water quality. In shrimp pond farming, factors like pond soil type, quality of affluent water, stage of the grow-out season, and management practices can all influence water quality (Ziemann *et al.*, 1992 in Jones and Preston, 1999). It may also be difficult to generalize about economic performance (in those cases where it has been evaluated) because of the complexity of economic analyses.

Economic performance is probably a main reason for the low implementation rate, even after so many trials, of integrated designs and species combinations, especially of sequential practices in shrimp farming. Economic constraints in production and operating costs often make the treatment of farm wastes difficult to support (Muir, 1982), particularly in developing countries. This would also be true for more technologically integrated farming approaches (i.e. re-circulation) that may be more capital-intensive with higher labor costs for handling and harvest. The economic feasibility of most integrated practices experimented so far has not yet been demonstrated, especially at large-scale implementation (commercial). Thus, even though there are opportunities for integration, there is a need to clearly show and explain to farmers how resource use, space requirements, management, marketing, and economic issues could be solved. Existing monoculture farmers would otherwise be reluctant to move towards integrated systems (Hambrey and Tanyaros, 2003).

Incentives that could be used to promote integrated practices are of economic (increased profits) and regulatory nature. The economic incentives may be related less to short-term profits than possibly to risk management, disease management, market acceptability, and additional sustainability considerations. Drivers for practising IMTA are found at different levels. The most obvious, at a farm level, is the economic gain from producing an additional crop. Thus, if no net benefits are resulting from inclusion and subsequent sale of added extractive species, the farmers will have no immediate profitability incentive to practise IMTA. This may excludes many extractive species. However, when the costs of environmental degradation by monoculture are estimated, internalized by regulations and taken into account in the production costs, this could increase the value of extractive species as their environmental services are accounted for. Further, where limitations to nutrient emissions apply, production of the main farmed organism could expand thanks to nutrients recycling by extractive species (a concept of nutrient credits, similar to that of carbon credits). Thus, from a societal perspective, these incentives together with potential consumer preferences for species produced in IMTA systems provide a higher return for the additional biofiltering (extractive) crop. Today the benefits are seen almost exclusively from a corporate/farm level, but not from a broader more general societal perspective.

Even though wastes from certain types of aquaculture are now considered by society as having wider negative environmental impacts, the costs of their mitigation represent no monetary compensation to the farms. This situation stems in part from the complexities involved in the identification and quantification of environmental impacts. Before the costs of certain mitigation efforts can be determined, it is necessary to know what values (goods and services) are being generated from the impacted system – i.e. a natural coastal ecosystem (or freshwater system), and how they are affected from aquaculture wastes (to be separated out from all other potential factors). Even though the information is scarce, this perspective needs to be addressed to encourage the development of new integrated technologies. An accurate or better estimate of overall ecological and economic benefits should create incentives for joint financing by diverse stakeholders within the sector (i.e. governments and the aquaculture industry).

While the initial financial risks may be steep for integrated practices at a shrimp farm, the possibility to run a closed system with biofilters could eliminate many of the production risks that are beyond the control of most shrimp farm operators (e.g. affluent water quality, diseases, etc.). However, this objective may be achieved also by other means than integrating with macroscopic animals and plants, illustrated by the recent development of "flock systems" in shrimp farming (Fast and Menasveta, 2000; Moss *et al.*, 2001; Rosenberry, 2006).

In general, polycultures or other forms of multi-species systems have the possibility to reduce the financial risks, e.g. securing income if markets change drastically or if disease outbreaks affect one species. However, in practice, many farmers still prefer the simplicity of farming only one species. Thus, to promote changes in this widely adopted practice there is a need for developing economic incentives, or even implementing regulations to encourage greater diversity in aquaculture. Culturing more than one species should of course not be an ultimate goal for all farmers, but in situations when farmers choose to culture species in systems generating negative environmental impacts, integration should be promoted. Also farmers seeking quick returns from focusing on only one international "cash crop" species (risking significant market price fluctuations), may benefit from diversifying production. Certification systems, that include integrated approaches, could create incentives for farmers to adopt such practices. However, the many small-scale producers, that today operate some of the most efficient, environmentally sustainable, and socially equitable systems (extensive practices), may not be able to participate in certification schemes and traceable supply due to the different and costly standards that need to be met.

CONCLUSIONS

There have been many different mixed species aquaculture systems in study and in operation throughout the tropics, especially so in South-East Asia. Of significance are the many varieties of polyculture in earthen ponds, the mangrove-mixed cultures and the rice-shrimp systems. Extensive shrimp and fish polyculture ponds dominate integration. Single-pond extensive polyculture techniques, which entail low levels of skill, capital investment and operation costs, are more suitable to small-scale farmers compared with sequential practices. However, in many countries there seems to be a trend of intensification in aquaculture. In many cases, this means also implementation of monocultures, whose adoption of IMTA practices requires separation of the cultured species in place and/or time.

The integration of shrimp with mangroves is an innovative approach, but before this can be promoted at any scale more research will be needed. This is also true for the special form of mixed mangrove-aquaculture. However, in addition to focusing on pond engineering and management in these systems, it is important to also focus on socio-economic characteristics of such practice, including both farm level and overall coastal communities at large. Mixed rice-shrimp culture has been practised in large scale and for a long time in many countries (e.g. Bangladesh, Viet Nam, and India), and these systems could be potentially be improved further.

The many experimental studies carried out on tropical species and systems have investigated various aspects of polyculture and integrated aquaculture. Most research efforts have been on different species combinations and systems aimed at generating additional crops, improving the quality of e.g. effluents discharged from shrimp cultures and to improve the culture environment. This has involved integration with species like tilapia, milkfish, oysters, mussels, seaweeds, etc. However, the many experimental trials on shrimp farms seem not to have been carried out in a systematic way and no real promotion/adoption of such systems seem to have been achieved. This may reflect that no successful system has been developed that is simple and profitable enough to appeal to farmers, considering the added costs involving new skills, investments and operation. Industrial research has also been carried out to promote and develop new technologies for re-circulation involving new shrimp species (*Penaeus vannamei*) and microorganisms (i.e. bacteria), something that probably offers a more interesting alternative for large-scale farms compared to integration with larger species. To make good long-term profits such farms must recognize the complexities involved when managing multitrophic species systems and, if needed, involve appropriate expertise. This is especially important in the start-up phase.

Without a clear recognition of the aquaculture sector's large-scale dependency and impact on natural ecosystems and traditional societies, the aquaculture industry is unlikely to either develop to its full potential or continue to supplement ocean fisheries (Naylor *et al.*, 2000; Chopin *et al.*, 2001). Thus, to increase accessibility of seafood to economically depressed people, or even to maintain it at current levels, aquaculture development must be based on the right species choices and sound technologies. This is even more relevant to developing countries (Naylor *et al.*, 2000; Williams *et al.*, 2000). Thus, in solving the environmental problems associated with aquaculture the best available technology should be searched for; this may also involve extensive farming of low trophic species, in polyculture or monoculture, or more intensive re-circulation systems building on microorganisms as biological filters, or integration with larger extractive organisms. The choice of methods or systems may vary from place to place, and will depend on both the ecological as well as the social settings. Different systems may have somewhat different aims, some targeting high volume of low priced food species, some targeting export higher valued products, and some aiming mainly at providing income alternatives for poorer segments of the society. For some integrated techniques to develop there is a need for incentives that stimulate farmers to adopting certain practices that benefit the society at large. These may include rewarding systems for e.g. choosing extractive species that decrease overall nutrient loading to coastal waters, or tax systems that increase the attraction for choosing certain species. The concept of integration should also be extended to integration of aquafarms into the coastal seascapes. Thus, this would imply the integration of different farming alternatives at a more local/regional level.

ACKNOWLEDGEMENTS

I am grateful to FAO for giving me the opportunity to write this review. This report would not have been possible without help from many people, I am especially grateful for the kind help during my visit to SEAFDEC, Tigbauan, Philippines, and there especially to Amelia Arisola at the Library; to AIT, Bangkok, Thailand, and there especially to Amararatne Yakupitiyage, Khun Lucia and Håkan Berg who kindly provided help during my visit; to the Network of Aquaculture Centres in Asia-Pacific (NACA), Bangkok, Thailand, and there especially to Koji Yamamoto who provided help in my search for publications. Aaron Conrey Hartmann provided invaluable help during data search and data compilation. I am most grateful to Amir Neori for critical and constructive comments on earlier versions of this report. Doris Soto provided inputs and helpful comments on earlier drafts.

I am also grateful for receiving publications and feedback on my questions from the following people: Oliver Schneider, Beni Giraspy, John Hambrey, Peter Edwards, Yang Yi, Johan Verreth, Albet Tacon, Fatimah Yusoff, James Muir, William FitzGerald, Jurgenne Primavera, Jocelyn Ladja, Eduard Rodriguez, Anthony Ostrowski, Alfredo Quarto, Fang Jianguang, Nesar Ahmed, Kevin Fitzimmons, Rajeev Raj, Jim Enright, Luis Martínez-Cordova, Narayan Kutty, Paul van Zwieten, Mohanakumaran Nair, Ana Milstein, Abdul Wahab, Louis Lebel, Nigel Preston, Gary Newkirk, Ed Glenn, Steven Purcell, Aviti Mmochi, Heidi Atwood, Nelzon Lopez, Kwei Lin, Dao Giap, Dirk Erler, Christian Lückstädt, Yoshimi Fujioka, C.V. Mohan, Yasunori Ishibashi, Yew-Hu Chien, Westly Rosario, Robert Twilley, Anong Chirapart, Olivier Joffre, Anocha Kiriyakit, Yuni Permana, Emmanuelle Roque d'Orbcastel, Yoram Avnimelech, Alexandre Alter Wainberg, Diego Valderrama, Kou Ikejima, Malcolm Beveridge, Anne Hurtado, Iain Neish, Xavier Irz, Junda Lin, Stephen Battaglene, Ms. Rahmah, Cuimei Fen, Barry Costa-Pierce, Gopinath Nagaraj, John Hunt, Jocilla Ooi, Thai Ngoc Chien, Teodora Bagarinao and Sandra Shumway.

REFERENCES

Ahmad, T. 2000. The use of mangrove stands for shrimp ponds waste-water treatment. In *Proceedings of the JIRCAS International Workshop on Brackishwater and Mangrove Ecosystems Productivity and Sustainable Utilization*, Tsukuba, Japan, 29 Feb.-1 Mar. 2000, pp.147-153.

Ahmad, T., Tjaronge, M. & Suryati, E. 2003. Performance of Tiger shrimp culture in environmentally friendly ponds. *Indonesian Journal of Agricultural Science*, 4(2): 48-55.

Ahmed, A.T.A. 1996. Policy guidelines for management of coastal shrimp culture development. A paper presented at the World Aquaculture '96 Conference, Bangkok.

AIMS, RIA-2, NACA,. 1999a. Termination Report; Project PN9412: *Mixed Shrimp Farming-Mangrove Forestry Models in the Mekong Delta. Part A – Main Report and Executive Summary*. Australian Institute of Marine Science (AIMS), Research Institute for Aquaculture, No. 2 (RIA-2), Ho Chi Minh City; and Network of Aquaculture Centres in Asia-Pacific (NACA), Bangkok.

AIMS, RIA-2, NACA, 1999b. Termination Report; Project PN9412: *Mixed Shrimp Farming-Mangrove Forestry Models in the Mekong Delta. Part B. Technical Appendices*. Australian Institute of Marine Science (AIMS), Research Institute for Aquaculture, No. 2 (RIA-2), Ho Chi Minh City; and Network of Aquaculture Centres in Asia-Pacific (NACA), Bangkok.

Akiyama, D.M. & Anggawa, A.M. 1999a. Polyculture of shrimp and tilapia in East Java. American Soybean Association (ASA), Technical Bulletin. AQ 47-1999. 7 pp.

Alcantara, L.B., Calumpong, H.P., Martinez-Goss, M.R., Menez, E.G. & Israel, A. 1999. Comparison of the performance of the agarophyte, *Gracilariopsis bailinae*, and the milkfish, *Chanos chanos*, in mono- and biculture. *Hydrobiologia*, 398/399: 443-453.

Alongi, D.M. 1996. The dynamics of benthic nutrient pools and fluxes in tropical mangrove forests. *Journal of Marine Resources,* 54, 123-148.

Alongi, D.M., Dixon, P., Johnston, D.J., Tien, D.V. & Xuan. T.T. 1999. Pelagic processes in the extensive shrimp ponds of the Mekong delta, Vietnam. *Aquaculture*, 175: 121-141.

Alongi, D.M., Johnston, D.J. & Xuan, T.T. 2000. Carbon and nitrogen budgets in shrimp ponds of extensive mixed shrimp-mangrove forestry farms in the Mekong delta, Vietnam. *Aquaculture Research*, 31(4): 387-399.

Anonymous, 1994. The closed recycle culture system for black tiger shrimp. C.P. Shrimp News, 2(5): 2- 3.

Anonymous, 2004. Environmental sustainability of brackish water Aquaculture in the Mekong delta Vietnam. Volume 1 – summary report. GAMBAS, European Commission, contract 99/362-B7/6200.

Anonymous, 1996a. ASEAN Cooperation in Food, Agriculture and Forestry Manual. ASAEN good shrimp farm management practice. Fisheries Publication Series No. 1.

Anonymous, 1996b. Anticipating the blue revolution: the socio-ecological impacts of shrimp culture in Indonesia. The National Consortium for forest and nature conservation in Indonesia. Konphalindo. 107 p.

Anonymous, 1996c. The recirculation system, new technology for shrimp culture. In C.K. Lin and G.L. Nash (eds). *Asian Shrimp News Collected Volume 1989-1995*. Asian Shrimp Culture Council, C.P. Tower, 313 Silom Rd., Bangkok 10500, pp. 44-46.

Anonymous, 1996d. The recycle system for shrimp culture. Ibid. pp. 52–54.

Anonymous, 1996e. Successful Indonesian experience in shrimp-fish integration in recycle system. Ibid pp. 56–58.

Avnimelech, Y. 2006. Bio-filters: The need for a new comprehensive approach. *Aquacultural Engineering*, 34: 172–178.

Aypa, S.M. & Baconguis, S.R. 1999. Philippines: Mangrove-friendly aquaculture. In: Primavera, J.H., Garcia, L., Ma. B., Castaños, M.T., Surtida, M.B. (eds). Proceedings of the Workshop on Mangrove-Friendly Aquaculture; 11-15 January 1999, SEAFDEC Aquaculture Department, Iloilo, Philippines, pp. 41-57.

Baconguis, S.R. 1991. Aquasilviculture technology: key to mangrove swamp rehabilitation and sustainable coastal zone development in the Philippines. *Canopy Intl.* 17(6): 5-12.

Baliao, D.D. 2000. Environment-Friendly Schemes in Intensive Shrimp Farming. State of the Art Series. SEAFDEC AQD, Iloilo, Philippines. 27 p.

Baliao, D.D. 2000. State of Art Environment-Friendly Schemes in Intensive Shrimp farming. Southeast Asian Fisheries Development Center, Association of Southeast Asian Nations, 24 p.

Baliao, D.D. & Tookwinas, S. 2002. Best Management Practices for a Mangrove- Friendly Shrimp Farming. Aquaculture Extension Manual No. 35, Aquaculture Department, Southeast Asian Fisheries Development Center, Tigbauan, Iloilo, Philippines, 50 p.

Barbier, E.B. 1994. Valuing environmental functions: tropical wetlands. *Land Economics,* 70: 155-173.

Barbier, E.B. 2007. Valuation of ecosystem services supporting aquatic and other landbased food systems. In D.M. Bartley, C. Brugère, D. Soto, P. Gerber and B. Harvey (eds). *Comparative assessment of the environmental costs of aquaculture and other food production sectors: methods for meaningful comparisons.* FAO/WFT Expert Workshop.24-28 April 2006, Vancouver, Canada. *FAO Fisheries Proceedings*. No. 10. Rome, FAO. 2007. pp. 71–86

Barraclough, S. & Finger-Stitch, A. 1996. Some ecological and social implications of commercial shrimp faming in Asia, UNRISD Discussion Paper 74. Geneve, Switzerland: United Nations Research Institute for Social Development and World-Wide Fund for Nature International.

Be, T.T. 1994. Sustainability of Rice-Shrimp Farming System in a Brackish Water Area in the Mekong Delta of Vietnam. Master thesis, University of Western Sydney-Hawkesbury, Australia. 199 p.

Be, T.T., Clayton, H. & Brennan, D. 2003. Socioeconomic characteristics of rice–shrimp farms in the study region. In N. Preston and H. Clayton (eds). *Rice–shrimp farming in the Mekong Delta: biophysical and socioeconomic issues*. ACIAR Technical Reports No. 52e, pp 15-27.

Bell, J.D., Agudo, N.N., Purcell, S.W., Blazer, P., Simutoga, M., Pham, D. & Patrona, L.D. 2007. Grow-out of sandfish *Holothuria scabra* in ponds shows that co-culture with shrimp *Litopenaeus stylirostris* is not viable. Aquaculture, 273: 509-519.

Bennett, E.M. & Balvanera, P. 2007. The future of production systems in a globalized world. Frontiers in Ecology and the Environment, Volume 5, Issue 4,191–198.

Berkes, F., Kislalioglu, M., Folke, C. & Gadgil, M. 1998. Exploring the Basic Ecological Unit: Ecosystem-Like Concepts in Traditional Societies. *Ecosystems*, 1(5): 409-415.

Beukeboom H, Lai C.K. & Otsuka M (eds). 1993. Report of the Regional Expert Consultation on Participatory Agroforestry and Silvofishery Systems in Southeast Asia, 15-21 Nov 1992, Ho Chi Minh City, Vietnam. APAN Report No. 6, 133 pp. Asia-Pacific Agroforestry Network, Bogor, Indonesia.

Beveridge, M.C.M., Phillips, M.J. & Macintosh, D.J. 1997. Aquaculture and the environment: the supply of and demand for environmental goods and services by Asian aquaculture and the implications for sustainability. *Aquaculture Research*, 28: 797-807.

Binh, C.T. 1994. An assessment of integrated shrimp-mangrove farming system in the Mekong delta of Vietnam. Master Thesis, Asian Institute of Technology, Bankok, Thailand.

Binh, C.T. & Lin, C.K. 1995. Shrimp culture in Vietnam. *World Aquaculture*, 26: 27-33.

Binh, C.T., Phillips, M.J. & Demaine, H. 1997. Integrated shrimp-mangrove farming systems in the Mekong delta of Vietnam. *Aquaculture Research*, 28: 599-610.

Boesch D. F. & Turner, R. E. 1984. Dependence of fishery species on salt marshes, the role of food and refuge. *Estuaries*, 7: 460–468.

Boonsong, K. & Eliumnoh, A. 1995. Integrated management system for mangrove conservation and shrimp farming: a case of Kung Krabaen Bay, Chanthaburi Province, Thailand. In C. Khemnark (ed), *Ecology and Management of Mangrove Restoration and Regeneration in East and Southeast Asia*. Proceedings of the ECOTONE IV. Surat Thani, Thailand, pp 48-66.

Boto, K.G. & Robertson, A.I. 1990. The relationship between nitrogen fixation and tidal exports of nitrogen in a tropical mangrove system. *Estuarine, Coastal and Shelf Science*, 31: 531-540.

Boyd, C.E. 1997. Environmental issues in shrimp farming. In D.E. Alston, B.W. Green and H.C. III Clifford (eds). *Cultivo Sostenible de Camarón y Tilapia*. IV Simposio Centroamericano de Acuicultura. ANDAH, Puerto Rico, pp. 9-23.

Boyd, C.E. & Tucker, C.S. 1998. *Pond Aquaculture Water Quality Management*. Kluwer, Boston.

Brennan, D., Preston, N., Clayton H. & Be, T.T. 2002. An evaluation of Rice-Shrimp Farming Systems in the Mekong Delta. Report prepared under the World Bank, NACA, WWF and FAO Consortium Program on Shrimp Farming and the Environment. Work in Progress for Public Discussion. Published by the Consortium. 10 p.

Briggs, M.R.P. & Funge-Smith, S.J. 1993. Macroalgae in aquaculture: an overview and their possible roles in shrimp culture. In Proceedings of the Conference on Marine Biology in the Asia Pacific Region, Bangkok, Thailand. 16-20 November 1993.

Briggs, M.R.P. & Funge-Smith, S.J. 1994. A nutrient budget of some intensive marine shrimp ponds in Thailand. *Aquacult. fish. Manag*, 25: 789–811.

Browdy, C.L., Bratvold, D., Hopkins, J.S., Stokes, A.D., & Sandifer, P.A. 2001. Emerging Technologies for Mitigation of Environmental Impacts Associated with Shrimp Aquaculture Pond Effluents. *Asian Fisheries Science*, 14: 255-267.

Brzeski, V. & Newkirk, G. 1997. Integrated coastal food production systems - a review of current literature. *Ocean & Coastal Management*, 34(1): 55-71.

Buakham, S. 1992. Assessment of the use of green mussels for the treatment of shrimp pond wastewater. M.Sc. thesis, Asian Institute of Technology, Bangkok, 98 pp.

Bwathondi, P.O.J. 1986. The future of floating cage culture in Tanzania. In E.A. Huisman (ed). *Proceedings of African Seminar on Aquaculture*, organized by IFS, October 1985, pp. 246-252.

Candido, A.S., de Melo, A.P., Costa, O.R., Mascarenhas dos Santos Costa, H.J. & Igarashi, M.A. 2005. Effect of different densities in feed conversion of tilapia *Oreochromis niloticus* with marine shrimp *Litopenaeus vannamei* in policulture system. *Revista Ciência Agronômica*, 36(3): 279-284.

Cha, M.W., Young, L. & Wong, K.M. 1997. The fate of traditional extensive (gei wai) shrimp farming at the Mai Po Marshes Nature Reserve, Hong Kong. *Hydrobiologia*, 352: 295-303.

Chaitanawisuti, N., Kritsanapuntu, A., Kathinmai, S. & Natsukari, Y. 2001. Growth trials for polyculture of hatchery-reared juvenile spotted babylon (*Babylonia areolata*) and sea bass (*Lates calcarifer*) in a flow-through seawater system. *Aquaculture Research*, 32: 247-250.

Chaiyakam, K. & Tanvilai, D. 1989. Use of mussel and *Gracilaria* to treat the effluent water from intensive shrimp ponds. National Institute for Coastal Aquaculture, Songkhla, Thai- land. Department of Fisheries Technical Paper, 1, 26 p.

Chaiyakam, K. & Tunvilai, D. 1992. Experiments on using green mussel, *Mytilus* sp. and seaweed, *Gracilaria* fishery for biological wastewater treatment from intensive culture of tiger shrimp ponds. Technical Paper No. 6/1992, NICA, National Institute of Coastal Aquaculture, Songkhla.

Chandrkrachang, S. 1990. Seaweed/fish polyculture, a new approach in Thailand. FAO Fisheries Report 401, supp. pp. 307-308.

Chandrkrachang, S., Chinadit, U., Chandayot, P. & Supasiri, T. 1991. "Profitable spin-offs from shrimp- Seaweed polyculture". *Infofish International*, 6: 26-28.

Chen, S.N. 1995. Current status of shrimp aquaculture in Taiwan. In C.L. Browdy and J.S. Hopkins (eds). *Swimming Through Troubled Water*, Proceedings of the Special Session on Shrimp Farming, Aquaculture'95. World Aquaculture Society, Baton Rouge, Louisiana. pp. 29-34.

Chen, T.P. 1976. Aquaculture practices in Taiwan. Fisheries New Books Ltd., Farnham, Surrey, England, xiii, 162 p.

Chiang, P., Chien, Y., Liu, H. & Kuo, C.M. 1990. Some ecological aspects of prawn culture problems in Taiwan. In R. Shirano and I. Hanyi (eds). *2nd Asian Fisheries Forum*, Manila, Philippines, Asian Fisheries Society, pp. 81-84.

Chiang, Y.M. 1981. Cultivation of Gracilaria (Rhodophycophyta, Gigartinales) in Taiwan, pp. 569-574. In T. Levring (ed). Proceedings of Tenth International Seaweed Symposium, Goeteborg, Sweden. Walter de Gruyter and Company, Berlin.

Chiang,Y.M. 1992. Seaweed culture in Taiwan. In I.C. Liao, J.H. Cheng, M.C. Wu and J.J. Guo (eds). *Proceedings of the Symposium on Aquaculture*. Institute of Oceanography, National Taiwan University, Taiwan, pp.143-151.

Chien, Y.-H. & Tsai, W.-S. 1985. Integrated pond culture: a type of spatially sequential polyculture. *Journal of the World Mariculture Society*, 16: 429-436.

Chien, Y.H. & Liao, I.C. 2001. Pond Management Research in Taiwan. In I.C. Liao and J. Baker (eds). *Aquaculture and Fisheries Resources Management: Proceedings of the Joint Taiwan-Australia Aquaculture and Fisheries Resources and Management Forum*, TFRI Conference Proceedings 4, Taiwan Fisheries Research Institute, Keelung, Taiwan, pp. 135-144.

Chien, Y.H. & Liao, I.C. 1995. Integrated approach to prawn growout system design. In C.L. Browdy and J.S. Hopkins (eds). *Swimming Through Troubled Water*, Proceedings of the Special Session on Shrimp Farming, Aquaculture '95. World Aquaculture Society, Baton Rouge, Louisiana. pp. 167-182.

Chien, Y-H. 1993. Research on prawn culture system and management in Taiwan. In I.C. Liao (ed). *Proceedings of the Symposium on Aquaculture*. Taiwan Fisheries Research Institute, Taiwan, pp. 101-117.

Chirapart, A. & Lewmanomont, L. 2004. Growth and production of Thai agarophyte cultured in natural pond using the effluent seawater from shrimp culture. *Hydrobiologia*, 512: 117–126..

Chopin, T. 2006. "Rationale for developing integrated multi-trophic aquaculture (IMTA): an example from Canada" in Fish Farmer, 29: 20-21.

Chopin, T. & Yarish, C. 1998. Nutrients or not nutrients? That is the question in seaweed aquaculture. . . and the answer depends on the type and purpose of the aquaculture system. *World Aquac. Mag*., 29: 31–33, 60– 61.

Chopin, T., Buschmann, A.H., Halling, C., Troell, M., Kautsky, N., Neori, A., Kraemer, G., Zertuche-Gonzalez, J., Yarish, C. & Neefus, C. 2001. Integrating seaweeds into aquaculture systems: a key towards sustainability. *J. Phycol*., 37: 975-986.

Chopin, T., Robinson, S.M.C., Troell, M., Neori, A., Buschmann, A. & Fang, J.G. 2008. Ecological Engineering: Multi-Trophic Integration for Sustainable Marine Aquaculture In S.E. Jorgensen & B. Fath (eds). *Encyclopedia of Ecology*. Amsterdam. Elsevier, 3120 p.

Chow, F., Macciavello, J., Santa Cruz, S. & Fonck, O. 2001. Utilization of Gracilaria chilensis (*Rhodophyta: Gracilariaceae*) as biofilter in the depuration of effluents from tank cultures of fish, oyster, and sea urchins. *J. World Aquac. Soc*. 32: 214- 220.

Chua, T.E. 1997. Sustainable aquaculture and integrated coastal management, p.177-199. In J.E. Bardach (ed). *Sustainable Aquaculture*. New Jersey, John Wiley & Sons. 251 p.

Chuenpagdee, R. & Pauly, D. 2004. Improving the State of the Coastal Areas. *Coastal Management*, 32: 3-15.

Clarke, P.J., Komatsu, T., Bell, J. D., Lasi, F., Oengpepa C. P. & Leqata, J. 2003. Combined culture of Trochus niloticus and giant clams (Tridacnidae): benefits for restocking and farming. *Aquaculture*, 215: 123-144.

Clough, B., Johnston, D., Xuan, T.T., Phillips, M., Pednekar, S.S., Thien, N.H., Dan, T.H. & Thong, P.L. 2002. *Silvofishery Farming Systems in Ca Mau Province, Vietnam*. Report prepared under the World Bank, NACA, WWF and FAO Consortium Program on Shrimp Farming and the Environment. Work in Progress for Public Discussion. Published by the Consortium. 73 p.

Clough, B.F. & Johnston, D.J. 1997. Project PN9412: *Mixed Shrimp Farming – Mangrove Forestry Models in the Mekong Delta*. Annual Report to the Australian Centre for International Agricultural Research. Australian Institute of Marine Science, Townsville, 123 p.

Clough, B.F., Tan, D.T., Buu, D.C. & Phuong, D.X. 1999. Mangrove forest structure and growth. In B. Clough (ed). *Mixed Shrimp Farming-Mangrove Forestry Models in the Mekong Delta*, Termination Report, Part B: Technical Appendices, Canberra, ACT, Australia: Australian Centre for International Agricultural Research, pp. 235-251.

Corre, K.G., Corre, V.L. & Gallardo, W. 1997. The Growth, Survival, and Production of Shrimp (*Panaeus monodon*) cultured with Green Mussel (*Perna viridis*) in Semi-intensive Ponds. *UPV. J. Nat. Sciences,* 2: 1-8.

Corre, V.L. Jr., Janeo, R.L., Caipang, C.M.A. & Calpe, A.T. 1999. Sustainable Shrimp Culture Techniques: *Use of Probiotics and Reservoirs with "Green Water"*. Philippine Council for Aquatic and Marine Research and Development, Los Baños, Laguna and University of the Philippines in the Visayas, Miag-ao, Iloilo. 32 p.

Corre, V.L. Jr., Janeo, R.L., Caipang, C.M.A. & Calpe, A.T. 2000. Tips from the Philippines - Use of Probiotics and Reservoirs with "Green Water"- and another tips for a successful shrimp culture. *Aquaculture Asia,* 5(2): 34-38.

Corredor, J.E. & Morell, M.J. 1994. Nitrate depuration of secondary sewage effluents in mangrove sediments. *Estuaries,* 17: 295-300.

Costa-Pierce, B.A. 2002. The Ahupua'a aquaculture ecosystems in Hawaii. In B. Costa-Pierce (ed). Ecological Aquaculture: The Evolution of the Blue Revolution. Blackwell Publishing Limited; 2 edition, pp. 30-45.

Cruz, P.S., Andalecio, M.N., Bolivar, R.B. & Fitzsimmons, K. 2007. Tilapia-Shrimp Polyculture in Negros Occidental, Philippines. Aquaculture CRSP Abstract report, Grant No. LAG-G-00-96-90015-00.

Darooncho, L. 1991. Experiment on seaweed *Polycavernosa fastigiata* cultivation in drained pond from shrimp culture, Chantaburi Coastal Aquaculture and Research Center, Coastal Aquaculture Division, Department of fisheries, Tech. Paper No. 4, 25 p.

D'orbcastel, E.R. & Blancheton, J.P. 2005. The wastes from marine fish production systems: characterization, minimization, treatment and valorization. *World Aquaculture*, September: 28-35.

DDP, 1985. Shrimp culture in the semi-saline zone of the Delta: final report. Technical Report No. 13, Bangladesh–Netherlands Joint Programme. The Hague, Delta Development Project.

de Graaf, G.J. & Xuan, T.T. 1998. Extensive Shrimp farming, mangrove clearance and marine fisheries in the southern provinces of Vietnam. *Mangroves and Salt Marshes*, 2: 159-166.

de la Cruz, C.R. 1995. Brackishwater integrated farming systems in Southeast Asia, pp. 23-36. In: T.U. Bagarinao and E.E.C. Flores (eds*). Towards Sustainable Aquaculture in Southeast Asia and Japan.* SEAFDEC Aquaculture Department, Iloilo, Philippines, pp. 23-36.

De Silva, S.S. 1998. Tropical mariculture: current status and prospects, In S.S. De Silva (ed). *Tropical Mariculture*. Academic Press, London. pp. 1-17.

De, N.N., Thai, L.X. & Phan. P.T. 2003. Selection of suitable rice varieties for monoculture and rice-shrimp farming systems in the Mekong Delta of Vietnam. In N. Preston and H. Clayton (eds). *Rice–shrimp farming in the Mekong Delta: biophysical and socioeconomic issues*. ACIAR Technical Reports No. 52e, pp. 53-70.

Denny, M., & Fuss, M. 1983. A general approach to intertemporal and interspatial productivity comparisons. *Journal of Econometrics*, 23(3): 315-330.

Ding, T., Li, M. & Liu, Z. 1995. The pattern and principles of sythetical culture of the prawn cultivating ponds. *J. Zhejiang Fish. College*, 15(2): 134–139.

DOF, 1992. Experiments on green mussel, *Mytilus* sp., and seaweed, *Gracilaria* sp. for biological wastewater discharge treatment from intensive shrimp ponds. Bangkok, National Institute of Coastal Aquaculture, Department of Fisheries Technical Paper No. 5, 24 p.

EAS. 1998. Sustainable Aquaculture. Proceedings of the Second International Symposium on Sustainable Aquaculture, Oslo, Norway 2.-5. November, Publisher: A.A.Balkema: Rotterdam/Brookfield 1998.

EAS. 2001a. New species. New technologies. International Conference Aquaculture Europe 2001, Trondheim, Norway, August 4-7, 2001. EAS Special Publication No.29. 2001, 286 pp.

EAS. 2001b. Better Use of Water, Nutrients and Space. Handbook from International Workshop, Trondheim, Norway, August 7, 2001, EAS Publication PUB-161, 62 pp.

EAS. 2002. Seafarming - Today and Tomorrow. International Conference Aquaculture Europe 2002, Trieste, Italy, October 16-19, 2002. EAS Special Publication No.32, 2002, 562 pp.

EAS. 2003. Beyond Monoculture. International conference Aquaculture Europe 2003, Trondheim, Norway, August 8-12, 2003. EAS Special Publication No.33, 2003, 408 pp.

Edwards, P. 1992. Reuse of human wastes in aquaculture. A technical review. UNDP - World Bank Water Sanitation Program. The World Bank, Washington, D.C., USA. 350 p

Edwards, P. 1993. Environmental issues in integrated agriculture-aquaculture and wastewater fed fish culture systems. In R.S.V. Pullin, H. Rosenthal and J.L. Maclean (eds). *Environment and aquaculture in developing countries*. ICLARM Conf. Proc. 31, pp. 139–170.

Edwards, P. 1998. A systems approach for the promotion of integrated aquaculture. *Aquac. Econ. Manag*, 2: 1-12.

Edwards, P., Pullin, R.S.V. & Gartner, J.A. 1988. Research and education for the development of integrated crop-livestock-fish farming systems in the tropics. ICLARM Stud. Rev., (16), 53 p.

EJF. 2003. In M. Shanahan, C. Thornton, S. Trent, and J. Williams (eds). *Risky Business: Vietnamese Shrimp Aquaculture – Impacts and Improvements*. Enviromental Justice Foundation (EJF), London, UK, 44 pp. [online] URL: http://www.ejfoundation.org/pdf/risky_business.pdf

Ekenam, S.B. 1983. Polyculture: A boost to the Green Revolution Programme. Proc. Annu. Conf. Fish. Soc. Nigeria 2, 117-119.

Eldani, A. & Primavera, J.H. 1981.Effect of different stocking combination on growth, production and survival of milkfish (*Chanos chanos* Forskal) and prawn (*Penaeus monodon* Fabricius) in polyculture in brackishwater ponds. *Aquaculture*, 23: 59-72.

Enander, M. & Hasselstrom, M. 1994. An experimental wastewater treatment system for a shrimp farm. *Infofish International,* 94(4): 56-61.

Erler, D.V., Pollard, P.C., Burke, M. & Knibb, W. 2000. Biological remediation of aquaculture waste: acombined finfish, artificial substrate treatment system. In M.S. Kumar (ed). *National Workshop on Wastewater Treatment and Integrated Aquaculture Production*, 17-19 September 1999. South Australian Research and Development Corporation, West Beach Adelaide, South Australia.

Erler, D., Pollard, P., Duncan, P. & Knibb, W. 2004. Treatment of shrimp farm effluent with omnivorous finfish and artificial substrates. *Aquaculture Research*, 35(9): 816-827.

Etienne G., Douet, D.-G., Le Bris, H., Bouju-Albert, A., Donnay-Moreno, C., Thorin C. & Pouliquen, H. 2006. Survey of antibiotic resistance in an integrated marine aquaculture system under oxolinic acid treatment. *FEMS Microbiol. Ecol.*, 55: 439–448.

Fang, J., Kuang, S., Sun, H., Li, F., Zhang, A., Wang, X. & Tang, T. 1996. Status and optimising measurements for the culture of scallop *Chlamys farreri* and kelp *Laminaria japonica* in Sanggou Bay. *Mar. Fish. Res.* (Haiyang Shuichan Yanjiu) 17: 95-102. (In Chinese).

FAO. 2006. *State of world aquaculture:* 2006. *FAO Fisheries Technical Paper*. No. 500. Rome, FAO. 134 p.

FAO. 2007. The National Aquaculture Sector Overview (NASO) – Indonesia. http://www.fao.org/fi/website/FIRetrieveAction.do?dom=countrysector&xml=naso_indonesia.xml.

FAO/NACA. 1995. Regional Study and Workshop on the Environmental Assessment and Management of Aquaculture Development (TCP/RAS/2253), Appendix II Country Reports, II-6, Indonesia. NACA Environment and Aquaculture Development Series No. 1. Network of Aquaculture Centres in Asia-Pacific, Bangkok, Thailand.

Fast, A.W. & Menasveta, P. 1998. Some recent innovations in marine shrimp pond recycling systems. In T.W. Flegel (ed). *Advances in shrimp biotechnology. National Center for Genetic Engineering and Biotechnology*, Bangkok.

Fast, A.W. & Menasveta, P. 2000. Some Recent Issues and Innovations in Marine Shrimp Pond Culture. *Reviews in Fisheries Science*, 8(3): 151–233.

Fernando, C. 2002. Bitter harvest-rice fields and fish culture. *World Aquac. Mag.*, 33(2): 23-24, 64.

FitzGerald W. J. 2002. Silvofisheries: Intergrated mangrove forest. In B. Costa-Pierce (ed). *Ecological Aquaculture - The Evolution and The Blue Revolution*, pp. 161-262.

FitzGerald, Jr. W.J. & Sutika, N. 1997. Mangrove rehabilitation and management project in Sulawesi: artisanal fisheries. Ministry of Forestry, Government of the Republic of Indonesia, 74 p.

FitzGerald, W.J. 1997. Silvofisheries - an environmentally sensitive integrated mangrove forest and aquaculture system. 1997. *Aquaculture Asia*, 2(3): 9-17.

Fitzsimmons, K. 2001. Polyculture of tilapia and penaeid shrimp. *Global Aquaculture Advocate*, 4(3): 43-44.

Fitzsimmons, K., Contreras-Sánchez, W.M., Macdonald-Vera, A. & Hernández-Vidal, U. 2003. Survey of tilapia-shrimp polyculture in Mexico and Honduras. Tenth Work Plan, New Aquaculture Systems/New Species Research 3C (10NSR3C)/ Experiment/Mexico. Final Report - Pond Dynamics/Aquaculture CRSP, Twenty-First Annual Technical Report 1 August 2002 to 31 July 2003.Oregon State University, Oregon.

Frei, M. & Becker, K. 2005. Integrated rice-fish culture: Coupled production saves resources. *Natural Resources Forum*, 29: 135–143.

Fujiokas, Y. 2005. Sustainable production systems of brackish mangrove areas: 2001-2005. In V.T. Sulit, E.T. Aldon, I.T. Tendencia, S.B. Alayon, and A.S. Ledesma (eds). *Report of the Regional Technical Consultation for the Development of Code of Practice for Responsible Aquaculture in Mangrove Ecosystems.* SEAFDEC Aquaculture Department, Tigbauan, Iloilo, Philippines.

Fujioka, Y., Srithong, C. & Shimoda, T. 2006. Studies on role of benthic organisms as food of shrimp aquaculture. JIRCAS Working report No. 44, pp. 31-36.

Fujioka, Y., Srithong, C., Shimoda, T. 2007. Role of benthic organisms in shrimp aquaculture and model experiment of recycling-oriented aquaculture system using natural production and purification. JIRCAS Working report No. 56, pp. 1-8.

Gautier, D. 2002. The Integration of Mangrove and Shrimp Farming: A Case Study on the Caribbean Coast of Colombia. Report prepared under the World Bank, NACA, WWF and FAO Consortium Program on Shrimp Farming and the Environment. Work in Progress for Public Discussion. Published by the Consortium. 26 p.

Gautier, D., Amador, J. & Newmark, F. 2001. The use of mangrove wetlands as a biofilter to treat shrimp pond effluents: preliminary results of an experiment on the Caribbean Coast of Colombia. *Aquaculture Research*, 32: 787-799.

Gavine, F. M., Phillips, M. J. & Kenway, M. 1996. The integration of treatment systems to reduce environmental impacts from coastal shrimp ponds – biological and physical constraints. Unpublished manuscript. Network of Aquaculture Centres in Asia-Pacific.

Giap, D.H. 2006. AC - Report - Shrimp farming systems in Hai Phong, Vietnam. Aquaculture Compendium. Wallingford, UK: CAB International.

Gomez, E.D. 1981. Potential for polyculture of *Gracilaria* with milkfish or crustaceans, pp. 91-93. In: G. C. Jr.Trono & E. Ganzon-Fortes (eds). *Report on the Training Course on Gracilaria Algae.* Manila, Philippines, 1-3 Apr 1981. South China Sea Fisheries Development Coordinating Programme, Manila.

Gomez, E.D. & Azanza-Corrales, R. 1988. Polyculture of seaweeds with marine animals. In: Report on the Training Course in Seaweed Farming, Manila, Philippines, 2-21 May 1988, ASEAN/SF/88/GEN/6. ASEAN/UNDP/FAO Regional Small-Scale Coastal Fisheries Development Project, Manila, pp. 81-85.

Gonzales-Corre, K. 1988. Polyculture of the tiger shrimp *Penaeus monodon* with the Nile tilapia *Oreochromis niloticus* in brackishwater fishponds. In R.S.V. Pullin, T. Bhukaswan, K. Tonguthai and J.L. Macleam (eds). *The Second International Symposium on Tilapia in Aquaculture*. Manila, Philippines, pp. 15 – 20.

Gordin, H., Motzkin, F., Hughes-Games, A. & Porter, C. 1981. Seawater mariculture pond - an integrated system. Eur. Aquac. Spec. Publ. 6, 1-13.

Guanzon Jr., N.G., de Castro-Mallare, T.R. & Lorque, F.M. 2004. Polyculture of milkfish *Chanos chanos* (Forsskal) and the red seaweed *Gracilariopsis bailinae* (Zhang et Xia) in brackish water earthen ponds. *Aquaculture Research,* 35: 423-431.

Guerrero, R.D. 1982. Control of tilapia reproduction. In R.S.V. Pullin and R.H. Lowe-McConnell (eds). *The biology and culture of tilapias.* ICLARM Conference Proceedings 7, Manila, Philippines, pp. 309-316.

Guerrero, R.D. 2006. Eco-Friendly Fish Farm Management and Production of Safe aquaculture foods in the Philippines. Paper presented at FFTC-RCA International workshop "Innovative Technologies for Eco-friendly Fish Farm Management and Production of Safe Aquaculture Foods". Denpasar, Bali, Indonesia.

Guerrero, R.D. & Guerrero, L.A. 2006. Brackishwater Culture of Tilapias in the Philippines: An Assessment. In: R. Bolivar, G. Mair, and K. Fitzsimmons (eds). Proceedings of 6:th International Symposium on Tilapia in Aquaculture, Manila, Philippines, pp. 421-425.

Gundermann, N. & Popper, D. 1977. A comparative study on three species of prawns and their suitability for polyculture with fish in Fiji Island. *Aquaculture*, 11: 63-74.

Hambrey, J. 1996a. The mangrove question. *Asian Shrimp News*, Asian Shrimp Culture Council, Bangkok, Thailand, Issue No. 26, 2nd Quarter, pp. 43-47.

Hambrey, J. 1996b. Comparative economics of land use options in mangroves. *Aquaculture Asia*, 1: 10-14.

Hambrey, J. & Tanyaros, S. 2003. Integrated aquaculture: global experience, opportunities and constraints. In H. Reinertsen (ed). Beyond Monoculture, Aquaculture Europe 2003. European Aquaculture Society, Trondheim, Norway, pp. 22-26.

Hamilton, L., Dixon, J. & Miller, G. 1989. Mangroves: an undervalued resource of the land and the sea. *Ocean Yearbook*, 8: 254- 288.

Hariati, A.M., Giadnya, D.G.R., Fadjar, M., Muhammad, S., Faber, R., Verdegem, M.C.J. & Boon, J.H. 1998. The impact of tiger shrimp, *Penaeus monodon* Fabricius, postlarvae stocking density on production in traditional tambak systems in East Java, Indonesia. *Aquaculture Research*, 29: 229-236.

Hasse, J. 1974. Utilization of Rabbitfish (Siganidae) in Tropical Oyster Culture. *The Progressive Fish-Culturist*, 36(3): 160-162.

He, X., Peng, T., Liu, S., Huang, J., He, Z., Xu, Q. & Huang, L. 1990. Studies on the elimination of stress factors in Penaeus diseases. *Tropical Oceanology Redai Haiyang*, 9(4): 61-67.

Hempel, E., Winther, U. & Hambrey, J. 2002. Can Shrimp Farming Be Undertaken Sustainably? World Bank/NACA/FAO/WWF Consortium Program on Shrimp Farming and the Environment.

Hong, P.N. 1996. Mangrove destruction for shrimp rearing in Minh Hai, Viet Nam: its damage to natural resources and the environment. *SEAFDEC Asian Aquaculture*, 18(3): 6-11.

Hopkins, J.S., Holloway, J.D., Sandifer, P.A. & Browdy, C.L. 1993. The production of bivalve molluscs in intensive shrimp ponds and effect on shrimp production and water quality. *World Aquaculture*, 24(2): 74-77.

Hopkins, J.S., Sandifer, P.A. & Browdy, C.L. 1995. A review of water management regimes which abate the environmental impacts of shrimp farming. In C.L. Browdy and J.S. Hopkins (eds). *Swimming Through Troubled Water,* Proceedings of the Special Session on Shrimp Farming, Aquaculture'95. World Aquaculture Society, Baton Rouge, Louisiana. pp.157-166.

Hopkins, J.S., Holloway, J.D., Sandifer, P.A. & Browdy, C.L. 1997. Results of recent controlled comparisons of intensive shrimp ponds operated with and without water exchange. In D.E. Alston, B.W. Green and H.C. Clifford (eds). *IV Symposium on Aquaculture in Central America: Focusing on Shrimp and Tilapia.* Asociation National de Aquicultores de Honduras, Tegucigalpa, Honduras, pp. 157-158.

Hurtado, A.Q. & Agbayani, R.F. 2000. The Farming of the seaweed Kappaphycus. Extension Manual No. 23. SEAFDEC.

Hurtado-Ponce, A.Q. 1992a. Cage culture of *Kappaphycus alvarezii* var. tambalang (Gigartinales, Rhodophyceae). *Journal of Applied Phycology,* 4: 311-313.

Hurtado-Ponce, A.Q. 1992b. Cage culture of *Kappaphycus alvarezii* cultivation (Doty) Doty andEpinephelus sp. In Alino (ed). *Proceedings of the Second National Symposium in MarineScience*, Tawi-Tawi, UP Marine Science Institute. 108 pp.

Hurtado-Ponce, A.Q. 1992c. Growth rate of *Gracilariopsis heteroclada* (Zhang et Xia) Zhang et Xia (Rhodophyta) in floating net cages as influenced by *Lates calcarifer* Bloch. In 2nd RP-USA Phycology Symposium/Workshop, 6-10 January 1992, Cebu City, Philippines, pp. 13-21.

ICAR. 2007. Indian Council of Agricultural Research (ICAR), India http://www.icar.org.in/Drought/Drought4.htm

ICLARM. 2002. Status of the research component of the project "Strategies and options for increasing and sustaining fisheries and aquaculture production to benefit poor households in Asia". ADB-RETA 5945 Inception Report.

Islam, M.S., Milstein, A., Wahab, M.A., Kamal, A.H.M. & Dewan, S. 2005. Production and economic return of shrimp aquaculture in coastal ponds of different sizes and with different management regimes. *Aquaculture International*, 13: 489-500.

Islam, M.S. & Wahab, M.A. 2005. A review on the present status and management of mangrove wetland habitat resources in Bangladesh with emphasis on mangrove fisheries and aquaculture. *Hydrobiologia*, 542:165-190.

Iwama, G.K. 1991. Interactions between aquaculture and the environment. *Crit. Rev. envir. Contr.*, 21: 177–216.

Izquierdo, M., Forster, I., Divakaran, S., Conquest, L., Decamp, O. & Tacon, A. 2006. Effect of green water and clear water and lipid source on survival, growth and biochemical composition of Pacific white shrimp *Litopenaeus vannamei. Aquaculture Nutrition,* 12: 192-202.

Jackson, C.J., Preston, N., Burford, M.A. & Thompson, P.J. 2003. Managing the development of sustainable shrimp farming in Australia: the role of sedimentation ponds in treatment of farm discharge water. *Aquaculture,* 226: 23–34.

Jacobs, M. 1991.The Green Economy. London, Pluto Press.

Jakob, G.S., Pruder. G-D. & Wang, J.K. 1993. Growth trial with the American oyster *Crassostrea virginica* using pond water as feed. *Journal of the World Aquaculture Society*, 24(3): 344-351.

James, P.S.B.R., Raju, A. & Rengaswamy, V.S. 1984. Further Observations of Finfishes and Prawns in Saltwater Ponds and in a Net-Pen in Mandapam. *Indian Journal of Fisheries* 31.

Joffre, O. in press. Salinity influenced coastal area Case study in Bac Lieu Province, Mekong Delta, Vietnam. World Fish Center, Challenge Program Water for Food n. 10. 78 pp.

Johnston, D., Cloug, B.F., Xuan, T.T. & Philips, M. 1999a. Mixed shrimp-mangrove forestry farming systems in Ca Mau Province, Vietnam. *Aquaculture Asia*, 4(2): 6-12.

Johnston, D., Lourey, M., Van Tien, D., Luu, T.T. & Xuan, T.T. 2002. Water quality and plankton densities in mixed shrimp-mangrove forestry farming systems in Vietnam. *Aquaculture Research,* 33: 785-798.

Johnston, D., Trong, N.V., Tuan, T.T. & Xuan, T.T. 1999b. Shrimp seed recruitment in mixed shrimp- mangrove forestry farming systems in Ca Mau Province, Southern Vietnam. *Aquaculture*, 4(2): 6-12.

Johnston, D.J., Trong, N.V., Tuan, T.T. & Xuan, T.T. 2000a. Shrimp seed recruitment in mixed shrimp and mangrove forestry farms in Ca Mau Province, Southern Vietnam, *Aquaculture*, 184: 89-104.

Johnston, D.J., Trong, N.V., Tien, D.V. & Xuan, T.T. 2000b. Shrimp yields and harvest characteristics of mixed shrimp-mangrove forestry farms in southern Vietnam: factors affecting production, *Aquaculture*,188: 263-284.

Jones, A.B., Dennison W.C. & Preston, N.P. 2001. Integrated treatment of shrimp effluent by sedimentation, oyster filtration and macroalgal absorption: a laboratory scale study. *Aquaculture*, 193: 155-178.

Jones, A.B., Preston, N.P. & Dennison, W.C. 2002. The efficiency and condition of oysters and macroalgae used as biological filters of shrimp pond effluent. *Aquaculture Research*, 33: 1-19.

Jones, A.B. & Preston, N.P. 1999. Sydney rock oyster, *Saccostrea commercialis* (Iredale & Roughley), filtration of shrimp farm effluent: the effects on water quality. *Aquaculture Research*, 30: 51-55.

Joseph, K.O. 1982. Observations on the mixed culture of brackishwater fishes and prawns in a pond at Adyar, Madras. In Proceedings of the Symposium on Coastal Aquaculture. Symp. Ser. Mar. Biol. Assoc. India, No. 6. Marine Biological Association of India, Cochin, pp. 244-250.

Kautsky N., Rönnbäck, P., Tedengren, M. & Troell, M. 2000. Ecosystem perspectives on management of disease in shrimp pond farming. *Aquaculture*, 191: 145-161.

Keenam, C. P. & Blackshaw, A. 1999. Mud crab aquaculture and biology. Proceedings of an international scientific forum held in Darwin, Australia. April 21-24, 1997. ACIAR proceedings No. 78. 216 p.

Khanh, N.H., Thai, N.C. & Dam, N.D. 2005. Study on technology for sustainable integrated marine polyculture. Research Institute for Aquaculture No. 3, Nha Trang. Vietnam, Monthly Fisheries Information Bulletin No. 08/2005.

Kristensen, E. 1997. Carbon, sulfur and nitrogen biogeochemistry of tropical mangrove sediments. In B.U. Haq, G. Kullenberg and J.H. Stel (eds).*Coastal zone management imperative for maritime developing nations*, Kluwer, Netherlands, pp.199-232.

Kritsanapuntu, S., Chaitanawisuti, N., Santhaweesuk, W. & Natsukari, Y. 2006b. Growth, production and economic evaluation of earthen ponds for monoculture and polyculture of juveniles spotted babylon (*Babylonia areolata*) to marketable sizes using large-scale operation. *Journal of Shellfish Research*, 25: 913-918.

Kritsanapuntu, S., Chaitanawisuti, N., Santhaweesuk, W. & Natsukari, Y. 2006a. Pilot study on polyculture of juveniles spotted babylon, *Babylonia areolata*, with milkfish, *Chanos chanos*, to marketable sizes using large-scale operation of earthen ponds in Thailand. *Aquaculture Research*, 37: 618–624.

Kuntiyo, Baliao, D. 1987. Comparative study between mono and polyculture systems on the production of prawn and milkfish in brackishwater ponds. Network of Aquaculture Centres in Asia. Bangkok, Thailand, NACA/WP/87/60.

Largo, B.D. 1989. Stock assessment of the agarophyte *Gracilaria* (Gracilariales, Rhodophyta) and its potential in polyculture in central Visayas, Philippines. In 22nd Annual Convention, Federation of Institutes of Marine and Freshwater Sciences. Aquatic Resources Development. Mindanao State University, Tawi Tawi College of Technology and Oceanography, Sanga-Sanga, Bongao, Tawi Tawi.

Le, T.H. 1992. Integration of crustacean aquaculture with coastal rice farming in Vietnam. *Naga* ICLARM Q. 15(2): 27-29.

Leaño, E.M., Lio-Po, G.D., Nadong, L.A., Tirado, A.C., Sadaba, R.B. & Guanzon, N.G. Jr. 2005. Microflora of the "green water" culture system of tiger shrimp *Penaeus monodon*. *Aquaculture Research*, 36: 1581-1587.

Li, D. & Dong, S. 2000. A summary of studies on closed-polyculture of penaeid shrimp with fishes and molluscans. *Chinese Journal of Oceanology and Limnology*, 18(1): 61-66.

Lijauco, M.M., Prospero, O.Q. & Rodriguez, E.M. 1980. Polyculture of milkfish (*Chanos chanos*) and mud crab (*Scylla serrata*) at two stocking densities. *QRR* 4(4), 19-23.

Lin, C.K. 1995. Progression of intensive marine shrimp farm in Thailand. In C.L. Browdy and J.S. Hopkins (eds). *Swimming Through Troubled Water,* Proceedings of the Special Session on Shrimp Farming, Aquaculture'95. World Aquaculture Society, Baton Rouge, Louisiana. pp. 13-22.

Lin, C.K. 2006. AC - Report - Integrated aquaculture-aquaculture systems (IAS). Aquaculture Compendium. Wallingford, UK: CAB International.

Lin, C.K. & Nash, G. 1996. Asian Shrimp News collected volume, 1989-1995, Asian Shrimp. Culture Council. Bangkok, Thailand. 312 pp.

Lin, C.K., Ruamthaveesub, P., Wanuchsoontorn, P. 1993. Integrated culture of the green muscle (*Perna viridis*) in wastewater from an intensive shrimp pond: concept and practice. *World Aquaculture,* 24(2): 68-73.

Lin, C.K. & Yi, Y. 1999. Developments in integrated aquaculture in Southeast Asia. In L.M.B. Garcia (ed). *Responsible Aquaculture Development in Southeast Asia*, Proceedings of the Seminar-Workshop on Aquaculture Development in Southeast Asia, 12–14 October 1999. Southeast Asian Fisheries Development Center (SEAFDEC), Iloilo, Philippines, pp. 77-88.

Lin, M.N., Lin, G.Y. & Huang, T.L. 1979. Preliminary report on the improvement of *Gracilaria* farming. Aquaculture 2(3): 22-31.

Lio-Po, G.D, Leaño, E.M., Peñaranda, M.M.D., Villa-Franco, A.U., Sombito, C.D. & Guanzon, N.G. Jr. 2005. Anti-luminous Vibrio factors associated with the "green water" grow-out culture of the tiger shrimp *Penaeus monodon*. *Aquaculture*, 250: 1-7.

Little, D. & Muir, J. 1987. A Guide to Integrated Warm Water Aquaculture. Institute of Aquaculture Publications, University of Stirling, Stirling, p. 238.

Lodeiros, C. & Garcia, N. 2004. The use of sea urchins to control fouling during suspended culture of bivalves. *Aquaculture*, 231: 293-298.

Lombardi, J.V., Marques, H.L.A., Barreto, O.J.S., Gelli, V.C., Pereira, R.T.L. & de Paula, E.J. 2001. Floating cages in open sea water: an alternative for promoting integrated aquaculture. *World Aquaculture*, 32(3): 47, 49-50.

Lombardi, J.V., Marques, H.L.A., Pereira, R.T.L., Barreto, O.J.S. & de Paula, E.J. 2006. Cage polyculture of the Pacific white shrimp *Litopenaeus vannamei* and the Phillipines seaweed *Kappaphycus alvarezii*. *Aquaculture* 258(1-4): 412-415.

Lutz, G. 2003. Polyculture: principles, practices, problems, and promise. *Aquaculture Magazine* March/April, 29(2): 34–39.

Macintosh, D. J. & Phillips, M. J. 1992. Environmental issues in shrimp farming. In H. de Saram and T. Singh (eds). *Shrimp '92, Proceedings of the 3rd Global Conference on the Shrimp Industry*. Infofish, Kuala Lumpur, Malaysia.

Mai, V.Q., Le, T.D., Dang, K.S., Pham, N.M. & Nguyen, N.D. 1992. Ricefield aquaculture systems in the Mekong Delta, Vietnam: potential and reality. In C.R. de la Cruz, C. Lightfoot, B.A. Costa-Pierce, V.R. Carangal and M.P. Bimbao (eds). *Rice-Fish Research and Development in Asia.* ICLARM Conference Proceedings 24, pp. 105-115.

Mair, G.C. & Little, D.C. 1991. Population control in farmed tilapia. *NAGA*, ICLARM Q. 17(4): 8-13.

Manzano, V.B. 1982. Determination of stocking rates of mullet (*Mugil sp.*) and prawn (*Penaeus monodon* Fabricus) in polyculture system. Master Thesis, University of the Philippines.

Marinho-Soriano, E., Morales, C. & Moriera, W.S.C. 2002. Cultivation of *Gracilaria* (Rhodophyta) in shrimp pond effluents in Brazil. *Aquaculture Research*, 33: 1081-1086.

Martínez-Cordero, F.J., Duncan, N.J. & Fitzsimmons, K. 2004. Feasibility of shrimp and tilapia polyculture in the Northwest of Mexico, with special reference to an economic study of a hypothetical polyculture farm. In R.B. Bolivar, G.C. Mair and K. Fitzsimmons (eds). *New dimensions on farmed tilapia.* Tilapia 6th International Symposium on Tilapia in Aquaculture Philippine International Convention Center Roxas Boulevard, Manila, Philippines, pp. 648-649.

Martínez-Cordero, F.J., FitzGerald W.J. Jr. & Leung, P.S. 1999. Evaluation of Productivity in Extensive Aquaculture Practices using Interspatial TFP Index, Sulawesi, Indonesia. *Asian Fisheries Science*, 12(3): 19-30.

Martínez-Córdova, L. & Pena-Messina, E. 2005. Biotic communities and feeding habits of *Litopenaeus vannamei* (Boone 1931) and *Litopenaeus stylirostris* (Stimpson 1974) in monoculture and polyculture semi-intensive ponds. *Aquaculture Research*, 36: 1075-1084.

Martínez-Córdova, L. & Martinez-Porchas, M. 2006. Polyculture of Pacific white shrimp, *Litopenaeus vannamei*, giant oyster, *Crassostrea gigas* and black clam, *Chione fluctifraga* in ponds in Sonora, Mexico. *Aquaculture*, 258: 321-326.

Massaut, L. 1999. Mangrove management and shrimp aquaculture. Auburn University, Research and Development series No. 44. Auburn, Alabama.

Mauksit, A., Maala, L. & Suspita, A. 2005. Seaweed Culture and Farmer Incomes in Bekasi, Indonesia. *STREAM* Journal 4(4), 1-3.

Mazid, M.A. 1994. Environmental issues and aquaculture development in Bangladesh. Country Paper, presented at the Final Workshop, FAO (Food and Agriculture Organization of the United Nations) Regional Office for Asia and the Pacific.

McVey, J.P., Stickney, R.R., Yarish, C. & Chopin, T. 2002. Aquatic polyculture and balanced ecosystem management: new paradigms in seafood production. In R.R. Stickney, & J.P. McVey (eds). *Responsible Marine Aquaculture*. CABI Publishing, Oxon, pp. 91- 104.

Melamed, P., Gong, Z., Fletcher, G. & Hew, C.L. 2002. The potential impact of modern biotechnology on fish aquaculture. Aquaculture 204, 255 – 269.

Milstein, A., Islam, M.S., Wahab, M.A., Kamal, A.H.M. & Dewan, S. 2005. Characterization of water quality in shrimp ponds of different sizes and with different management regimes using multivariate statistical analysis. *Aquaculture International*, 13: 501-518.

Minh, T.H. 2001. Management of the Integrated. Mangrove-Aquaculture farming Systems in the. Mekong Delta of Vietnam. M.Sc. Thesis. Asian Institute for Technology (AIT), Bangkok, Thailand.

Minh, T.H., Jackson, C.J., Hoa, T.T.T., Ngoc, L.B., Preston, N. & Phuong, N.T. 2003. The shrimp pond environment: factors affecting shrimp production. Part A: Growth and survival of *Penaeus monodon* in relation to the physical conditions in rice–shrimp ponds in the Mekong Delta. In N. Preston and C. Clayton (eds). Rice–shrimp farming in the Mekong Delta: biophysical and socioeconomic issues. ACIAR Technical Reports No. 52e, pp 27-34.

Minh, T.H., Yakupitiyage, A. & Macintosh, D.J. 2001. Management of Integrated Mangrove-Aquaculture Farming Systems in the Mekong Delta of Vietnam. *Integrated Tropical Coastal Zone Management*, 24 p.

Mmochi, A. J. & Mwandya, A.W. 2003. Water Quality in the Integrated Mariculture Pond Systems (IMPS) at Makoba Bay, Zanzibar, Tanzania. *Western Indian Ocean Journal of Marine Science*, 2(1): 15-23.

Mmochi, A.J., Dubi, A.M., Mamboya, F.A. & Mwandya, A.W. 2002. Effects of Fish Culture on Water Quality of an Integrated Mariculture Pond System. *Western Indian Ocean Journal of Marine Science*, 1(1): 53-63.

Mohan, J.M., Sathiadhas, R. & Gopakumar, G. 2006 Marine farming: Country analysis-India. The future of mariculture: A regional approach for responsible development of marine farming in the Asia-Pacific Region. FAO/NACA/China Regional Workshop Shenzhen/Guangzhou, Guangdong Province, P.R. China, 6-11 March.

Morissens, P., Macary, C.S., Grandmougin, B. & Lazard, J. 2004. The dynamics of aquaculture development in the Philippines: Intensification and extensification in the milkfish and tilapia production sectors. In R. Bolivar, G. Mair and K. Fitzsimmons (eds). *New Dimensions in Farmed Tilapia: Proceedings of the Sixth International Symposium on Tilapia in Aquaculture.* Editors: American Tilapia Association, Aquaculture CRSP, and Ministry of Agriculture, Philippines. Manila. 854 p.

Moss, S.M., Arce, S.M., Argue, B.J., Otoshi, C.A., Calderon, F.R.O. & Tacon, A.G.J. 2001. Greening of the blue revolution: efforts toward environmentally responsible shrimp culture. In C.L. Browdy and D.E Jory (eds). *The New Wave, Proceedings of the Special Session on Sustainable Shrimp Culture*, Aquaculture 2001. The World Aquaculture Society, Baton Rouge, LA USA, pp.1-19.

Msuya, F.E., Kyewalyanga, M.S. & Salum, D. 2006. The performance of the seaweed Ulva reticulata as a biofilter in a low-tech, low-cost, gravity generated water flow regime in Zanzibar, Tanzania. *Aquaculture,* 254: 284 – 292.

Msuya, F.E. & Neori, A. 2002. *Ulva reticulata* and *Gracilaria crassa*: macroalgae that can biofilter effluent from tidal fishponds in Tanzania, *Western Indian Ocean Journal of Marine Science*, 1: 117–126.

Muangkeow, B., Ikejima, K., Powtongsook, S. & Yi, Y. in press. Effects of white shrimp, *Oreochromis Litopenaeus vannamei* (Boone), and Nile tilapia, *Orochromis niloticus* L., stocking density on growth, nutrient conversion rate and economic return in integrated closed recirculation system. *Aquaculture*

Mukherjee, R. 2006. The current status of mariculture in India and livelihood opportunities for coastal communities. The future of mariculture: A regional approach for responsible development of marine farming in the Asia-Pacific Region. FAO/NACA/China Regional Workshop Shenzhen/Guangzhou, Guangdong Province, P.R. China, 6–11 March.

Myers, J.M., Heggelund, P.O., Hudson, G. & Iwamoto, R.N. 2001. Genetics and broodstock management of coho salmon. Aquaculture 197: 43– 62.

NACA/FAO. 2000. Aquaculture Development Beyond 2000: the Bangkok Declaration and Strategy. Conference on Aquaculture in the Third Millennium, 20-25 February 2000, Bangkok, Thailand. NACA, Bangkok and FAO, Rome. 27p.

Nagahama, T. & Hirata, H. 1990. Nitrogen uptake by the sterile *Ulva pertusa*, Ohmura strain, and their interaction to the bacterial communities. *Suisanzoshoku* 38: 285-290.(In Japanese).

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

Nedwell, D.B. 1975. Inorganic nitrogen metabolism in a eutrophicated tropical mangrove estuary. *Water Resource,* 9: 221-231.

Nelson, S.G., Glenn, E.P., Conn, J., Moore, D., Walsh, T. & Akutagawa, M. 2001. Cultivation of *Gracilaria parvispora* (Rhodophyta) in shrimp-farm effluent ditches and floating cages in Hawaii: a two-phase polyculture system. *Aquaculture*,193: 239-248.

Neori, A., Troell., M., Chopin, T., Yarish, C., Critchley, A., & Buschmann, A.H. 2007. The need for a balanced ecosystem approach to blue revolution aquaculture. *Environment,* 49(3): 36-43.

Neori, A., Chopin, T., Troell, M., Buschmann, A.H., Kraemer, G.P., Halling, C., Shpigel, M. & Yarish, C. 2004. Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. *Aquaculture,* 231: 361–391.

Ngo, V.H. 2000. The integrated intensive culture of giant tiger shrimp (*Penaeus monodon*) with AquaMatsTM and tilapia (*Oreochromis niloticus*) in a closed low salinity system. AIT Thesis no. AQ-00-19.

Ngoc, T. 2006. Polyculture of the sea cucumber (*Holothura scabra*) with tiger shrimp for water quality improvement. CAB International, 2006. Aquaculture Compendium. Wallingford, UK: CAB International.

Nuruzzaman, M., Anwari, B., Shahjahan, M. & Maniruzzaman, M. 2001. The dynamics and diversity of the shrimp farming in Bangladesh. Draft Final Report. Fourth Fisheries Project, Shrimp and Coastal Aquaculture Component, Department of Fisheries, 63 p.

Oliviera, A. & Brito, L.O. 2005. Treating shrimp farming effluent using the native oyster, Crassostrea rhizophorae, in Brazil. *World Aquaculture*, 36(3): 60-63.

O'Bryen, P.J. & Lee, C.-S. 2003. Management of Aquaculture effluents workshop discussion summary. *Aquaculture*, 226: 227-242.

Paclibare, J.O., Usero, R.C., Somga, J.R. & Visitacion, R.N. 2002. Integration of finfish in shrimp (*Penaeus monodon*) culture: an effective disease prevention strategy. In Y. Inui and E.R. Cruz-Lacierda (eds). *Disease Control in Fish and Shrimp Aquaculture in Southeast Asia—Diagnosis and Husbandry Techniques*. SEAFDEC AQD, Iloilo, Philippines, pp. 151-171.

Pang, S.J., Xiao, T. & Bao, Y. 2006. Dynamic changes of total bacteria and Vibrio in an integrated seaweed-abalone culture system. *Aquaculture*, 252: 289-297.

Pham, T.D., Do, H.H., Hoang, T.D. & Vo, T.H.T. 2004. Combined culture of mussel: a tool for providing live feed and improving environmental quality for lobster aquaculture in Vietnam. In K.C. Williams (ed). *Spiny lobster ecology and exploitation in the South China Sea region.* Proceedings of a workshop held at the Institute of Oceanography, Nha Trang, Vietnam. ACIAR Proceedings No. 120, pp.57-58.

Pham, H.N. 2004. Sustainable lobster breeding lets farmer's claw way out of poverty. Viet Nam News, Tuesday, September 7, 2004.

Pham, T.D., Do, H.H., Hoang, T.D. & Vo, T.H.T. 2005. The results of the experimental study on combined culture of mussel *Perna viridis* with lobster at Xuan Tu (Van Ninh, Khanh Hoa). Journal of marine science and technology. Institute of Oceanography (Nha Trang), Vietnam.

Phang, S.M. Shaharuddin, S., Noraishah, H. & Sasekumar, A. 1996. Studies on *Gracilaria changii* (Gracilariales, Rhodophyta) from Malaysian mangroves. *Hydrobiologia*, 326/327: 347–352.

Phillips, M.J. 1998. Tropical mariculture and coastal environmental integrity. In S.S. De Silva (ed). *Tropical Mariculture*. Academic Press, London, pp. 17-110.

Pitt, R., Duy, N.D.Q., Duy, T.V. & Long, H.T.C. 2004. Sandfish (Holothuria scabra) with shrimp (*Penaeus monodon*) co-culture tank trials. SPC Beche-de-mer Information Bulletin No. 20, August, pp. 12-22.

Preston, N., Brennan, D. & Clayton, H. 2003. An overview of the project research. In N. Preston and H. Clayton (eds). *Rice–shrimp farming in the Mekong Delta: biophysical and socioeconomic issues*. ACIAR Technical Reports No. 52e, pp 7-14.

Primavera, J.H. 1993. A critical review of shrimp pond culture in the Philippines. *Rev. Fish. Sci.*, 1: 151- 201.

Primavera, J.H. 1994. Environmental and socioeconomic effects of shrimp farming: the Philippine experience. *INFOFISH Int.*, 1/94: 44–49.

Primavera, J.H. 1995. Mangroves and brackishwater pond culture in the Philippines. *Hydrobiologia*, 295: 303-309.

Primavera, J.H. 1998. Mangroves as nurseries: shrimp populations in mangrove and non-mangrove habitats. *Estuar. Coast. Shelf Sci.*, 46: 457-464.

Primavera, J.H. 2000. Integrated Mangrove-Aquaculture Systems in Asia. Integrated *Coastal Zone Management* (Autumn Edition), 121-130.

Primavera, J.H. 2005. Mangroves and Aquaculture in Southeast Asia. In V.T. Sulit *et al.* (eds). *Report of the Regional Technical Consultation for the Development of Code of Practice for Responsible Aquaculture in Mangrove Ecosystems,* Southeast Asian Fisheries Development Center, Aquaculture Department, Tigbauan, Iloilo, Philippines, pp. 25-37.

Primavera, J.H. & Agbayani, R.F. 1997. Comparative strategies in community-based mangrove rehabilitation programmes in the Philippines. In P.N. Hong, N. Ishwaran, H.T. San, N.H. Tri and M.S. Tuan (eds). *Proceedings of Ecotone V, Community Participation in Conservation, Sustainable Use and Rehabilitation of Mangroves in Southeast Asia.* UNESCO, Japanese Man and the Biosphere National Committee and Mangrove Ecosystem Research Centre, Vietnam, pp. 229-243.

Primavera, J.H., Altamirano, J. P., Lebata, M. J. H. L., de los Reyes, A. A. Jr. & Pitogo, C. L. 2007. Mangroves and shrimp pond culture effluents in Aklan, Panay Is., central Philippines. *Bull. Mar. Sci.*, 80: 795-804.

Primavera, J.H., Binas, J., Tan, G.S., Lebata, J., Alava, V.R., Walton, M. & LeVay, L. in revision. Environmental considerations in mud crab pen culture- impacts on mangrove community structure and replacement of fish feed requirement. *Journal of Sea Research.*

Pudadera, B. 1980. Growth and survival of milkfish in a polyculture system. Asian *Aquaculture*, 3(9) 4.

Pudadera, B.J. Jr. & Lim, C. 1982. Evaluation of milkfish (*Chanos chanos* Forskal) and prawn (*Penaeus monodon* Fabricius) in polyculture system. *Fish. Res. J. Philipp.*, 7: 51-59.

Purcell, S. W., Patrois, J. & Fraisse, N. 2006. Experimental evaluation of co-culture of juvenile sea cucumbers, *Holothuria scabra* (Jaeger), with juvenile blue shrimp, *Litopenaeus stylirostris* (Stimpson). *Aquaculture Research,* 37: 515–522.

Qi, Z., Li, D., Zang, M. & Dong, S. 2001. Comparative study on nitrogen budgets of closed shrimp polyculture systems. *Chinese Journal of Oceanology and Limnology*, 19(3): 233-242.

Qian, P.Y., Wu, C.Y., Wu, M. & Xie., Y.K. 1996. Integrated cultivation of the red alga *Kappaphycus alvarezii* and the pearl oyster *Pinctada martensi. Aquaculture*, 147: 21-35.

Ranoemihardjo, B.S. 1986. Improved methods on finfish cultivation in brackishwater pond in Indonesia. *Bull. Brackishwater Aqua. Dev. Cent.*, 8(1); 1-11.

Ridha, M. & Cruz, E.M. 1992. Stocking of sea bream (*Acanthopagus cuvieri* Day) with tilapia (*Oreochromis spilurs* Gunther) in sea cages. *J. Aqua. Trop.*, 7: 1-6.

Ridler, N., Robinson, B., Chopin, T., Robinson, S. & Page, F. 2006. Development of integrated multi-trophic aquaculture in the Bay of Fundy, Canada: a socio-economic case study. *World Aquaculture*, 37(3): 43-48.

Rivera-Monroy, V.H., Torres, L.A., Bahamon, N., Newmark, F. & Twilley, R.R. 1999. The potential use of mangrove forests as nitrogen sinks of shrimp aquaculture pond effluents: the role of denitrification. Journal of the World Aquaculture Society 30(1), 12-25.

Rivera-Monroy, V.H., Twilley, R.R. & Castañeda, E. 2001. Integrative Management and Rehabilitation of Mangrove Resources to Develop Sustainable Shrimp Mariculture in the Gulf of Fonseca, Honduras. USGS Activity B7 Technical Report. University of Louisiana at Lafayette, Lafayette, Louisiana, USA.

Robertson, A.I. & Duke, N.C. 1987. Mangroves as nursery sites: comparisons of the abundance and species composition of fish and crustaceans in mangroves and other nearshore habitats in tropical Australia. *Marine Biology,* 96: 193-205.

Robertson, A.I. & Phillips, M.J. 1995. Mangroves as filters of shrimp effluent: predictions and biogeochemical research needs. *Hydrobiologia,* 295: 311-321.

Rönnbäck, P. 1999. The Ecological Basis for the Economic Value of Mangrove Forests in Seafood Production. *Ecological Economics*, 29: 235-252.

Rönnbäck, P. 2000. Fisheries and shrimp aquaculture supported by mangroves: the ecological basis for economic valuation. Paper presented at the thematic session on Rational Use of Estuaries at the International Society for Mangroves (ISME) conference Sustainable use of estuaries and mangroves: Challenges and prospects, 22-28 May, 2000, Recife, Brasil.

Rönnbäck, P. 2001. Shrimp aquaculture - State of the art. Swedish EIA Centre, Report 1. Swedish University of Agricultural Sciences (SLU), Uppsala. (ISBN 91-576-6113-8).

Rönnbäck, P. & Primavera, J.H. 2000. Illuminating the need for ecological knowledge in economic valuation of mangroves under different management regimes–a critique. *Ecological Economics*, 35: 135-141.

Rosenberry, B. 2006. World Shrimp Farming, 2006. *Shrimp News International*, San Diego.

Saelee, W. 2004. Shrimp-tilapia polyculture in low salinity water. Asian Institue of Technology (AIT), Master Thesis no. AQ-02-41. 99 pp.

Saenger, P., Hegerl, E.J. & Davie, J.D.S. 1983. Global status of mangrove ecosystems. Commission on Ecology Papers No.3. IUCN. Gland, Switzerland. 88 pp.

Samonte, G. P.B., Agbayayani, R.F. & Tumaliuan, R.E. 1991. Economic feasibility of polyculture of tiger shrimp (*Penaeus monodon*) with Nile tilapia (*Oreochromis niloticus*) in brackishwater ponds. *Asian Fisheries Science*, 4: 335-343.

Sansanayuth, P., Phadungchep, A., Ngammontha, S., Ngdngam, S., Sukasem, P., Hoshino, H. & Ttabucanon, M.S. 1996. Shrimp pond effluent: pollution problems and treatment by constructed wetlands. *Water Science and Technology*, 34: 93–98.

Sathirathai, S. 1998. Economic Valuation of Mangroves and the Roles of Local Communities in the Conservation of Natural Resources: Case Study of Surat Thani, South of Thailand. EEPSEA Research Report Series, Economy and Environment Program for Southeast Asia (EEPSEA), Singapore, 38 p.

Schneider, O., Sereti, V., Eding, E.H. & Verreth, J.A.J. 2005. Analysis of nutrient flows in integrated intensive aquaculture systems. *Aquacultural Engineering*, 32: 379–401.

Shang, Y.C. 1976. Economic aspects of *Gracilaria* culture in Taiwan. *Aquaculture*, 8: 1-7.

Shen, Y. & Lai, Q. 1994. Present status of mangrove crab (*Scylla serrata* Forskal) culture in China. *NAGA*: the ICLARM Q., 171, 28-29.

Shiva, V. & Karir, G. 1997. Towards sustainable aquaculture. Research Foundation for Science, New Dehli, India, 133 p.

Shyu, C.-Z. & Liao, C. 2004. Development of Sustainable Aquaculture in Asia: Challenges and Strategies. *J. Fish. Soc. Taiwan*, 31(3): 159-172.

Smith, P.T. (ed). 1999. Coastal shrimp aquaculture in Thailand: key issues forresearch. ACIAR Technical Reports No. 47, 131 p.

Soletchnik, P., Lambert, C. & Costil, K. 2005. Summer mortality of *Crassostrea gigas* in relation to environmental rearing conditions. *J. Shellfish Res.*, 24: 197–208.

Spalding, M., Blasco, F. & Field, C. (eds). 1997. World Mangrove Atlas. The International Society for Mangrove Ecosystems, Okinawa, Japan, 178 p.

Sparsis, M., Lin, J. & Hagood, R.W. 2001. Growth, suvivorship, and nutrient uptake of giant clams (Tridacna) in aquaculture effluent. *Journal of shellfish research,* 20(1): 171-176.

Stevenson, J.R., Irz, X. T., Alcalde, R-G., Petit, J. & Morissens, P. 2004. Working Paper 1 - A typology of brackish-water pond aquaculture systems in the Philippines. Research project R8288: Assessing the sustainability of brackish water aquaculture systems in the Philippines, DFID, Department for International Development, University of Reading, 42 p.

Stickney, R.R. 1979. Principles of Warmwater Aquaculture. New York: John Wiley and Sons. 375 p.

Stonich, S.C., Bort, J.R. & Ovares, L.L. 1997. Globalization of shrimp mariculture: the impact on social justice and environmental quality in Central America. *Society for Natural Resources*, 10: 161-179.

Sudarno, B.S.R. & Kusnendar, E. 1980. The effect of stocking density on the rate of the growth of tiger shrimps (*Penaeus monodon* Fabricius) and milkfish (*Chanos chanos* Forskal). *Bull. Brackishwater Aqua. Dev. Cent.*, 6: 454-461.

Sukardjo, S. 1989. Tumpang sari pond as a multiple use concept to save the mangrove forest in Java. *Biotrop*. Spec. Publ. 37: 115-128.

Sutika, I.N. & Ali, S.A. 1990. Experiments on the polyculture of seaweed, shrimps and milkfish. In W.G Yap(ed). *Shrimp Culture Industry Workshop*. Jepara, Indonesia, 25-28 Sep. pp. 129-132.

Tam, N.F.Y. & Wong, Y.S. 1993. Retention of nutrients and heavy metals in mangrove sediment receiving wastewater of different strengths. *Environmental Technology*, 14: 719-729.

Tam, N.F.Y. & Wong, Y.S. 1995. Mangrove soils as sinks for wastewater-borne pollutants. *Hydrobiologia*, 295: 231-242.

Tam, N.F.Y. & Wong, Y.S. 1996. Retention of wastewater-borne nitrogen and phosphorous in mangrove soils. *Environ. Technol.*, 17 851-859.

Tam, N.F.Y., Yang, Q. & Wong, Y.S. 2006. Mangroves fore wastewater treatment: potential and limitations. Paper presented at "International conference and exhibition on managroves of Indian and Western Pacific Oceans", ICEMAN 2006, 21-24 August, Luala Lumpur. Maritime Institute of Malaysia.

Tanyaros, S. 2001. Use of oyster (*Crassostrea belcheri* (Sowerby)) as a biofilter in intensive shrimp pond water. PhD Thesis, Asian Institute of Technology, Bangkok, Thailand. 172 pp.

Taylor, J. 2004. Defining the Appropriate Regulatory and Policy Framework for the Development of Integrated Multi-Trophic Aquaculture Practices: The Department of Fisheries and Oceans Perspective. Bull. Aquacul. Assoc. Canada, 104-3:68-70.

Tendencia, E.A. & de la Peña, M.R. 2003. Investigation of some components of the green water system which makes it effective in the initial control of luminous bacteria. *Aquaculture*, 218: 115-119.

Tendencia, E.A., de la Peña, M.R., Fermin, A.C., Lio-Po, G. & Choresca C.H. Jr. 2004. Antibacterial activity of tilapia *Tilapia hornorum* against *Vibrio harveyi. Aquaculture*, 232: 145-152.

Tendencia, E.A., de la Peña, M.R. & Choresca C.H. Jr. 2005. Efficiency of *Chlorella* sp. and *Tilapia hornorum* in controlling the growth of luminous bacteria in a simulated shrimp culture environment. *Aquaculture*, 249: 55-62.

Tendencia, E.A., de la Peña, M.R. & Choresca, C.H. Jr. 2006. Effect of shrimp biomass and feeding on the anti-Vibrio harveyi activity of Tilapia sp. in a simulated shrimp–tilapia polyculture system. *Aquaculture*, 253: 154-162.

Tendencia, E.A., Fermin, A.C., dela Peña, M.R. & Choresca, C.H. 2006. Effect of *Epinephelus coioides*, *Chanos chanos*, and GIFT tilapia in polyculture with *Penaeus monodon* on the growth of the luminous bacteria Vibrio harveyi. *Aquaculture*, 253: 48-56.

Thampy, D.M., Jose, S., Mohan, M.V. & Koya, M.S.S.I. 1988. Short-term biculture of tiger prawn *Penaeus monodon* Fabricus and milk fish *Chanos chanos* Forskal in a low saline pond. In M.M. Joseph (ed). *The First Indian Fisheries Forum, Proceedings*. Asian Fisheries Society, Indian Branch, Mangalore. pp. 139-141.

Thien, P.C. 2003. Effects of adding shrimp (*Penaeus monodon*) into intensive culture ponds of Nile tilapia (*Oreochromis niloticus*) at different densities. AIT Thesis no. AQ-03-38.

Thien, P.C., Yi, Y. & Fitzsimmons, K. 2004. Effects of adding shrimp (*Penaeus monodon*) into intensive culture ponds of Nile tilapia (*Oreochromis niloticus*) at different densities. In: R. Bolivar, G. Mair, and K. Fitzsimmons (eds). *New Dimensions in Farmed Tilapia*. Proceedings of ISTA 6. Bureau of Fisheries and Aquatic Resources. Manila, Philippines, pp. 794-805.

Thornton, C., Shanahan, M. & Williams, J. 2003. From wetlands to wastelands: Impacts of shrimp farming. *SWS Bulleti,n* 20(3): 48–53.

Tian, X., Li, D., Dong, S., Yan, X., Qi, Z., Liu, G. & Lu, J. 2001a. An experimental study on closed-polyculture of penaeid shrimp with tilapia and constricted tagelus. *Aquaculture*, 202: 57-71.

Tian, X., Li, D., Dong, S., Yan, X., Liu, G., Qi, Z. & Lu, J. 2001b. Water quality of closed polyculture of penaeid shrimp with tilapia and constricted tagelus. *Yingyong Shengtai Xuebao*, 12: 287-292.

Ting, Y.Y & Wu, J.T. 1992. Handbook for Application of Water Recycle Technique in Shrimp Ponds. Council of Agriculture, Taiwan. 52 pp.

Tobey, J., Poespitasari, H. & Wiryawan, B. 2002. Good Practices for Community-based Planning and Management of Shrimp Aquaculture in Sumatra, Indonesia. Report prepared under the World Bank, NACA, WWF and FAO Consortium Program on Shrimp Farming and the Environment. Work in Progress for Public Discussion. Published by the Consortium. 18 pages.

Tookwinas, S. 2003. Country Papers: Thailand (2). In D.A. Cruz (ed). *Aquaculture Management*. APO Seminar on Aquaculture Management held in the Republic of China, 3–8 December 2001. Asian Productivity Organization, Tokyo, and Taiwan Fisheries Research Institute, Keelung, pp. 239–254.

Tran, T.B., Dung, L.C. & Brennan, D.C. 1999. Environmental costs of shrimp culture in the rice growing regions of the Mekong Delta. *Aquaculture Economics and Management*, 3(1): 31-43.

Trino, A.T. & Rodriguez, E.M. 2002. Pen culture of mud crab *Scylla serrata* in tidal flats reforested with mangrove trees. *Aquaculture*, 211: 125-134.

Troell , M. & Norberg, J. 1998. Modelling output and retention of suspended solids in an integrated salmon–mussel culture. *Ecological Modelling,* 110: 65-77.

Troell, M., Rönnbäck, P., Kautsky, N., Halling, C., & Buschmann, A. 1999. Ecological engineering in aquaculture: use of seaweeds for removing nutrients from intensive aquaculture. *Journal of Applied Phycology*, 11: 89-97.

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

Troell, M., Halling, C., Neori, A., Chopin, T., Buschmann, A.H., Kautsky, N. & Yarish, C. 2003. Integrated mariculture: asking the right questions. *Aquaculture,* 226: 69-90.

Troell, M., Neori, A., Chopin, T. & Buschmann, A.H. 2005. Biological wastewater treatment in aquaculture - more than just bacteria. *World Aquaculture*, 36: 27-31.

Troell, M., Tydemer, P., Rönnbäck, P. & Kautsky, N. 2004. Aquaculture- energy use. In C. Cleveland (ed). *Encyclopedia of Energy.* Elsevier Inc. pp. 97-108.

Tsutsui, I., Aueumnuoy, D., Srisapoome, P. & Hamano, K. 2007. Possible implications of the co-cultivation of black tiger shrimp and Cladophoraceae species on a Southeast Asian shrimp farm. Paper presented at XIX Seaweed Symposium, Kobe, March 2007

Twilley, R.R., Chen, R.H. & Hargis, T. 1992. Carbon sinks in mangrove forests and their implications to the carbon budget of tropical coastal ecosystems. *Water, Air and Soil Pollution,* 64: 256-288.

UNEP. 1995. *Global Biodiversity Assessment*. Cambridge University Press, pp. 387-393.

Valderrama, D. & Engle, C.R. 2002. Economics of Better Management Practices (BMP) for semi-intensive shrimp farms in Honduras and shrimp cooperatives in Nicaragua. Report prepared under the World Bank, NACA, WWF and FAO Consortium Program on Shrimp Farming and the Environment. Work in Progress for Public Discussion. Published by the Consortium. 53 p.

Vuong, D.Q.T. & Lin, C.K. 2001. Rice-Shrimp Farming in the Seawater Intrusion Zone of the Mekong Delta, Vietnam. ITCZM Monograph No. 6. Asian Institute of Technology, Bangkok, Thailand. 16 p.

Wahab M.A. (ed.). 2003. Environmental and socioeconomic impacts of shrimp farming in Bangladesh. Technical Proc. BAU-NORAD Workshop, 5 March 2002, BARC Centre, Dhaka, Bangladesh. Bangladesh Agricultural University, Mymensingh, Bangladesh, 101 p.

Wainberg, A. 2005. *Shrimp farm strives for success after organic conversion*. New-Ventures - WRI © 2007

Walrut, B.P. 2003. Regulation of aquaculture in Australia: integrated aquaculture- where does it fit? In H. Reinertsen (ed). *Beyond Monoculture*, Aquaculture Europe 2003. European Aquaculture Society, Trondheim, Norway.

Wang, J.K. 1990. Managing shrimp pond water to reduce discharge problems. *Aquacultural Engineering*, 9: 61-73.

Wang, J.K. & Jakob. G.S. 1991. Pond design and water management strategy for an integrated oyster and shrimp production system. In P. Giovannini (ed). *Aquaculture Systems Engineering*. American Society of Aquacultural Engineers, St. Joseph, Michigan USA, pp. 70- 82.

Wang, J.K., Lam, C.Y. & Jakob. G.S. 1990. Preliminary investigation of an oyster-shrimp joint production system. Transactions of the ASAE 33(3), 975-980.

Wang, J.K. 2003. Conceptual design of a microalgae-based recirculating oyster and shrimp system. *Aquacultural Engineerin,g* 28: 37-46.

Wang, J., Li, D., Dong, S. Wang, K. & Tian, X. 1998. Experimental studies on polyculture in closed shrimp ponds. I. Intensive polyculture of Chinese shrimp (*Penaeus chinensis*) with tilapia hybrids. *Aquaculture*, 163(1-2): 11-27.

Wang, R., Wang, Z. & Zhang, J. 1993. Marine Culture of Molluscs. Publishing House of Ocean University of Qingdao, Qingdao, pp. 244–252.

Wattayakom, G., Wolanski, E. & Kjerfve, B. 1990 Mixing, trapping and outwelling in the Klong Ngao Mangrove swamp, Thailand. *Estuarine, Coastal and Shelf Science*, 31: 667-688.

White, H. & Pickering, H. 2003. Environmental impact mitigation and bi-culture: a comparative legal analysis of flexibility within European legal regimes- Biofilter deployment. In H. Reinertsen (ed). *Beyond Monoculture*, Aquaculture Europe 2003. European Aquaculture Society, Trondheim, Norway.

Williams, M.J., Bell, J.D., Gupta, M.V., Dey, M., Ahmed, M., Prein, M., Child, S., Gardiner, P.R., Brummett, R. & Jamu, D. 2000. Responsible aquaculture can aid food problems. *Nature*, 406: 673.

Williams, M.J. & Primavera, J.H. 2001. Choosing Tropical Portunid Species for Culture, Domestication and Stock Enhancement in the Indo-Pacific. *Asian Fisheries Science*, 14: 121-142.

Wong, Y.S., Lan, C.Y., Chen, G.Z., Li, S.H., Chen, X.R., Liu Z.P. & Tam, N.F.Y. 1995. Effect of wastewater discharge on nutrient contamination of mangrove soils and plants. *Hydrobiologia*, 295: 243-254.

Wongwai, S. 1989. Fundamentals of agarophyte culture in Thailand. In: Report on the seminar on *Gracilaria* production and utilization in the Bay of Bengal Region, Songkhla, Thailand 23-27 Oct. BOBP/REP 45, 25-26.

World Commission on Environmental Development. 1987. The world: our common future. Oxford, Oxford University Press, 400 p.

Wu, M., Mak, K.K., Zhang, X.J. & Qian, P.Y. 2003. The effect of co-cultivation on the pearl yield of *Pinctada martensi* (Dumker). *Aquaculture*, 221(1): 347-356.

Wu, X., Zhao, Z., Li, D., Chang, K., Tong, Z., Si L. & Xu, K. 2005. Closed recirculating system for shrimp-mollusc polyculture. *Chinese Journal of Oceanology and Limnology*, 23(4): 461-468.

Yacoob, S.Y. 1994. Eutrophication problem in shrimp (*Penaeus monodon*) ponds and the biological control using Nile Tilapia (*Oreochromis niloticus*). M.Sc. Thesis, Asian Institute of Technology, Bangkok, Thailand.

Yi, Y. & Fitzsimmons, K. 2004. Tilapia - shrimp polyculture in Thailand. In R. Bolivar, G. Mair and K. Fitzsimmons (eds). *Proceedings of 6:th International Symposium on Tilapia in Aquaculture*, Manila, Philippines, pp. 777-790.

Yi, Y., Fitzsimmons, K., Saelee, W. & Clayden, P. 2004. Stocking densities of Nile tilapia in shrimp ponds under different feeding strategies. In R. Bolivar, G. Mair and K. Fitzsimmons (eds). *Proceedings of 6:th International Symposium on Tilapia in Aquaculture*, Manila, Philippines, pp. 402 - 420.

Yokoyama, H., Higano, J., Adachi, K., Ishihi, Y., Yamada, Y. & Pitchicul, P. 2002. Evaluation of shrimp polyculture system in Thailand based on stable carbon and nitrogen isotope ratios. *Fish. Sci.*, 68: 745–750.

Young, L. 1996. Mai Po Marshes. In M. Katz (ed). *Wetlands, Biodiversity and the Ramsar Convention.* Ramsar Convention Bureau, Gland, Switzerland, pp. 52-53.

Young, L. 1997. Mangrove conservation and shrimp aquaculture,. In B.W. Darvell (ed). *Challenges in a Crowded World.* Proceedings of the First International Symposium on Marine Conservation, Hong Kong, 26-27 Oct. 1996. Hong Kong Marine Conservation Society, Hong Kong, pp. 128-133.

Ziemann, D. A., Walsh, W. A., Saphore, E. G. & Fulton-Bennet, K. 1992. A survey of water quality characteristics of effluent from Hawaiian aquaculture facilities. *Journal of the World Aquaculture Society*, 23: 180-191.

APPENDIX 1 – SOURCES

This study was mainly performed as a desktop review with interviews (by e-mail, letter, telephone and in-person) with key people. Besides standard search in common aquaculture journals, in electronic or print format, the study was complemented by visits to some key aquaculture centres in Asia. These include: Southeast Asian Fisheries Development Center (SEAFDEC), Iloilo, The Philippines; Asian Institute for Technology (AIT), Bangkok, Thailand; and Network of Aquaculture Centres in Asia-Pacific (NACA), Bangkok, Thailand.

Other sources of information included the Seaweb programme (www.seaweb.org); the aquaculture and aquatic resources management library in the Asian Institute for Technology in Bangkok, Thailand (AIT); the Web site of the Aquatic Health and Food Safety Committee of Baja California (CESAIBC, www.cesaibc.org); the Support to Regional Aquatic Resources Management programme (STREAM) Virtual Library (www.streaminitiative.org/Library/); the Western Indian Ocean Marine Science Association (WIOMSA) reference data base; and the Web site of the World Aquaculture Society (WAS).

APPENDIX 2

Brief overview of experimental work conducted on integrated mariculture in tropical regions

A= Polyculture, B= Sequential Integration, D= Mangrove Integration. Waste release Mitigation (WM), Increased Profits Multiple Species (IPMS), Treating culture water + culture env. (WT), Habitat preservation (HP).

System	Species	Country	Aims	Logistics of culture
P	• Sea bass (*Lates calcarifer*) • Seaweed (*Kappaphycus alvarezii*)	Philippines	IPMS	Seaweed cultured in 3 × 3 m bamboo rafts installed inside a 4 × 4 m floating net cage of sea bass (broodstock).
SI	• Shrimp (*Penaeus monodon*) • Mangrove (*Rhizophora mucronata*)	Thailand	WM	Effluents from Shrimp ponds (40 x 20 m) led into water treatment ponds with planted (1 stand per m^2) mangroves. Water re-circulated back. Also mixed ponds was studied. Role of benthic organisms in focus.
P	• Shrimp (*Penaeus monodon*) • Tilapia	Thailand	IPMS WM	Three brackishwater ponds were stocked with 1) only shrimp 2) shrimp and high-density tilapia 3) shrimp and low-density tilapia. Ponds were fed by either variable feed concentrations or fixed concentrations.
P	• Shrimp (*Penaeus chinensis*) *x O. niloticus* • Constricted Tagelus (*Sinonovacula constricta*)	China	IPMS WM	Three species were cultured in an net cage within an closed experimental pond.
P	• Shrimp (*Penaeus chinensis*) • Tilapia (*Oreochromis mossabicus x O. niloticus*) • Constricted Tagelus (*Sinonovacula constricta*) • Scallop (*Argopecten irradians*)	China	IPMS WM	Four species were co-cultured with shrimps in an net cage within an closed experimental pond. Treatments: Shrimp-tagelus (biomass ratio of 1:3), Shrimp-scallop (1:1), Shrimp-tilapia (1:1), Shrimp-tilapia-tagelus (1:0.3:2).
P	• Shrimp (*Penaeus monodon*) • Tilapia	Indonesia	IPMS WM	Tilapia initially stocked in cages inside in earthen shrimp ponds (1800-4000 m^2). Fish then released 60 days after shrimp were stocked. Shrimp stocked at 40 ind. m^2 and tilapia 0.3 ind. m^2
P	• Shrimp (*Penaeus monodon*) • Green mussel (*Perna viridis*)	Philippines	IPMS WM	Polyculture and monoculture of two species in experimental ponds for comparison of a variety of parameters (growth, water quality, etc.). Mussels grown on ropes hung from rafts in the pond.
S	• Shrimp (*Penaeus monodon*) • Green mussel (*Perna viridis*)	Thailand	IPMS WM	Intensive shrimp pond wastewater (stocking 30 ind. M^2 in 0.3-0.4 ha ponds) channelled into a drain with green mussels on bamboo sticks. Water exchange 10-13% daily.
P	• Milkfish (*Chanos chanos*) • Seaweed (*Gracilariopsis bailinae*)	Philippines	IPMS	Pond (18 m^2) and aquarium bi- and mono-cultures of both species. Fish stocking density 5000 ind. ha-1 and receiving feed pellets. Water replenishment once or twice fortnightly. Experimental period 16 weeks.
P	• Milkfish (*Chanos chanos*) • Seaweed (*Gracilariopsis bailinae*)	Pilippines	IPMS WM	Fine mesh nets submerged in earthen brackish water ponds (each 100 m^2). Three different fish-seaweed combinations tested: 30 fingerlings and 11 kg seaweed, 30 fingerlings and 112 kg seaweed, 30 fingerlings and no seaweed. Water exchange every spring tide (one-third of the pond water) and application of inorganic fertilizers. Two years study.
P	• Milkfish (*Chanos chanos*) • Spotted Babylon (*Babylonia areolata*)	Thailand	IPMS	Polyculture in 400 m^2 earthen ponds. Stocking density: 200 snails m^{-2}, 5 fish m^{-2}. Trashfish used for the snails and natural food + pellets for the fish. 50% of seawater exchanged at 15 days intervals.

Colour codes

Mixed Mangrove Ponds/Pens
Tanks
Open Water
Earthen Ponds

Results and discussion	General conclusions	Comments	Reference
Total production of approximately 123 t (fresh) or 37 t (dried) ha-1 in the 5-month culture period.	Seaweed growth comparable, or somewhat higher, to commercial production in the Philippines.	No comparison was made with controls outside fish cages.	Hurtado-Ponce, 1992a
There was no significant difference in nutrient concentrations. Benthic fauna diversity, density and biomass were higher in mangrove ponds. Shrimp pond sediment deteriorated.	Mangroves overloaded if receiving shrimp wastes from shrimp area twice the size of the mangrove area. Similar size mangrove pond improved shrimp production but only extended time before deteriorated.	Experiment lasted between 50-147 days. Maybe to short time for all effects to be seen. Not enough replication	Fujioka *et al.,* 2006; Fujioka *et al.,* 2005; Fujioka *et al.,* 2007
Shrimp yield significantly higher in low-density fixed feed experiment, as opposed to mono- or high-density bi-culture. Tilapia growth was fast and independent of density suggesting not reached carrying capacity in system.	Greater yield of shrimp in low-density polyculture, diversification of production with addition of tilapia. Higher food conversion ratios and higher water quality. Net returns significantly higher in low-density polyculture with fixed feed. No difference between variable feed experiments. Tilapia enhanced water quality.	Optimal stocking density of tilapia for greatest return must still be assessed.	Yi *et al*., 2004.
Accumulation of N and P in the sediment of polyculture was 40% and 51%, lower than those of monoculture. DO and COD levels higher in polyculture and less fluctuating. Bacteria, phytoplankton and suspended organic matter in polyculture significantly lower.	Enhanced production, diversification of products. Benefits gained from co-culture and higher FCR. Tilapia and tagelus enhanced pond water and sediment quality, and reduced waste emission.		Tian *et al.,* 2001a; Tian *et al.,* 2001b; Qi *et al.*, 2001
The “shrimp-tilapia-tagelus” system raised the production by 28% and the utilization efficiency of input nitrogen by 85%.	All polyculture combinations superior to shrimp monoculture with respect to economic and ecological efficiencies.		Li and Dong, 2000.
Shrimp production level was increased by 20%. More stable water quality in polyculture.	Benefits gained from increased shrimp production and additional species. Tilapia believed to enhance water quality and increase biturbation.	High water exchange- 5-40 % two times a day.	Akiyama and Anggawati, 1999
Presence of green mussels only slightly improve water quality but enhanced growth rate and overall production of shrimp.	Benefits gained from increased shrimp production and additional species. To obtain a effective biofilter further studies of stocking densities are needed.	No significant differences.	Corre *et al.*, 1997
Mussel growth 12 to 42 g in 18 weeks. Water quality in drainage channels stable and suitable for mussel growth.	Potential improvement of quality of shrimp pond waste water and production of additional product.	No measurement of nutrient removal capacity or changes in water quality parameters. Only mussel growth measured.	Lin *et al.*, 1993
Both species had higher growth rates in polyculture than in monoculture, however, milkfish unable to control epiphytes on seaweeds. Seaweeds increased DO.	Successful integration but growth rates of both fish and seaweed declined over time. Declined seaweed growth probably due to epifytism (green algae).	Good replication. Short duration. No explanation for slower fish growth.	Alcantara *et al.*, 1999
Milkfish growth unaffected by presence of seaweed. Fish growth similar to other studies on fish monoculture. Seaweed growth unaffected by tested stocking densities. Season and salinity had greatest effect on overall growth. Growth rates of seaweed similar to other studies in open water and brackishwater ponds.	Seaweed can act as biofilter and provide additional income. Due to seasonal changes it was difficult to maintain gracilaria production for extended periods. Night respiration increased with seaweeds but kept within tolerable limits.	No control for seaweed growth. No measurement of nutrients.	Guanzon *et al.*, 2004
Polyculture is more economically beneficial than monoculture but further research is needed into efficiency Return on investment was 2.62.	Better economic returns from polyculture, potential use of earthen ponds that have been abandoned by shrimp farmers.	No comparison with monoculture. Beneficial effects from polyculture not investigated or discussed. No water quality parameters monitored. Economic calculations only including profits from snails.	Kritsanapuntu *et al.*, 2006a Kritsanapuntu *et al.*, 2006b

System	Species	Country	Aims	Logistics of culture
SI	• Shrimp (*Penaeus monodon*) • Seaweed (*Gracilaria* sp.)	Brazil	IPMS WM	Shrimp effluent water from commercial shrimp pond culture drained into ditches with seaweed placed on frames. Seaweeds at 0.3 m below surface and 1.2 m above bottom. Shrimp stocked at 25 ind. Fertilization and pellet feeds. Five month study.
P	• Shrimp (*Penaeus monodon*) • Milkfish (*Chanos chanos*) • Mullet (*Mugil cephalus*)	Taiwan	IPMS	Culture of three species in inland ponds which receive water from deep salt water wells.
P	• Shrimp (*Penaeus monodon*) • Milkfish (*Chanos chanos*)	India	IPMS	Brackishwater pond (440 m^2). Stocking rate: 21000 shrimp per ha, 1000 milkfish per ha. Formulated feeds. 72 days study.
P	• Shrimp (*Penaeus monodon*) • Tilapia (*Oreochromis niloticus*)	Thailand	WM	Nine 200 m^2 earthen ponds. Three different shrimp: fish ratios (ind. per m^2) was investigated: 30:0, 30:0.25 and 30:0.5. Nutrients and solids quantified in pond water. Different draining schemes investigated.
P	• Shrimp (*Penaeus monodon*) • Tilapia (*Oreochromis niloticus*)	Thailand	IPMS WT	Nine 200 m^2 earthen ponds. Three different shrimp: fish ratios (ind. per m^2) was investigated: 15:1, 15:2 and 15:4. Culture period 133 days.
P	• Shrimp (*Penaeus monodon*) • Mullet (*Mugil* sp.)	Philippines	IPMS	Brackishwater ponds (21 x 171 m^2) polyculture to find optimal stocking densities for both species. Treatment ratios shrimp and mullet: 5000:0, 0:5000, 0:7500, 0:10000, 5000:5000, 5000:7500,5000:10000. 120 days trial.
P	• Sea cucumber (*Holothuria scabra*) • Shrimp (*Litopenaeus stylirostris*)		IPMS WM	Juvenile sandfish stocked at 0.8 and 1.6 individuals m^{-2} in hapas within 0.2-ha earthen shrimp ponds. Shrimp post-larvae stocked at 20 ind. m^{-2}.
P (SI)	• Sea cucumber (*Holothuria scabra*) • Shrimp (*Litopenaeus stylirostris*)	New Caledonia, (France)	IPMS	Shrimp and sea cucumber were co-cultured in experimental salt water tanks. Shrimp feed not accessible for sea cucumbers. Tanks, 500 L. Juveniles of both shrimps and sea cucumbers used.
P	• Shrimp (*Litopenaeus stylirostris*) • Sea Cucumber	Viet Nam	IPMS	Outdoor fibreglass tanks (1.15 m^3), 6 m^3 outdoor concrete tanks, high water exchange. Many different trials were carrier out, including different combinations and treatments.
P	• Shrimp (*Penaeus monodon*) • Tilapia (*Oreochromis niloticus*)	Pilippines	IPMS WM	all inoculation and tank experiment. Fish (500 g m^{-2}) in net-cages inside 3 m^2 outdoor tanks. Shrimps stocked at different densities (80 and 110 g m^{-2}) directly in the tank. Different feeding rates tested. Tank water inoculated with V. Harveyi. Incubation for 15-21 days without water exchange.
P	• Shrimp (*Penaeus monodon*) • Grouper (*Epinephelus coioides*) • Milkfish (*Chanos chanos*) • Tilapia (*Oreochromis niloticus*)	Pilippines	IPMS WM	Small inoculation and tank experiment. Fish (500 g m^{-2}) in net-cages inside 3 m^2 outdoor tanks. Shrimps (80 g m^{-2}) stocked directly in tanks. Tank water inoculated with V. Harveyi. Incubation for 21 days without water exchange.

Results and discussion	General conclusions	Comments	Reference
Seaweed growth rates varied between 1.8 to 8.8%. Silt accumulation on fronds removed every two days. High ammonia concentrations probably inhibiting seaweed growth after some time of culture.	Ammonia in excess may have had negative effect on red seaweed growth. High water turbidity impacting negatively on growth. Integration possible but more studies to find optimal design needed.	No information about water exchange given.	Marinho-Soriano *et al.*, 2002
Polyculture was more effective than any tiger shrimp monoculture. Higher shrimp growth rate in polyculture. Production: Polyculture-1.5 t shrimp + 13.75 t fish; Monoculture- 10.5 t shrimp. Less phytoplankton fluctuation in polyculture ponds.	The impact of inland ponds (10-20km) which use salt-water must be assessed - fresh-water salinization, water exchange, etc. Polyculture reducing risk of harvest loss.	Study summarised in Brzeski and Newkirk 1997. Higher stocking density of shrimps in monoculture resulting in more shrimps being produced. Poor relocation and no economic analysis.	Chiang *et al.*, 1990
High survival rate (>90%) for both shrimp and fish. Highest recorded production of shrimp compared to previous monoculture.	Polyculture showed upon greater returns than monoculture.	No replication. No detailed economic analysis. No monoculture experiments carried out within the study.	Thampy *et al.*, 1988
Results not revealing the different nutrient reduction capacities for the different treatments (with or without tilapia). Tilapia not affecting shrimp growth even if competing for feed. Higher feed input to polyculture did not result in higher phytoplankton abundance. Tilapia consuming phytoplankton and stabilizing water quality, and decreasing water turbidity. More nutrients bound in biomass in polyculture.	The present study showed that shrimp-tilapia polyculture is feasible technically, however, but not attractive economically. Economically viable to co-culture Tilapia with shrimps, but monoculture higher net return.		Saelee, 2004
Growth parameters of shrimp including total weight, survival rate, gross and net yields in the high tilapia density treatment were significantly poorer than those in the medium and low tilapia density treatments. Higher fish density resulted in less DO and higher TAN.	Not attractive economically with high fish density as survival of shrimps decreased. More research needed to optimize the tilapia-shrimp polyculture system. Survival and production of shrimps did not differ between the low tilapia densities.	No comparison was made between monoculture of tilapia and co-culture with shrimps. Only different densities of tilapia together with shrimps was evaluated.	Thien *et al.*, 2004. Thien *2003*
No competition between the two species, but intraspecific competition in highest fish density treatment. Highest total production in combination with shrimps and highest fish density, and lowest production in low density fish monoculture.	Diversification of products seems feasible using the co-culture of shrimps and mullet.	Abstract. Feeding? Nutrients?	Manzano 1982
Survival and growth of sandfish reared with shrimp significantly lower compared to monoculture. Increased shrimp stocking densities impacted negatively on sandfish survival. High stocking density of juvenile sandfish had no significant effects on growth and survival of shrimp.	Co-culture of larger individuals not viable but monoculture in earthen ponds seems promising.		Bell *et al.*, 2007
Growth of shrimp did not differ between monoculture and co-culture. Sandfish grew significantly slower in co-culture. Shrimps lowering water quality for sandfish (increased TAN). Sea cucumber add to turbation but don't significantly remove excess nutrients - not an effective biofilter,	Polyculture at the juvenile stage of both species seems possible. Co-culture may, despite slowed sandfish growth, be more financially sustainable compared to monoculture. Juvenile sandfish cannot be expected to be significant bioremediators for shrimp ponds. Further studies on waste discharge by larger sandfish at higher densities needed.	Researchers suggest seaweed as possible addition to system for biofiltration purpose.	Purcell *et al.*, 2006
Somewhat promising results but predation of sandfish by shrimps was a problem under certain conditions. Authors recommend more research needed before any conclusions can be drawn. Co-culture viable under certain conditions. Study only used many variations on stocking but few replicates.	Potentially co-culture of sandfish at no extra cost and no negative impact on shrimp growth. Harassment and predation of sandfish occurred under some conditions. Predation by shrimps under certain conditions. To high shrimp densities making sediment environment unsuitable for the sandfish. Successful co-culture means greater return for farmers using system.	No economic performance assessed in this study	Pitt *et al.*, 2004
Feeding enhances the antibacterial activity or improves the efficiency of tilapia to inhibit bacteria. Increased shrimp biomass (>80 g m^{-3}) resulted in decreased efficiency in tilapia to inhibit bacteria growth. Shrimp survival was lowest in control tanks without any fish.	Results explain discrepancies found in the use of tilapia to control luminous bacterial disease in shrimp ponds.	Small scale tank experiments conducted during short time.	Tendencia, de la Peña and Choresca, 2006
Tilapia and grouper decreased luminous bacteria levels resulting in increased shrimp survival. Milkfish had no such effect. Shrimp survival was lowest in control tanks without any fish.	Study proved that the presence of tilapia, grouper and milkfish positively affects shrimp survival (tilapia most effectively).	Small scale tank experiments conducted during short time.	Tendencia *et al.*, 2006, Tendencia *et al.*, 2003, Tendencia *et al.*, 2004, Tendencia *et al.*, 2005

System	Species	Country	Aims	Logistics of culture
P	• Oyster (*Pinctada martensi*) • Seaweed (*Kappaphycus alvarezii*)	China	IPMS WM	Both lab. and open sea experiments. Glass container (20 L) used for evaluating seaweed nutrient uptake. Open water experiments: 1) both species cultured in offshore cages, 2) oyster growth in cages in seaweed farm, 3) seaweed grown in cages in oyster farm.
SI	• Oyster (*Pinctada martensi*) • Sea Urchins (*Lytechinus variegatus, Echinometra lucunter*)	Venezuela	WM	Two species of sea urchins were placed on oyster lines in order to attempt to control fouling on the lines and on the oyster.
SI	• Shrimp (*Penaeus monodon*) • Seaweed (*Gracilaria parvispora*)	Hawaii	IPMS WM	Two phase system: fertilization and initial growth of seaweed in ditches, periodically were filled with shrimp pond effluents, and then moved to floating cages in a lagoon for grow-out.
P	• Oyster (*Pteria, Ostrea nomades*) • Siganid (*Siganus canaliculatus, Siganus lineatus*)	Micronesia	IPMS	Oysters were grown on stringers which were placed in pens stocked with rabbit fish
P	• Shrimp (*Penaeus indicus*) • Milkfish (*Chanos chanos*) • Mullet (*Valamugil seheli*) • Sillago (*Liza macrolepis*)	India	IPMS	Polyculture of four species conducted in earthen ponds and coastal net-pens for comparison
SI	• Shrimp (*Penaeus monodon*) • Shrimp (*Fenneropenaeus merguiensis*) • Green mussle (*Perna viridis*)	Thailand	WM	Stable isotope analysis, treatment ponds with mussels
P	• Shrimp (*Litopenaeus vannamei*) • Oyster (*Crassostrea gigas*) • Black clam (*Chione fluctifraga*)	Mexico	IPMS WT WM	Earthen ponds. Monoculture of shrimps compared to polyculture. Growth as well as water quality studied. Study period nine month. Two oyster densities (10 and 16 m^{-2}), two clam densities (8 and 10 m^{-2}) and one shrimp density (30 m^{-2}) was investigated.
P	• Shrimp (*Litopenaeus vannamei*) • Shrimp (*Litopenaeus stylirostris*)	Mexico	IPMS	Earthen ponds
P	• Spotted babylon, (*Babylonia areolata*) • Sea Bass (*Lates calcarifer*)	Thailand	IPMS WM	Indoor tanks
P	• Tilapia (*Oreochromis niloticus*) • Shrimp (*Litopenaeus vannamei*)	Brazil	IPMS	Tanks 1 m^{-3}. Many different densities of both fish and shrimp tested, as well as different sizes fish of (50-200g). Cultivation period 120 days.
P	• Giant Clams (*Tridacna derasa*) • Trochus (*Trochus niloticus*)	Solomon Island	IPMS	Initial rearing of trochus in tanks, then open water cages for grow-out together with giant clams. Species produced mainly for re-stocking but the system could potential also be used for grow-out.

Results and discussion	General conclusions	Comments	Reference
Both species grew faster in polyculture than monoculture. Oyster nitrogen waste stimulated seaweed growth.	*Kappaphycus* can be used as a nitrogenous waste remover in pearl oyster farming and also stimulate pearl oyster production.	Unclear how oysters benefit from seaweeds as they compete with phytoplankton for nutrients.	Qian *et al.,* 1996 Wu *et al*., 2003
One species of sea urchin reduced fouling on lines and shells significantly, while the other only reduced fouling on the lines. Combination of both urchin species reduced fouling on lines and shells as well.	Sea urchins may be viable biocontrolers for fouling in bi-valve line systems. No difference in pearl oyster growth was, however, recorded and this is consistent with past research that oysters are not sensitive to fouling. Reduction in fouling on shells can reduce the amount of cleaning involved before sale, as well as increase overall value of bi-valve product.	No investigation of costs involved for cleaning the oysters and what the reduced fouling by sea urchins could imply from an economic point of view.	Lodeiros and Garcia 2004
Relative growth rates of effluent-enriched thalli in the cage system ranged from 8.8% to 10.4% day^{-1}. Growth of thalli fertilized with inorganic fertilizer was 4.6% day^{-1} Thalli in the effluent ditch had mean growth rates of 4.7% day^{-1}.	Enhanced growth of seaweed and the use of effluent from commercial shrimp farms as a resource.	Costs involved in maintenance (handling, transportation, etc.) not considered.	Nelson *et al*., 2001
Siganids observed to eat algae which normally creates fouling, and more spat settled on nets when fish were present.	Cleaner equipment, decreased demand on labourers, greater production of oysters as a result of less fouling, and benefits of additional commercially viable species in rabbit fish. Enhances production, additional commercially viable product.		Hasse 1974
Mullet and Sillago showed better growth in net-pen, while milkfish showed better growth in pond. No difference between fertilized and unfertilized ponds in terms of growth.	Diversification of products. Benefits of multiple commercially viable products.	Abstract	James *et al*., 1984
dC value suggesting that shrimp feed was the main food source for the mussels	Reduced particle load from biofilteering by the mussels.	Growth was not measured and no comparisons was made with monoculture outflow (i.e. biofiltering efficiency not made). Study just showing potential for co-culture. No economics considered.	Yokoyama *et al*., 2002
Total ammonium nitrogen, total suspended solids and chlorophyll-a significantly lower in the ponds with the highest combined density of molluscs. Increased shrimp growth in Polyculture.	*Crassostrea gigas* showed not to be a good prospect for this polyculture (low survival (10-16%) due to high temperature).	No estimation of extra costs involved for farming multiple species.	Martinez-Cordova and Martinez-Porchas 2006
Litopenaeus vannamei and *L. stylirostris* exhibit some differences in their feeding preferences. Litopenaeus stylirostris is probably more carnivorous than *L. vannamei*, which can consume plant material quite well.	Lower FCR for polyculture, Higher production from increased growth (*Litopenaeus stylirostris*) and higher survival (both species). No economic analysis (even though data on FCR, growth available)		Martínez-Córdova and Pena-Messina 2005
Average growth, survival, FCR and total production of spotted babylon and sea bass from polyculture were not significantly different from those in monoculture.	Unclear. No obvious benefits. Decreased culture area could be one benefit from polyculture. No water parameters measured. No decreased resource usage.		Chaitanawisuti *et al*., 2001
L. vannamei can be grown in association with tilapia *O. niloticus* in different combinations and receiving only one type of feed).	Polyculture showed upon similar growth and survival as monoculture.	Not evaluated but potential for more efficient resource utilisation and increased profits from an additional crop. Water quality not considered.	Candido *et al*., 2005 *(In Spanish- abstract English)*
Trochus had no deleterious effects on the growth and survival of giant clams. Some indications of higher growth and survival of the giant clams at the highest stocking density of trochus. *Trochus* ineffective at removing larger species of algae.	Utilizing an existing culture facility (multiple crops). Growth and survival of the giant clams were improved at the highest stocking density of trochus, but this density was not optimal for trochus growth.		Clarke *et al*., 2003

System	Species	Country	Aims	Logistics of culture
SI	• Shrimp (*Penaeus japonicus*) • Oyster, (*Saccostrea commercialis*) • Seaweed (*Gracilaria edulis*)	Australia	WM	Effluents from commercial shrimp ponds transferred to 11 indoor tanks. Biofiltration efficiency measured in a three-stage effluent treatment system consisting of sedimentation tank, oyster and seaweed. Close monitoring of suspended particles and dissolved nutrients. 24-48 hours experiments.
MI	• Shrimp (*Litopenaeus vannamei*) • Mangroves	Colombia	WM	Shrimp pond wastes from a 286 ha farmpartially recirculated through a 120 ha mangrove. Study conducted over three month period. Suspended solids and inorganic nutrients measured.
P	• Milkfish (*Chanos chanos*) • Siganid (*Siganus rivulatus*) • Seaweed (*Eucheuma denticulatum, Kappaphycus alvarzii, Ulva* spp., *Gracilaria crassa*) • Shellfish (*Pinctada margaretifira, Anadara antiquata, Isognomon isognomon*)	Tanzania	IPMS WM	Pond culture of milkfish and rabbit fish and two seaweed species (*Euchuema* spp.). Fish fed artificial feeds. 40000 m^{-2} large reservoir and and 300 m^{-2} treatment ponds. Study conducted over 8 month period.
SI	• Shrimp (*Litopenaeus vannamei*) • Oyster (*Crassostrea rhizophorae*)	Brazil	IPMS WM	Experiments carried out at two commercial shrimp farms. Oysters were cultivated on constructed beds after the sluice gate of the farm. Oysters harvested after 3 month. 4500 oysters per sluice gate (6 gates).
SI	• Shrimp (*Penaeus monodon*) • Tilapia (*Oreochromis niloticus*)	Thailand	IPMS WT WM	Shrimps grown in 5 m^{-2} concrete tanks with tilapia in cages within the tanks. No water exchange and experiment conducted for 60 days. Effects from different tilapia stocking densities on shrimp growth and water quality evaluated. Economic performance also evaluated.
SI	• Shrimp (*Penaeus monodon*) • Oyster (*Crassostrea belcheri*)	Thailand	WM	Lab. experiments to study oyster feeding. Field experiment where shrimp pond water was diverted into small tanks with Oysters. Part of the study also to qualitative and quantitative analysis of shrimp pond effluents (from 20 farms).
SI	• Shrimp (*Penaeus monodon*) • Mussel (*Perna viridis*)	Thailand	WM	Experiment 1: culture of mussels in drainage canal, testing culture methods; Experiment 2: 3 Litres tanks stocked with mussels received water from a commercial shrimp pond. Investigating filtration and biodeposition.
P	• Shrimp (*Penaeus monodon*) • Milkfish (*Chanos chanos*) • Siganid (*Siganus* spp.)	Indonesia	IPMS	Earthen ponds (> 1 ha). Testing growth performance and water quality under different species combinations (milkfish monoculture, shrimp-milkfish, siganid-shrimp).
P	• Milkfish (*Chanos chanos*) • Shrimp (*Penaeus monodon*)	Thailand	IPMS	Milkfish and shrimps reared in different combinations for 100 days in 500 m^{-2} earthen ponds.

Results and discussion	General conclusions	Comments	Reference
Detailed information regarding potential sedimentation and nutrient regeneration rates, oyster filtration rates, and nutrient uptake rates. Overall, improvements in water quality TSS 12%; total N 28% ; total P 14% ; NH 76% ; NO 30%; PO_4 35%; bacteria 30% ; and chlorophyll a 0.7%. High N content in the small unsettleable particles being removed by the oysters.	Showing upon the capacity to filter shrimp wastes using oysters and seaweeds.	Small-scale experiment difficult to really extrapolate to commercial conditions. Flow rate through the different treatment staged of great importance. Proper controls without biofiltering organisms.	Jones *et al.*, 2001
Phytoplankton and zooplankton density decreased passing the mangrove filter. Total and organic particulate removal rate in the biofilter was about 95% and 93%, respectively. Dissolved inorganic nitrogen and phosphorus increased (probably due to presence of large bird communities in the forest).	Possible use of mangrove wetlands as biofilters for effluent treatment will be less predictable than expected.	No replication or controls. No separation of dilution effects and true uptake/ transformation. Not known how long the biofilter function persists. Effects from permanent flooding of the mangroves also not known. Effects on forest functions not known. Supply water and biofilter exit close?	Gautier *et al.*, 2001
Water quality deteriorated significantly, with low DO and high ammonia levels. Poor seaweed growth in ponds but high growth in the channels.	Potential benefits of multiple commercially viable species. Water quality deteriorated potentially having an adverse effect on growth of cultured species and the environment.	Water quality deteriorated suggesting that this system may not be sustainable.	Mmochi *et al.*, 2002, Mmochi and Mwandya 2003
Decreasing Inorganic P and Chlorophyll a. No clear effect on dissolved N, some month decreasing concentrations in effluents and some month increasing.	Reduction of Chlorophyll and production of secondary crop. Potential for co-culture and potential for increasing farmers income.	Sometimes dissolved nitrogen increased. Not known if total particulate loading was effected as this was not studied. Growth was measured but no comparison with other cultivation methods performed and no overall economic analysis was carried out.	Oliviera and Brito 2005
Tilapia lowered dissolved N (but not significant) but increased Chlorophyll a. Tilapia regenerating N from shrimp wastes. No effect on dissolved P from integration. Competition between shrimp and tilapia for detritus. Tilapia increased economic returns only at lower stocking densities of shrimps (5-25 ind. per m^3).	Lowering dissolved N. Increasing economic return at low stocking densities of shrimps. Increasing phytoplankton densities, competition for detritus at higher stocking rates.		Yacoob 1994
More testing the suitability for using oysters fed shrimp waste water (feed quality (phytoplankton), optimal water velocities, pre-settling of waste water). Ammonia-N increased by 2.7 %, nitrite 10.1% and nitrate 4.6%.	A hypothetical 1 ha integrated farm could by using 5 % area for oyster units remove 21 % of total suspended solids, 9% of total N and 6 % of total P. This removal are based on 40% water exchange per day.	Very mechanistic study- difficult to extrapolate to commercial scale. Anticipated that it should be profitable under good management, but no economic calculations presented. Settling ponds removed more than double the amounts removed by oysters.	Tanyaros 2001
The experiment failed to say something about how efficient mussels can reduce particles in shrimp waste water due to logistical problems. Also changes in water nutrient concentrations could not be conclusive.	Mussels did grow but the growth period was to short (due to shrimp diseases) to be able to say something about the potential growth. They could utilize food in the waste water.	Mussels died twice due to salinity fluctuation. Problems with epiphytic growth on culture trays. Low water exchange caused stagnant water in canals- leading to low food availability and high temperatures. Experiments could not show upon effects on water quality form mussel filtration (due to design).	Buakham 1992
Lower production (biomass) in polyculture. Integration of shrimps and siganids successful-occupying different nisches (shrimp bottom feeded, siganids pelagic feeder).	Total production lower in polyculture but generating a higher value due to shrimp production (compared to milkfish monoculture).	Difficult to evaluate as different stocking densities and feed inputs been used.	Ranoemihardjo 1986
Negative impact on shrimps from milkfish but a positive effect from shrimps on milkfish.	If focus is on milkfish adding shrimps could increase fish growth. Water quality not changing in polyculture compared to monoculture but stocking densities very low (max 1 ind. per m^2).	Slow growth of shrimps if reared in higher densities due to insufficient feed (natural production stimulated by fertilisers).	Pudadera and Lim 1982, Pudadera 1980

System	Species	Country	Aims	Logistics of culture
SI	• Shrimp (*Penaeus monodon*) • Grey mullet (*Mugil cephalus*) • Siganid (*Siganus nebulosus*) • Seaweed (*Ulva* sp.)	Australia	WM	Earthen ponds (1 ha) and 10 m^3 tanks. Inclusion of vertical artificial substrates (VAS, AquaMatt™).
SI	• Milkfish (*Chanos chanos*) • Siganid (*Siganus rivulatus*) • Seaweed (*Ulva reticulata*)	Tanzania	WM	Gravity fed earthen ponds. Seaweeds suspended in fishnet cages in outflow channels. Low stocking density of fish. Only focus on seaweed performance.
SI	• Milkfish (*Chanos chanos*) • Siganid (*Siganus rivulatus*) • Seaweed (*Ulva reticulata, Gracilaria crassa, Eucheuma denticulatum, Chaetomorpha crassa*)	Tanzania	WM	Gravity fed earthen ponds. Seaweeds suspended in fishnet cages in outflow channels (except *Eucheuma* that was planted using 20-mm nylon ropes) . Low stocking density of fish. Only focus on seaweed performance.
P	• Shrimp (*Penaeus vannamei*) • Oyster (*Crassostrea virginica*) • Mullet (*Mugil cephalus*) • Tilapia (?)	USA	IPMS WM	Main focus on water exchange regime in shrimp pond farming. No-exchange ponds (600 m^2) were occasionally recirculated through a 0.1 ha pond containing oysters, mullet, tilapia and bait fish. Shrimps stocked at 38-78 PL per m^2. Manure and Urea supplemented. Pellet feed used as supplemental feeding for shrimps.
P	• Shrimp (*Penaeus monodon*) • Milkfish (*Chanos chanos*)	Philippines	IPMS	Eight 500 m^2 earthen ponds stocked with different combinations of fish and shrimps: 20,000 juv. shrimps with 2,000 milkfish fingerlings per ha; 20,000 juv. shrimps; 2,000 milkfish fingerlings per ha in monoculture. Natural production of food in ponds through fertilization. Experiment conducted for 109 days.
P	• Shrimp (*Litopenaeus vannamei*) • Seaweed (*Kappaphycus alvarezii*)	Brazil	IPMS WM HP	Experimental PVC cages (grow-out 100 shrimp per m^{-2}) with seaweed fixed in floating tubes and disposed inside. Experiment carried out for 103 days.
SI	• Shrimp (*Penaeus japonicus*) • Oyster (*Saccostrea commercialis*) • *Gracilaria edulis*	Australia	IPMS WM	Effluents from earthen shrimp ponds (6x1 ha) pumped into 15x34L oyster tanks (oysters on trays). Three different oyster densities: 24, 16 and 8 per tank. Controls with dead oysters included in the study.

Results and discussion	General conclusions	Comments	Reference
Mullet alone not resulting in significant N reduction (only 1.8- 2.4%), but contribute to control of macroalgal (*Ulva*) biomass. Mullet probably inhibit nitrification but process sedimented organic material.	Removal of algae and consumption of detritus. No significant effect on N removal and possible reduction of nitrification. Artificial substrate important for particle settlement.		Erler 2000 Erler 2004
Seaweed growth 4% per day under study period. TAN removal 65%. Controls without seaweeds also removing TAN – efficiently pH and oxygen level raised by seaweed.	Growth possible. Nutrients will be removed. Increased oxygen and pH	Study covered short period. Not clear if nutrient concentrations in outflow from fish ponds is representative for commercial practice. Special setting with gravity fed water to biofilter unit. This may not be applicable to most farms. The need for area will be large in commercial production and area in channels will probably not be sufficient. Controls without seaweeds also removed TAN efficiently.	Msuya *et al.*, 2006
Poor growth *Gracilaria crassa* and *Ulva reticulata* (1.5 and 1.2 %) but good quality with protein dry weight contents of 13%. *Eucheuma* and *Chaetomorpha* performed poorly in the fishpond effluents. Nutrient uptake (nutrient removal) based on nutrient content in seaweeds.	Growth possible for three of the investigated species. Removal of nutrients. Increased oxygen and pH	Study only covered short period. Not clear if nutrient concentrations in outflow from fish ponds represent commercial practice. Study mainly showing that the seaweeds can grow in present set-up. No. Special setting with gravity fed water to biofilter unit. This may not be applicable to most farms. The need for area will be large in commercial production and area in channels will probably not be sufficient.	Msuya and Neori 2002.
Good survival but somewhat lower in systems with no exchange of water compared to 15% exchange in monoculture. Trends towards higher production in ponds with exchange. Higher BOD in re-circ. system. No clear difference in dissolved nutrients but generally higher TSS in the re-circulation system. No significant difference in growth and survival rates between the different combinations.	Good water quality at used stocking densities, sufficient DO, extra crops and saving cost for water pumping. Water could also be reused. Reduction of effluents to the environment.	Results not clear and the two experiments indicate large variability in system performance. Potential lower production of shrimps in re-circ. system. Higher FCR in re-circ. System. Only pumping costs discussed and these decrease in re-circ. system. No other costs or profits included.	Hopkins *et al.*, 1997
No negative interaction between milkfish and shrimps. Good growth and survival in all treatments. Physio-Chemical Parameters similar between mono-polyculture.	Additional crop in polyculture systems with kept growth rates for individual species. No feed input.	Very low stocking densities (2 ind. per m^{-2}) with natural food in pond. Thorough economic analysis. Best economic return from polyculture. Economic feasibility with return on investment (ROI) valued at 45 percent for polyculture. Large land areas needed for increased production.	Kuntiyo and Baliao 1987
Floating cages are a viable alternative for rearing *L. vannamei* in open sea water and also with co-culture of seaweeds. Annual shrimp production 25-30 mt per ha. Rather poor seaweed growth (0.8-1.3% day^{-1}).	Multiple crops, nutrient reduction. Positive aspects from shrimps using algae as shelters and production of natural food need to be further investigated. Nutrient removal. Farming shrimps in open water reduce pressure on coastal land.	There were no negative interferences in culturing shrimps and algae inside the same cage. Cages seem to limit growth compared to rope cultures. Only profitable on small commercial scale. NO monoculture of seaweeds investigated. Why not seaweeds on surface?	Lombardi *et al.*, 2006, Lombardi *et al.*, 2001
Most effective oyster filtration (24 oyster treatment) could reduce concentration of TSS (49%), TN (80%), TP (67%), Chl. a (8%), bacteria (58%) in incoming water.	Reduction of particles, phytoplankton and total nutrients in effluent waters A 20% water exchange in a 1ha shrimp pond would need 0.12 ha oyster tanks (120000 oysters, 24 oysters per tank).	Not separating dissolved and particulate nutrients (possible build-up of NH4). Experiment short and limited period of the year.	Jones and Preston 1999

System	Species	Country	Aims	Logistics of culture
SI	• Shrimp (*Penaeus japonicus*) • Oyster (*Saccostrea commercialis*) • *Gracilaria edulis*	Australia	IPMS WM	Earthen shrimp ponds (1 ha), 1500 L concrete raceways , flow-through and re-circulation experiments.
P	• Shrimp (*Penaeus monodon*) • Sandfish (*Holothuria scabra*)	Viet Nam	WM	Earthen ponds (1.2 ha + 0.45 ha). Polyculture, 30 PL shrimps per m^2, and 50 and 100 g sandfish m^{-2}. Shrimp receiving artificial feeds.
SI	• Shrimp (*Penaeus monodon*) • Gracilaria (*Gracilaria fisheri, G. Tenuistipitata*)	Thailand	IPMS	Earthen ponds (800 m^{-2}) stocked with seaweeds receiving waste water from extensive shrimp ponds.
SI	• Shrimp (*Penaeus monodon*) • Cockle (*Scapharca inaequivalvis*) • Gracilaria (*Gracilaria* sp.)	Malaysia	IPMS WM	Shrimp pond wastes (5.5 m^3 per day) pumped into earthen ponds: one (30 m^{-2}) stocked with cockles and one (18 m^{-2}) stocked with seaweeds. System running for one month.
P	• Shrimp (*Penaeus chinensis*) • Tilapia (*Oreochromis mossambicus x O. Niloticus*)	China	IPMS	Net enclosures (5.0 x 5.0 x 1.8 m) with fish in a closed 1.7 ha seawater pond. Fish also stocked outside the cages. Stocking: 4.5- 7.5 shrimp and 0-0.32 fish per m^2. Fertilizers and pellet feeds added..
P	• Shrimp (*Penaeus monodon*) • Milkfish (*Chanos chanos*) • Seaweed (*Gracilaria lichenoides*)	Indonesia	IPMS	Earthen ponds (0.1 ha) . Different stocking combinations investigated. Three planting methods for seaweeds investigated.
P	• Shrimp (*Penaeus monodon*) • Tilapia (*Oreochromis niloticus*)	Philippines	IPMS	Monoculture was compared with polyculture two times during a year. Production 81-138 kg per ha for shrimps, Stocking 0.6 shrimps per m^2 (final weight 26-30 g per ind.), 0.4-0.6 fish per m^{-2}
MI	• Mud crab (*Scylla serrata*) • Mangrove (reforested)	Philippines	IPMS HP	Crabs held in 200 m^2 pens and effects of stocking density (0.5 or 1.5 m^{-2}) and feed (fish or mixture fish/mussel) was tested for 160 days.
P	• Shrimp (*P. Monodon, P. Japonicus, P. merguensis*) • Tilapia (*Tilapia Mossambicia*) • Milkfish (*Chanos chanos*) • Sidanid (*Siganus vermiculatus*)	Indonesia	IPMS	Sea water in earth fishponds (2000 m^2) on reclaimed mangrove areas. Chicken manure, brewery waste and sugar mill wastes used as inputs.
P	• Sea bream (*Acanthopagus cuvieri*) • Tilapia (*Oreochromis spilurs*)	Kuwait	IPMS	Different sea bream densities (3, 6, 9 ind. per m^2) stocked in twelve 1 m^3 floating cages with tilapia (200 ind. per m^2) to decrease competition over feeds with wild fish. Experiment was conducted over eight weeks.
P	• Shrimp (*Litopenaeus vannamei, juveniles*) • Tilapia (*Oreochromis niloticus, juveniles*)	Thailand	IPMS WT WM	Different densities of fish and shrimps in same outdoor tank (2×2.5×1.1 m^3). Shrimps stocked at 40 ind. per m^{-2} and tilapia: 0, 0.4, 1, 2, 3 fish per m^2. Shrimps fed pellets.
P	• Shrimp (*Penaeus monodon*) • Tilapia (*Oreochromis niloticus*)	Thailand	IPMS WT	Fish and shrimps stocked in same outdoor brackishwater tanks (fish: 30 ind. m^{-2}, shrimp PL 50 m^{-3}) (also using AquaMats). Shrimp was fed pellet feeds.

Results and discussion	General conclusions	Comments	Reference
Different oyster densities tested. Oyster filtration reduced concentration of TSS (29%), TN (66%), TP (56%), Chl. a (39%), bacteria (35%) of the initial concentration. Seaweeds of low quality in high density oyster treatment and in high particulate concentration. Settling ponds important for reducing TSS before oyster filtration.	Oyster survival sensitive to both oyster and seaweed densities, as well as particulate loading. Reduction of wastes from shrimp ponds by the tested approach feasible.		Jones *et al.*, 2002
Polyculture had lower conc. of bacteria H_2S, $N0_2$ and total organic compounds. Also sediment in polyculture had lower content of organic matter. Growth rate of shrimps increased in polyculture with sandfish.	Seems possible to culture shrimp and sandfish in polyculture or shrimp followed by sandfish. Increased quality of pond environment in polyculture, as well as increased growth of shrimps.		Ngoc 2006
Growth 37-40 % better in ponds receiving shrimp waste water. Growth rates between 2.6-3.1%.	G. fisheri could be grown all around the year, but *G. Tenuistipitata* only possible 6-7 month of the year (due to too high temperatures and low salinity).	Growth rates low compared to other cultures of gracilaria. Interfering epiphytic seaweeds making the cultured seaweeds float to the surface.	Chirapart and Lewmanomont 2004
An average reduction of 83% of phosphate; 61% in total phosphorus; 81% in ammonium; 19% in nitrite; and 72% in total nitrogen. Gracilaria out competed by green algae (*Enteromorpha* sp.).	Cockles could probably be exchanged by oysters that could be stocked in existing channels system at the farm. Seaweeds could be controlled by chemicals.	Short study. No controls identifying effects from the ponds themselves.	Enander and Hasselstrom 1994
Production of shrimps at 6 ind per m^{-2} was 514 kg per ha^{-1}. Optimum stocking density of shrimp and tilapia was 60,000 shrimp and 400 kg tilapia per ha.	Growth rate and survival of shrimp increased with increasing stocking density of tilapia. Tilapia maintained optimal and constant biomass of phytoplankton. Tilapia enhances water movement and nutrient cycling.	Tilapia competed with the shrimp for food if not separated in cages (or feeding grounds for shrimp surrounded by a net).	Wang *et al.*, 1998
Focus on addition of seaweeds to existing Tambaks. Seaweeds attached to bamboo screens resulted in best growth (ca 3% daily growth rate). Calculating with 25% seaweed cover in ponds result in 3000 Kg per ha per year.	Good seaweed growth when cultured with shrimps or fish. Seaweed growth decreased when cultured with both species. Decreased growth of shrimps when cultured with fish, and vice versa.	No control present and therefore difficult to say anything about the effects from the animals.	Sutika *et al.*, 1990
Higher growth of both shrimps and fish in combination 0.4 fish per m-2 compared to monoculture treatments.	Detailed economic analysis (in Samonte *et al.*). Two crops per year provided a 70% return on investment and a 1.2 years payback. This was higher return compared to monoculture using same densities .	Using data from Gonzales-Corre 1988 to perform a detailed economic analysis.	Gonzales-Corre 1988, Samonte *et al.*, 1991
Growth was not significantly affected by stocking density or feed types.	The integration of crab aquaculture within natural mangroves is feasible, providing both immediate and long-term commercial and environmental benefits. Return on capital investment of 49–68%.	Not showing how mangroves are effected by this kind of culture.	Trino and Rodriguez 2002
Shrimp performance was compared and *P. monodon* had highest survival and growth rate. The other shrimp species could possibly survive better in more sandy soils.	Polyculture of *P. monodon* and fish possible.	Performance and interaction with fish difficult to access as different stocking rates was used and no controls.	Gundermann and Popper 1977
No effect on tilapia production. Placing sea bream monoculture cages close to tilapia cages could potentially minimize interaction from wild fish.	No benefits that not could be obtained from placing sea bream cages in the vicinity from tilapia cages (no need to be inside).	Thorough economic calculation. Potentially can sea bream feed being utilized by tilapia.	Ridha and Cruz 1992
Tilapia stocking significantly improved P conversion rate but the N conversion and shrimp growth rates decreased with high tilapia stocking. Net income was not significantly different between mono and polyculture.	Integrated system with a low tilapia–shrimp ratio (the ratio of 0.01 and 0.025) were effective to improve the nutrient conversion rate to culture animals without lowering shrimp growth.		Muangkeow *et al.*, (in press)
Tilapia increased shrimp survival but decreased growth.	Potential improved water quality in co-culture with tilapia but decreased shrimp growth. Questionable if fish production can compensate for lower shrimp yields		Ngo 2000

System	Species	Country	Aims	Logistics of culture
SI	• Shrimp (*Penaeus monodon*) • Mussel (*Mytilus* sp.) • Seaweed (*Gracilaria fisheri*)	Thailand	WT	Indoor 200 L tanks stocked with different combinations of species. Experiments conducted over 12-48 hours.
P	• Mudcrab (*Scylla serrata*) • Milkfish (*Chanos chanos*)	Philippines	IPMS	Different stocking densities of milkfish and crabs was tested in polyculture in three 0.1 ha earthen ponds (subdivided by bamboo screens). Culture period 130 days.
SI	• Shrimp (*Penaeus vannamei*) • Oyster (*Crassostrea virginica*) • Clams (*Mercenaria mercenaria*)	USA	IPMS	Shrimp and biofilter ponds 0.1 ha in re-circulation. Treatment pond with oysters on trays or directly on pond bottom, and clams directly on bottom. Shrimps stocked at 60 ind. per m^{-2}.
P	• Shrimp (*Penaeus monodon*) • Milkfish (*Chanos chanos*)	Philippines	IPMS	Earthen ponds, $500m^{-2}$, three different stocking combinations; monoculture milkfish, low (4000 ind. per ha) and high (8000 ind. per ha) shrimp polyculture. Only fertilizers used as input.
SI	• Shrimp (*Penaeus vannamei*) • Oyster (*Crassostrea virginica*)	Thailand	IPMS	Two flow through tanks (310 L) receiving waste water from commercial semi-intensive shrimp ponds. Oysters stocked on trays and pond water flowed downward through each of two seven tray stacks. Experiment lasted for 268 days.
SI	• Shrimp (*Litopenaeus vannamei*) • Constricted tagelus (*Sinonovacula constricta*)	China	IPMS WM	Two systems containing six shrimp ponds (tot area 0.93-1.3 ha), one mollusc pond (0.67-1.20 ha) and a a reservoir was run in recirculation mode. Culture period 81–106 d^{-1} for shrimps, and 240–350 d^{-1} for tagelus. Shrimps stocked at 128-135 ind. per m^2. Natural foods in the water from the shrimp ponds used for tagelus, being stimulated by adding fertilisers . Daily circulation rate was 10%–20% of the total water volume of the system (excluding reservoir volume) in early stage, 20%–30% in middle stage, and 40% in late stage. System also included artificial biofilm.
P SI	• Shrimp (*Penaeus monodon*) • Seaweed (*Gracilaria changii*)	Malaysia	IPMS WM	Gracilaria was cultured on i m^2 frames on lines, at 15 cm interval from the surface. The frames were placed in the middle of a shrimp pond and also in irrigation canal. A third treatment was seaweeds placed in ponds in the mangroves. Growth was studied during 12 weeks and repeated 3 times.
SI	• Shrimp (*Penaeus monodon*) • Mangrove (*Rhizophora mucronata*)	Indonesia	WT	Mangroves in a natural "reservoir pond" receiving shrimp pond effluents from 12 2500 m" earthen ponds. Artificial pellets, stocking rate 40 per m^2.
P	• Sea bass (*Lates calcarifer*) • Seaweed (*Gracilariopsis heteroclada*)	Philippines	IPMS WT	Seaweeds on ropes suspended at different depth in Sea bass (fingerlings) cages. Empty fish cages used as controls. Polycultue with fish mainly as biological control (predation on herbivorous fish).
P	• Grouper (*Epinephelus* sp.) • Seaweed (*Kappaphycus alvarezii*)	Philippines	IPMS WT	Seaweeds on ropes suspended at different depth in Grouper (juveniles) cages. Empty fish cages used as controls. Polycultue with fish mainly as biological control (predation on herbivorous fish). Different culturing techniques of seaweeds were tested.

Results and discussion	General conclusions	Comments	Reference
Ammonia-nitrogen decreased 67% in seaweed treatment, but increased in mussel and mussel/ seaweed with over 600%. between 8-54% in all treatments during 48 hours. Treatment had no significant effect on suspended solids. Chlorophyll a and BOD+COD decreased (20-100%) in all treatments ($P<0.05$) during 48 hours.	Variable results depending on duration of incubation.	Small scale and short term experiments (indoor) which makes it difficult to extrapolate to outdoor conditions. Large variation within treatments.	Chaiyakam and Tunvilai 1992, Chaiyakam and Tunvilai 1989, DOF 1992
Net production of crabs was higher in polyculture at both stocking densities (5 and 10 000 per ha). For milkfish the opposite was observed.	Fish may 1) increase food availability for the crabs, and 2) their presence may reduce movement of crabs and thereby minimizing interactions between crabs. .	FCR given but no information about feeding.	Lijauco *et al.*, 1980
Growth and survival of shrimps not effected by bivalves. Good growth of bivalves with the exception during the warmer period. High mortality of clams only immediately after stocking. Oyster survival high only for oysters in trays.	Only ammonia-N decreased (30%) in polyculture ponds. Not possible to grow oysters directly on bottom. Fairly high infestation of oyster shell mud blister (caused by *Polydora* sp.).	No costs or profits included. Mentioning of low investment costs for co-culture but potentially higher costs for handling. Difficult to explain the decrease in ammonia-N and that only minor differences was found in particle conc.	Hopkins *et al.*, 1993
Highest combined milkfish and shrimp production in high shrimp density treatment. Shrimps had a positive effect on milkfish production. Mean survival rate ranged from 90 to 96% for milkfish and was about 50% for shrimps; it did not differ significantly with treatment.	Extensive system reaching max. 380 kg milkfish and 116 kg shrimp per ha per 4 month culture period.		Eldani and Primavera 1981
Mean oyster growth rate was 2 g week^{-1} (up to 3.7 g wk^{-1} in upper layer certain period) and survival was 79%. It was concluded that the prospects for shrimp and bivalve co-culture appear promising.			Jakob *et al.*, 1993, Wang *et al.*, 1990
Tagelus pond decreased the concentrations of suspended matters and PO_4-P, and also COD and inorganic nitrogen to certain extent. TAN reduced by 19-64% and suspended solids by 45-90%.	The water quality in the ponds was maintained at a desirable level and no viral epidemics were discovered. Income from mollusc culture accounted for 22.1% of the systems total, the profit accounts for 52.6% of the total.	Probiotics (mostly nitrifiers) and fertilizers applied in tagelus ponds. Low profits from shrimps due to late stocking (small sizes). No controls used to isolate the filter feeding effects from pond effect (sedimentation etc.).	Wu *et al.*, 2005
Seaweed growth rate was three times higher in the irrigation canal compared to the shrimp pond and the natural mangrove (8.4, 3.6 and 3.3%, respectively). The seaweed cultivated inside the shrimp pond were heavily epiphytised and grazed upon (by fish). Seaweed growth best at the surface.	Seaweed growth was limited by epiphytes and high water turbidity. This could to some extent probably be solved through better placing in the pond , i.e. towards the edge of the pond. No quality measurement (i.e. Agar) was done on seaweeds cultured in the shrimp pond or in irrigation canal.		Phang *et al.*, 1996
Water nutrient concentrations were lower in the mangrove reservoir pond but e.g. NH_4 followed the slowly build-up experienced in the shrimp ponds. Tank experiment with mangroves showed upon large uptake capacity of mangroves (70% of NO_2, NH_4).	Difficult to say anything about nutrient removal efficiency as no controls were used in pond experiment, and no details were given about the tank experiments. Only 7 week experiment.		Ahmad *et al.*, 2003
Specific growth rate of seaweeds significantly influenced by the fish. Probability from predation of small herbivore fish. Best growth at 25 cm depth. Approx. 172 g (dry) m^{-2} month^{-1} was produced.	Presence of fish not increasing seaweed growth all month (not in April when seaweed growth was highest).	Not studied how fish growth is being impacted by the presence of seaweeds.	Hurtado-Ponce 1992c
Better growth using horizontal technique (ca. 5%).	Illustrates the potential to co-culture the seaweed with groupers in cages.	No comparison was made with cages without fish. The potential positive effect from either increased nutrients or prevention of grazing could therefore not be studied.	Hurtado-Ponce 1992b

System	Species	Country	Aims	Logistics of culture
SI	• Mangroves (impounded, predominantly *Avicennia rumphiana/A. officinalis/ Nypa fruticans*) • Shrimp (*Penaeus monodon*)	Philippines	IPMS WT HP	Wastes from intensive shrimp ponds (with milkfish in net-pens) diverted into natural mangrove stand. Shimp stocking density 10-30 shrimp postlarvae per m^2.
P MI	• Mangroves (predominantly *Avicennia marina*) • Mud crab (*Scylla olivacea, S. Serrata, S. Tranquebarica*)	Philippines	IPMS HP	Mud crabs stocked at 0.5-0.8 m^{-2} in 200 m^2 net-pens. Different feed combinations evaluated.
SI	• Green mussel (*Perna viridis*) • Spiny rock lobster (*Panulirus ornatus*)	Viet Nam	IPMS WM	Investigating growth of lobster fed different feed combinations- one being mussels farmed outside cages. Also measuring how integration effected different environmental quality parameters.
SI	• Green mussel (*Perna viridis*) • Seaweed (*Kappaphycus alvarezii*) • Grouper (*Epinephelus fuscoguttatus*) • Abalone (*Haliotes asinina*)	Viet Nam	IPMS WM	Grouper in 9 m^2 cages, mussels and seaweeds hanging on long lines outside cages, abalone kept in baskets inside fish cages. The weight ratio of cultured grouper, green mussel and alga was 3:1:12. Dissolved oxygen measured weekly and NH_3-N, NO_2-N, PO_4-P, Chlorophyll once a month. Grouper was fed on trash fish and experimental period lasted 10 month.
SI	• Giant Clams (*Tridacna derasa, T. Gigas, T. Maxima, T. Squamosa*)	USA	IPMS WM	Clams stocked in indoor raceways (2.5 x 0.3 m) receiving waste water from fish culture. Clam sizes between 32- 87 mm. Two month experiment.
SI	• Giant Clams (*Tridacna derasa*) • Snails (*Astrea tecta*)	USA	IPMS WM	Clams stocked in two indoor tanks (300 L) receiving waste water from fish culture (0.01 kg fish (snappers) per L) in re-circulated system. Clam sizes between 4.5 - 11 cm. Six month experiment. Herbivorous snails added to control biofouling.

Results and discussion	General conclusions	Comments	Reference
Mangroves reduced wastes by 64.2% for TSS, 34.0% for sulphide, 24.8% for NH_3 and 18.7% for NO_3 in the first 6 h. Night-time draining resulted in net production of nutrients from the mangroves. Growth of saplings and trees was 2.5 times greater in the treated mangroves compared to controls.	Based on overall findings it was estimated that a 2.18-4.36 ha of mangroves would be needed to treat N wastes from one ha of shrimp pond.		Primavera *et al.*, 2007
S. olivacea had low growth and low survival rates in all treatments.	Crabs have no impacts on adult mangrove trees, only on seedlings and saplings. Economic analysis showed that crab culture in mangrove pens using a combination of fish biomass and pellets is viable.		Primavera *et al.*, in press
Lobsters fed on mussel had higher survival rate than those fed by-catch. Growth rate the same. Organic matter in the deep water and sediment was lower under the combined culture compared to monoculture of lobster. Also bacterial densities decreased.	The results suggest that mussel and lobster co-culture potentially can lessen dependence on capture fishery resources, increase lobster growth reduce negative environmental impacts.	Preliminary results without statistical analysis.	Pham *et al.*, 2004, Pham *et al.*, 2005
No significant difference between polyculture and monoculture systems with respect to environmental factors. Fish growth not different between monoculture and integration. Mussel growth low (0.007 cm day^{-1}), seaweed daily growth rate 3.91% but showed signs of ice-ice infection at the end of the farming period. Abalone grew fast (0.016 cm day^{-1}.	The profits from polyculture system was 21.23% higher compared to monoculture. Investments and total production costs were only 9% and 17.5% higher, respectively.	Surprisingly low mussel growth!	Khanh *et al.*, 2005
Three of the species had high survival , but *T. Gigas* had 50% mortality. Only *T. derasa* grew faster in fish effluent water, the other clam species showing no growth. Clams able to remove some nutrients e.g. nitrogen and phosphorus concentrations lower in treatment tanks.	Nutrient reduction capacity not enough for integration with food fish aquaculture but possible for ornamental fish aquaria's.	Short term study and only on juveniles! No controls with only shells.	Sparsis *et al.*, 2001
Significant higher survival and growth rates for clams in fish effluent water. Nutrients measured but no uptake calculated. 2.5 times higher zooxanthellae density in clams in fish effluents.	Nutrient reduction capacity not enough for integration with food fish aquaculture but possible for ornamental fish aquaria's.		Lin *et al.*, 2001

Integrated aquaculture (INTAQ) as a tool for an ecosystem approach to the marine farming sector in the Mediterranean Sea

Dror Angel
Recanati Institute for Maritime Studies, Haifa University, Mt. Carmel, 31905, Israel
E-mail: adror@research.haifa.ac.il

Shirra Freeman
Department of Geography and Environmental Studies, Haifa University, Mt. Carmel, 31905, Israel
E-mail: shira@geo.haifa.ac.il

Angel, D. and Freeman, S. 2009. Integrated aquaculture (INTAQ) as a tool for an ecosystem approach to the marine farming sector in the Mediterranean Sea. In D. Soto (ed.). Integrated mariculture: a global review. *FAO Fisheries and Aquaculture Technical Paper.* No. 529. Rome, FAO. pp. 133–183.

CONTENTS

Abstract **134**
Introduction **137**
Objectives and approach 138
Analytic framework **142**
Synthesis of studies and reports 149
Country overview 150
Formal regulations, legislation and guidelines governing the environmental impacts of aquaculture and potentially of INTAQ 154
Technological requirements and general investment range for a variety of systems 156
Environmental considerations 161
Geographical areas and coastal zones most commonly used: where is INTAQ most likely to occur? 166
Information requirements for better understanding of current practices and realization of major opportunities 169
General evaluation of the major opportunities and constraints for INTAQ 169
Conclusions and recommendations **173**
Acknowledgements **174**
References **175**
Appendix – Key events in the evolution of ecosystem management relevant for aquaculture **182**

ABSTRACT

Aquaculture accounts for nearly 50 percent of worldwide fish landings (FAO, 2009). While aquaculture is an important source of fish stock, employment and profits, it also presents ecological, environmental and socio-economic challenges. *Integrated aquaculture* (INTAQ) has been proposed as one of a number of farming methods with the potential to mitigate some of the environmental problems associated with mono-specific aquaculture (monoculture) and to increase total production in a given site. INTAQ is the culture of two or more species of different trophic levels in a single farm or in close enough proximity that they interact in a way that mimics the energy flow pathways in natural ecosystems. Of particular interest is the combination of finfish culture with detritivores and algae both of which use finfish waste as food. Their presence reduces waste effluent into the environment as compared to a monoculture finfish installation with no waste treatment. It also produces added product that has a market value. The purpose of this report is to examine opportunities for INTAQ in the Mediterranean Sea basin for industry and local communities reliant on aquaculture and the commercial fisheries as well as its potential for lowering environmental impacts compared to capture fisheries, monoculture farming and other uses of coastal and marine resources. Thus, the main question guiding this study is whether and in what ways, INTAQ can significantly improve the productivity of selected areas in the Mediterranean Sea without increasing (and perhaps even decreasing) the negative externalities associated with monoculture. The study applies the ecosystem approach to analyze the potential of INTAQ and therefore considers a wide range of physical, ecological, social, political and business factors that determine the feasibility, social acceptability and ecological sustainability of INTAQ. The following four issues are addressed in order to assess the potential of INTAQ:

1. To what extent does INTAQ permits natural adjustments at the ecological level? As with any use of natural and environmental resources INTAQ will have impacts that may be positive, negative or neutral. An important issue in assessing INTAQ is the extent to which it alters the environment and this report attempts to describe and where possible quantify the potential effects.
2. With respect to their impacts, how does INTAQ compare with alternative uses of the same environment? The main comparison in this report is between monoculture and INTAQ, but in principle a wide range of alternative uses (e.g.: urban, industrial, tourism, recreation, capture fisheries, preservation) could also be considered as they coexist and often compete with aquaculture operations for the same coastal environment.
3. Given the fact that there is intense competition for coastal and marine resources, where does INTAQ fit in terms of regional priorities (e.g.: local development; economic viability; communities reliant on the fishery sector)?
4. What are the technical, engineering, production, investment, and regulatory challenges, opportunities and risks for business?

INTAQ is in its infancy and comes under several spheres of influence, including the aquaculture industry and fisheries sector, the coastal zones, a variety of ecosystems and several regulatory jurisdictions. This report therefore gives considerable attention to describing each of these in order to provide clear point of reference. Where needed, examples from experience outside of the Mediterranean Sea region have been used. Particular attention is given to:

- the ecology of the Mediterranean Sea basin and major environmental concerns;
- background to the aquaculture industry as a whole (including INTAQ);
- classification and description of INTAQ practices in the region;
- comparison between the impacts (known and potential) of monoculture and INTAQ;
- regulatory background;
- technical, production and financial issues; and

- potential of INTAQ for the growth and development of mariculture in the Mediterranean Sea.

The European Environmental Agency lists aquaculture as an important potential cause of environmental deterioration in the region if it is developed in unregulated and inappropriate modes. It identifies eleven potential negative impacts on the environment stemming from aquaculture (EEA, 2006). Since aquaculture has become such an important source of sea products, these concerns must be addressed if the industry is to be sustainable in the long run. Equally important for sustainability is the fact that aquaculture is also challenged by pollution, congestion and other environmental pressures from the surrounding ecosystem. Urban and industrial pollution and intense competition for space in many coastal areas are very real constraints on the potential for aquaculture in parts of the Mediterranean Sea region.

We have found that the main environmental advantage that distinguishes INTAQ from monoculture is its capacity to reduce farm effluent in the form of uneaten food, faeces and excretory wastes. Since this report is concerned with the potential advantages of INTAQ over more standard practices, effluent reduction and production enhancement are the focus of this study. This does not mean that other environmental impacts of concern to the EEA and others are less important, rather, they are shared by both INTAQ and other forms of aquaculture. Any discussion of sustainable mariculture must in fact include issues such as pathogen transfer between cultured and wild fish stocks, genetic contamination and visual distress associated with fish farms. But this needs to be done in a wider forum whose focus is mariculture in general.

Experience with INTAQ in the Mediterranean Sea is largely restricted to experimental and small scale pilot projects. These offer meaningful information on production possibilities and ecological impacts. For indications of potential business opportunities (e.g. investment, operating costs, market risks) we have relied on evidence from more advanced pilot and early commercial projects outside of the region, in particular in North America, Chile, and the United Kingdom. There are preliminary indications that there is potential for significant improvement in the return on investment mainly from increased production in the form of lower trophic taxa without the necessity of augmenting manufactured feed inputs. Moreover, INTAQ may have significant advantages in risk management at the business level because it offers diversification of products and access to multiple markets for finfish, shellfish, macroalgae and other seafood directly as well as derivative products.

In order to realize the potential of INTAQ more information is needed on most aspects of the practice. Research and commercial scale experience is required. Information on the potential risks and returns to investment will be especially important in order to facilitate entry at the enterprise levels. INTAQ as a business must be convincingly marketed to business operators as they will not engage in the practice unless they are well informed and confident of success. In addition, information on the environmental and broader social consequences must be disseminated efficiently and public education increased in order to counter prevailing skepticism and negative attitudes toward mariculture and INTAQ. A favorable and consistent regulatory climate with efficient policy design and implementation involving a wide stakeholder base will also facilitate acceptance and expansion.

Introduction

Of the three reviews included in this technical publication, the Mediterranean Sea has the smallest presence of integrated aquaculture (INTAQ). As a result, our assessment focuses on the reasons that the incidence is so low and on its potential and the requirements for expansion in the region. We have also relied on selected examples from outside the region in the belief that practitioners, the industry, regulators and the public at large in the Mediterranean Sea can benefit from experience from outside the region. The review of the history, current state, and major challenges and opportunities in the region is comprehensive in breadth. In order to gain the in-depth understanding needed, for the promotion of INTAQ, extensive fieldwork and further country and site specific research is required and this is beyond the scope of this desktop undertaking, however, we provide insights on a number of these requirements.

In its various freshwater and marine forms aquaculture has been practised alongside capture fisheries for centuries, and over the last half century has exhibited unprecedented growth worldwide. This accelerated growth is the result of a combination of technical advances in engineering, species' domestication and husbandry that have made aquaculture more cost-effective; increased demand for fish globally; and the depletion of wild fish stocks[1]. In many places increasing demand and rising prices have transformed aquaculture from a set of *backstop technologies*[2] to a viable and important substitute for capture fisheries. This is particularly true in temperate zones and the Mediterranean Sea region where modern production methods and advances in technology have driven expansion within the industry. In contrast, growth in tropical aquaculture has often (though not exclusively) been characterized by the proliferation of traditional methods (Troell, 2009. In 2006, aquaculture accounted for over 47 percent of worldwide fish landings (FAO, 2009). It may also prove to be a source of new food and non-food products and a spur for local development and food security in less developed countries. While aquaculture is an important source of fish protein, aquatic products, employment and profits, it also presents ecological socio-economic and political challenges.

The co-culture of several different trophic level taxa, with the specific objective of obtaining both environmental and production benefits goes by several names including, *integrated aquaculture* (INTAQ) and *integrated multitrophic aquaculture* (IMTA or IMT-aquaculture; Chopin, 2006; Barrington, Chopin and Robinson, 2009) and *polytrophic aquaculture*. We use the first to refer to a group of practices that includes the rearing of fed finfish, together with one or more species of bivalve, shellfish and macrophyte. It also can include other productive practices such capture fisheries in the vicinity of fish farms or artificial reefs. (Please refer to the section *Concepts and Definitions* for a more detailed description.) INTAQ is one of a number of farming

---

[1] According to the Fisheries and Aquaculture Department of the Food and Agricultural Organization of the UN, 80 percent of world fisheries are fully exploited or overexploited (FAO, 2009).

[2] The concept of *backstop technology* was introduced by Hotelling (1931). In the original conceptualization, it referred to alternative sources for the services from scarce exhaustible natural resources but is also applicable to cases in which the demand for renewable resource such as fish outstrips supply. In general, a *backstop technology is* an alternative source of supply for the scarce commodity and becomes economically viable when the cost of securing the commodity using conventional means rises to the point at which it equals (or exceeds) the cost of securing the same commodity using the backstop technology. In many cases, aquaculture conforms to this definition, as wild stock biomass falls, the cost of capture fisheries rises and demand outstrips supply forcing up the market price of fish. The higher price justifies investment in aquaculture and there is a proliferation as enterprises are attracted by potential profits.

methods that has the potential to mitigate some of the problems associated with mono-specific aquaculture (monoculture) and to increase total production. Though very rare in the Mediterranean Sea, there are a number of examples of INTAQ internationally, the results of which point to the need for further examination of its technical feasibility, environmental and economic benefits and costs in the context of the Mediterranean Sea ecosystem. The basin is quite oligotrophic, especially in its western regions and this means that primary productivity and nutrients may be insufficient to support the co-cultivation of filter feeders and algae in many areas. This may be one of the reasons for the lack of INTAQ in the Mediterranean Sea compared to other areas of the world and attention needs to be paid to baseline primary productivity in different parts of the region in order to understand the potential for expanding INTAQ. INTAQ is also quite new and many farmers may be unaware of its potential in providing additional nutrients where they are scarce. Thus information may also be a factor in the absence of INTAQ.

OBJECTIVES AND APPROACH

The purpose of this report is to assess the opportunities and challenges for marine and brackish water INTAQ in the Mediterranean Sea basin for enterprises, industry and communities reliant or potentially reliant on aquaculture. We consider these opportunities with reference to an ecosystem approach taking into account the ecological and wider environmental interactions (i.e. physical, ecological, social, economic and political) associated with INTAQ and the potential benefits that INTAQ offers in comparison to monoculture, capture fisheries and other uses of the coastal and marine resources. The report synthesizes information from the field, including research and government reports, policy papers, regulatory reviews, scientific publications and industry information. It brings together several disciplines and gives an overview of the main positive descriptions and normative prescriptions.

The main motivating elements behind this report are:

1. ***Pressures on the fishing industry (rising demand/falling supply) and opportunities for aquaculture***: The decline in capture fisheries and increasing demand for fish in the Mediterranean Sea basin (and globally) has created unprecedented opportunities for aquaculture. The sector is proving to be a technologically and economically viable source of fish and on the ecological side has the potential to prevent further over-fishing that would lead to large scale collapse of existing wild stocks. A caution to this statement regards the potential pressure that aquaculture demand for fishmeal can exert on wild stocks. However concerning the situation of the Mediterranean Sea aquaculture offers an alternative to avoid further depletion of wild stocks and may even be a source of replenishment considering nutrient inputs to the ecosystem. Aquaculture also has the benefit of reliability in the sense that quantities and prices may be less variable than is currently the case in capture fisheries. From the standpoint of communities that rely on fishing, fish farms and related industries may also serve as an alternative source of employment and income. The rapid expansion of aquaculture has largely occurred in a policy vacuum. Though this report focuses on integrated forms of aquaculture, an important point of reference is directions within the industry as a whole. This is especially important in the Mediterranean Sea region, where INTAQ is rare and its potential will be heavily influenced by developments in policy, markets and public attitudes towards aquaculture in general.
2. ***Issues within the aquaculture sector (better management of environmental impacts, improving operations and profit)***: Preliminary evidence, mainly from pilot studies outside the Mediterranean Sea region, indicates that INTAQ can lower costs, diversify and increase production and improve profits while

solving a number of the environmental challenges posed by monoculture aquaculture. At the same time it requires a higher level of technological and engineering sophistication and up-front investment. If practised by means of different operators (e.g. independent fish farmers and mussel farmers) working in concert, it would require close collaboration and coordination of management and production activities. Presently, there is also a measure of uncertainty associated with INTAQ since it is so new in the Mediterranean Sea and this can be a deterrent for operators.

3. ***Issues in the management of multiple use marine and coastal resources (stakeholder competition and resource allocation)***: While aquaculture has the potential to release pressure on fish resources and INTAQ has specific potential benefits for the enterprises and the environment, fish farming competes with other users for the scarce coastal and marine habitats. Stakeholder conflicts are common and range from concerns about pollution and impacts on wild fish populations to site allocation and local priorities. The challenges for expanding INTAQ practice are therefore significant although it can offer a mitigation opportunity to those areas where mariculture has a poor public image and competes for space with other activities. Few countries in the Mediterranean Sea region have national aquaculture plans or well developed integrated management of coastal zones. This means that decisions on site selection, licensing and regulation are often ad hoc and highly subject to political pressures and local priorities. Moreover, as congestion in the coastal zone increases, many mariculture sites are threatened by urban and industrial pollution and accidental damage.

The main objectives of this report are:

1. to compile available information on integrated aquaculture in the Mediterranean Sea;
2. to determine the potential for integrated aquaculture considering major obstacles and opportunities in this ecosystem; and
3. to identify key issues and priorities in order to provide recommendations and a way forward to the implementation of INTAQ in the Mediterranean Sea.

To achieve these objectives, a broad range of stakeholders and information sources is considered. Factual background on INTAQ in the Mediterranean Sea, together with a synthesis of relevant research and key reports from academia, governmental organizations (national, regional and international), industrial and other organizations, are provided. Since the countries of the Mediterranean Sea region are varied in terms of their level of development and potential objectives associated with INTAQ, we attempt to consider, as much as possible, country specific scenarios and issues such as food security in the case of countries in the southern Mediterranean Sea and needs of different local communities and stakeholders over the region. Specific attention is given to gaps in current knowledge and research needs because INTAQ in marine areas is relatively new worldwide and experience in the Mediterranean Sea is scarce. In many places, mariculture is the subject of public and political concern, ranging from water quality and biodiversity to conflicts among different users of coastal and marine resources. The potential environmental improvements, that INTAQ offers over conventional monoculture, may improve public attitudes and those of decision-makers. Therefore, the issue of public perceptions and public education also receives attention.

In order to provide the reader with a clear frame of reference, the following two sections are devoted to defining the terms, INTAQ and ecosystem approach and providing the analytic framework used to evaluate the potential for INTAQ. This is followed by an introduction to the Mediterranean Sea ecosystem, a review of mariculture in the region and key issues for expanding the practice of INTAQ. These sections provide background for understanding why there is less INTAQ practised in the Mediterranean Sea than in many other parts of the world and for considering its potential in the region. The main body of the report is a synthesis that describes different types of INTAQ practices and documents them on a country-by-country basis together with close-to-INTAQ practices. It also reviews relevant policy/governance provisions, technological requirements and environmental considerations; identifies places where INTAQ is likely to flourish, provides information requirements; and summarizes the main opportunities and constraints.

CONCEPTS AND DEFINITIONS

What is INTAQ?

As defined earlier in this review, *integrated aquaculture* (INTAQ) is the culture of aquatic species within or together with the undertaking of other productive activity including different types of aquaculture or capture fisheries. As in the case of IMTA, these activities may take place within a single farm or adjacent installations (e.g. mussel and finfish farms located close together, as found in Slovenia and in some parts of Croatia). Similarly, benefits can be achieved on a larger scale, involving a number of operators, locating farms growing seaweed, fed finfish and detritivores in close proximity to each other (ICES, 2005).

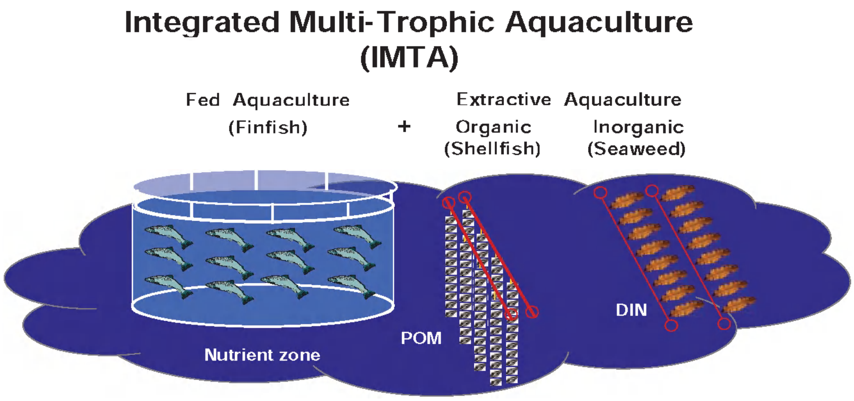
INTAQ also includes enhanced productive opportunities from combinations of fish farming with, for example artificial reefs that enhance local fish biomass around farms by providing refuge and additional food opportunity (from the fed aquaculture). Facilities may also be land based. INTAQ must meet two criteria; first that the co-cultivation or the coupled activities (e.g. fish farm plus artificial reefs) increase net production and second, that it has fewer associated negative environmental impacts in comparison to monoculture.

The discussion in this study focuses on combinations involving *intensive* marine net cage fish farms, and to a lesser extent, on-land man-made ponds or tanks. These are the main forms of mariculture in the Mediterranean Sea and stand to benefit the most from INTAQ approaches (Mathe *et al.*, 2006). *Intensive* aquaculture involves hand or mechanical feeding of the farmed stock, often using formulated feeds and rearing organisms at high stocking densities. Figure 1 illustrates an intensive salmon-mussel-macroalgae IMTA installation (Chopin, 2006; Barrington, Chopin and Robinson, 2009). The selection of species satisfies a variety of criteria, including environmental suitability, market value and compatibility with a variety of social and political objectives.

Environmental sustainability is one of the main considerations in INTAQ, thus, one of the criteria guiding species selection is the replication of natural ecosystem functions by balancing biological and chemical interactions between the cultivated organisms and surrounding ecosystem. INTAQ has been shown to generate less waste than its monoculture counterparts. It is also more sustainable than many other types of polyculture, the co-cultivation of different species without reference to their trophic level. Chopin (2006) provides the example of the joint culture of salmon-cod-halibut, stressing that while qualifying as polyculture, the system is not INTAQ because all three finfish species share the same basic biological and chemical processes that can lead to significant shifts in the ecosystem, mainly as a consequence of food waste, faeces and excretory discharges.

The production benefits of INTAQ stem from its potential to increase biomass per unit of artificial feed. Manufactured feed is one of the highest variable cost components of aquaculture. By exploiting the extractive capacities of co-cultured lower trophic-level taxa, and/or by enhancing use of excess feed and organic matter from the farm

FIGURE 1
Conceptual diagram of an integrated multi-trophic aquaculture (IMTA) operation combining fed aquaculture (finfish) with organic extractive aquaculture (shellfish), taking advantage of the enrichment in particulate organic matter (POM), and inorganic extractive aquaculture (seaweeds), taking advantage of the enrichment in dissolved inorganic nutrients (DIN)



Source: from Chopin (2006).

by wild species around site (e.g. in the artificial reefs case) the farm can obtain added products that can outweigh the added costs involved in constructing and operating an INTAQ farm. This is quite different from traditional forms of *extensive* polyculture, for example Italian *valliculture* observed in the Mediterranean Sea region. *Valliculture* involves the trapping of young finfish, during seasonal migrations into estuaries or lagoons and rearing them together with the natural fauna and flora in a brackish-water environment. The fish grow on naturally occurring plankton, or detritus, and are harvested when they have attained market size. While *valliculture* may be more environmentally sustainable than monoculture, it lacks the added value of joint, complementary production that characterizes INTAQ.

Ecosystem approach

Broadly defined, the ecosystem approach attempts to account for all the significant interactions stemming from human uses and other sources of change in the natural environment. The interdisciplinary perspective of the ecosystem approach can take advantage of using the collective strengths of each discipline but is challenged by the need to integrate across different methodological approaches and emphases that characterize individual disciplines (Falkenmark and Tropp, 2005; Adamowicz and Veeman, 1998). Given the importance of sustainability in resource management, the ecosystem approach is necessary because it recognizes a wide range of factors and interactions. In this report, the main underlying principle is that INTAQ shall be designed to be an integral part of the ecosystem. Aquaculture in general and INTAQ in particular is not examined in isolation as a source of external disturbance, nor as simply reactive in the face of surrounding change.

Like most human activities, INTAQ will impact the physical and human environment and these effects may be positive, negative or neutral (Choo, 2001). Similarly, it will be influenced by its surroundings and has the capacity to be proactive. Moreover, INTAQ is only one of many activities in coastal marine ecosystems and therefore any discussion of policies, management and decision-making must be in the general context of these other activities.

Over the last twenty years, systems approaches have been increasingly applied to the management of natural resources. The Appendix presents, in tabular form, a history of the evolution of the Ecosystem Approach to Fisheries (EAF). This is the point of departure for applying the ecosystem approach to aquaculture. Since 1980, there has been a shift from species (e.g. marine mammals) or sectoral (e.g.: fisheries) emphases towards a focus on functional integration with agreements on protection of marine environments and the establishment of marine protected areas. Also, over time, agreements have increasingly recognized the challenge presented by complex, dynamic, multifunctional environments, the wide variation among ecosystems in terms of size and composition, and the importance of sustainability. In varying degrees these approaches emphasize the needs of human beings; the preservation of resources for future generations and precaution in the face of risk and uncertainty. Many of the recent provisions itemized in the Appendix, such as the Code of Conduct for Responsible Fisheries and MARPOL include clauses specific to fish farms, especially sea-based farms. FAO (2007) applies the following definition to aquaculture:

> *An ecosystem approach to aquaculture (EAA) strives to balance diverse societal objectives, by taking account of the knowledge and uncertainties of biotic, abiotic and human components of ecosystems including their interactions, flows and processes and applying an integrated approach to aquaculture within ecological and operational meaningful boundaries.*

In order to apply this definition, a clear set of principles and outlines must be developed. One such example can be found in the ecosystem approach to fisheries (EAF). Garcia *et al.* (2003) provide a very thorough review of the foundations of the EAF. It includes several definitions currently in use, principles and operational guidelines that are relevant for aquaculture as well as capture fisheries. The issues of scale and complexity are key features as are the risk, risk reduction and the promotion of the Precautionary Principle. These last three are particularly important for INTAQ as a relatively new set of practice, offering potential benefits compared to the industry standard, but still facing many uncertainties.

In their definition, Garcia *et al.* (2003) focus on complexity and interaction. The ecosystem is defined as "a system of complex interactions of populations between themselves and with their environment" or as "the joint functioning and interaction of these two compartments (populations and environment) in a functional unit of variable size" (Odum, 1975; Nybakken, 1982; Scialabba, 1998). "Populations" include people, in particular people involved in the industry. In addition to complexity and interaction, ecosystems must be considered at different geographical scales, from "a grain of sand with its rich microfauna, to a whole beach, a coastal area or estuary, a semi-enclosed sea and, eventually, the whole Earth". Lackey (1998) observes that ecosystems are defined by scales of observation, "from a drop of dew to an ocean, …from a people to a planet". Ecosystems are nested, consisting of smaller ones within larger ones, each exchanging matter and information with others. Efficient management of ecosystems involves mapping them and this can be a major challenge since their geographic boundaries are not always easy to determine, given their dependence on scale, function and processes; especially processes that change with time. For example, seasonal variability is often higher in the pelagic than in the benthic domain and this is significant for aquaculture-environmental interactions. More recently, FAO proposed the farm, the watershed or relevant water body and the global market as the most relevant scales (Soto, Aguilar-Manjarrez and Hishamunda, 2008).

Analytic framework

In order to apply the ecosystem approach to aquaculture and to set up the proper context for INTAQ in the Mediterranean Sea, it is necessary to incorporate some of the above definitions and concepts into a practical analytic framework. For INTAQ and its complex ecosystem interaction we use three conceptual tools: carrying capacities, zones of influence and level of impact (primary, secondary and tertiary). Mc Kindsey *et al.* (2006) and Inglis, Hayden and Ross (2000) applied the concept of carrying capacity to consider the physical, biotic and human aspects of the ecosystem and the interaction among them to the assessment of bivalve culture. They used four categories of carrying capacity that can be very meaningful when designing INTAQ within the ecosystem's perspective:

1. physical carrying capacity;
2. ecological carrying capacity
3. production carrying capacity, and
4. social carrying capacity.

The first refers to the non-biological, physical features such as type of substrate, depth, hydrodynamics, temperature and salinity and their relation to the target species. It determines such things as the size of the farm and specific engineering requirements with respect to the physical conditions of a given location.

Ecological carrying capacity is defined by thresholds of viability for ecosystem functions and other definitions of "acceptable" ecological impacts. Spatially, it can refer to the immediate area of the farm or larger spatial/ecological units. Some of the ecological impacts of most concern, especially in monoculture, are those resulting from farm effluent (i.e. uneaten food, faeces, and metabolic waste) on the water column and benthos. Very delicate or unique ecosystems will have the lowest carrying capacity or tolerance for perturbations as these may cause irreversible change. Similarly, areas already subject to urbanization, recreation and other pressures will also have a lower capacity to handle additional perturbation.

The *productive carrying capacity* describes the ways in which the physical and ecological carrying capacities determine the potential level of production. For example, if the ecological carrying capacity of potential inshore sites requires very low levels of effluent, then the operator must consider a combination of effluent treatment options, including INTAQ together with alternative site selection options. In the case of alternative sites, there are clear tradeoffs between ecological, physical and productive carrying capacities. While the higher flow-through gives alternative less protected sites a higher tolerance for effluent, it may impose restrictions on the type of culture that is feasible; for example, exposed offshore sites may be unsuited to the cultivation of many macroalgal species that are not adapted to withstand rough seas.

Social carrying capacity reflects the tradeoffs among all stakeholders using common property resources. It is the most difficult of the four to quantify but the most critical from the management perspective because if there is widespread opposition to aquaculture in general and INTAQ in particular, the prospects for its expansion will be limited.

Another conceptual tool that this report uses is the differentiation among primary, secondary and tertiary impacts. This allows us to describe effects in terms of their duration or longevity[3] and their zone of influence[4] (AMEC, 2002). This conceptualization is a useful complement to the carrying capacity framework because it permits the tracking of a given event (e.g.: farm waste, escaped fish, urban pollution) through time and space in a dose-response format that accounts for downstream effects and feedback mechanisms. Many of the primary impacts pertain to the productive carrying capacity, in particular, at the farm level. For example, farm effluent is a primary impact that depends on the type of culture, design and management of the farm. These discharges may physically smother organisms living on the sea floor and rapidly change the biogeochemistry of the surface sediments. The release of nutrients into the water may increase primary productivity and in some extreme cases

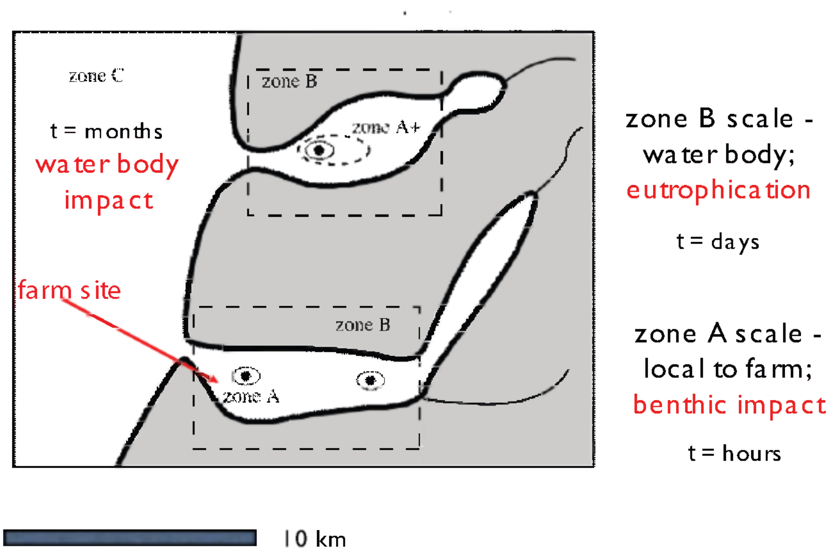
---

[3] Duration or longevity refers to the length of time that an effect is in evidence or the amount of time that is needed for an ecosystem to recover. For example an impact may be reversible over the short, medium or long-term; it may be permanent or irreversible; it may be cyclical or seasonal.

[4] Zone of influence refers to the impacts over space i.e. near-field/immediate vicinity of farm or far-field/surrounding environment.

FIGURE 2
Scales: spatial extent and time scale

(ecosystem scale considered must be relevant to scale of the farmacy and impact)



Source: modified from Tett (2007).

lead to problems such as algal blooms. The severity of secondary impacts such as these, affecting the quality of the benthos and water column, depends largely on the ecological carrying capacity of the site and its zone of influence. The physical carrying capacity is also relevant in that hydrology influences the rate at which effluent is dispersed. Tertiary impacts tend to be more relevant for the social carrying capacities. For example, changes in environmental quality (and perceptions of these changes) that affect different stakeholders will determine the social acceptability of aquaculture. For example, monoculture aquaculture in Europe and North America is often perceived to be a source of pollution. Ridler *et al.* (2007) have shown that when people are informed about the environmental improvements offered by INTAQ they have a much more favorable attitude toward the practice. The secondary effects may also occur further afield, especially if they are the result of cumulative effects of several farms concentrated in a given area. In Figure 2, Tett (2007) provides a useful, complementary diagrammatic conceptualization for the three levels of impacts over space and time.

The scales, Zone A, Zone B and Zone C correspond closely to the extent of primary, secondary and tertiary impacts. Zone A, the farm location is the area most subject to primary impact. In the example above, benthic and water quality secondary impacts from farm effluent occur almost immediately after discharge and are restricted to a well defined area close to the farm. Water body or Zone B impacts and regional or Zone C impacts affect larger areas, and generally take more time and potentially affect more components of the ecosystem and stakeholders. This conceptualization is especially relevant for the different configurations in which INTAQ can occur. In the case of IMTA, Zone A, and its interaction with Zones B and C are key. In contrast, if INTAQ is the result of several farms operating in proximity to one another, then the ecological integration and production enhancements must be considered not only for the individual farm but over the water body, or Zone B in which the farms operate.

In implementing INTAQ within the ecosystem approach framework we have used three questions as a guide:

- First, to what extent does INTAQ permit natural adjustments? That is, to what extent are changes permanent and to what extent do they alter the natural ecosystem? For example, it has been suggested that even large changes in the water column and benthic environments around cages can be managed by introducing a farming cycle that includes fallow periods (Pearson and Black, 2001). If INTAQ has a smaller ecological footprint, it is possible that the need for fallow periods may be reduced

- Second, what is the relevance of each carrying capacity to the main issues of concern for INTAQ in the Mediterranean Sea region? As we have noted, in several important respects, INTAQ is more consistent with the ecosystem approach than monoculture. This is especially true in terms of ecological carrying capacities. In terms of the social carrying capacity, INTAQ shares many issues with monoculture. Restrictions on site selection in the congested coastal areas of Turkey illustrate the limits to the social carrying capacity. Aquaculture sites have come into increasing competition with the Turkish tourist industry for coastal habitats and the result has been that many farms have been forced to relocate to sites of the coast or far offshore (G. Yucel, pers. comm.). The offshore requirement can be restrictive for certain types of INTAQ. If, for example it involves the culture of macro-algae, the rougher waters can damage both the infrastructure and the plants themselves. Instances of conflict over the location of nearshore cages in the face of increased demand for other uses of the coastline are common throughout the Mediterranean Sea region. Similarly, urban sewage and industrial effluent and their effect on water quality in and around cage farms have clear implications for INTAQ operations. The costs and benefits of potential sites must be considered in terms of the full range of interactions and the resulting costs and benefits.
- Third, how does INTAQ compare in terms of impacts with alternatives? The main alternative considered in this report is monoculture but the list of candidate alternatives is long, and need not be restricted to aquaculture. In principle, comparisons could be made among all possible competing (though not necessarily mutually exclusive) uses of coastal zone and marine resources in which INTAQ takes place in order to obtain an indication of which use(s) or combination of uses offer the highest value to society. This type of assessment would also require the application of common metric(s) (e.g. physical, monetary or other ranking) and is beyond the scope of this study. We therefore focus on a quantification of primary impacts in the ecological carrying capacity and a qualitative description of impacts and interactions in the other three carrying capacities with reference to secondary and tertiary impacts.

MEDITERRANEAN SEA

Description of the ecosystem

The Mediterranean Sea is a large semi-enclosed, saline sea bordered by 22 countries[5] and having two distinct basins divided by a narrow (150 km), relatively shallow (400 m) channel between Sicily in the north and Tunisia in the south (see Figure 2 below). The areal division of the sea between the western and eastern basin is approximately 1/3: 2/3. The eastern basin is somewhat more saline than the western basin, especially in the vicinity of the Suez Canal. On the whole, the Mediterranean Sea is considered oligotrophic (though some limited regions and coastal areas, such as parts of the northern Adriatic, may be eutrophic), however it is warmer and more oligotrophic in its southern and eastern areas. While the sea accounts for one percent of the world's total marine area, it contains six percent of the world's marine species with

[5] The countries bordering the sea are, Albania, Algeria, Bosnia and Herzegovina, Croatia, Egypt, France, Greece, Israel, Italy, Tunisia, Lebanon, Libyan Arab Jamahiriya, Monaco, Montenegro, Morocco, Slovenia, Spain, the Syrian Arab Republic and Turkey. Island States within the sea are Cyprus and Malta.

FIGURE 3
Mediterranean Sea and its basin

over 400 endemic species of fish, shellfish, corals, sponges and seaweeds with greater diversity in the western basin (EEA, 2006). Notwithstanding this large variety, overall biomass is relatively low because of the low level of phytoplankton production.

Box 1 provides an ecological summary of the Mediterranean Sea proposed by the European Environment Agency, EEA (2006).

In terms of human settlement and uses of natural and environmental resources of the Mediterranean Sea, 82 million people live in coastal cities and 32 percent of the population lives in North Africa. Levels of development vary widely over the region. Population growth in urban and southern areas is the highest in the region. Tourism brings over 100 million visitors to coastal areas annually and is a major source of seasonal population pressure. Tourism is a major competing sector with aquaculture.

BOX 1
Main ecological characteristics of the Mediterranean Sea

- high temperatures/metabolic rates
- high salinity
- microtidal/low renewal rates: tides are typically less that 40 cm creating low potential for dilution and dispersion of dissolved and particulate waste
- oligotrophic: high oxygen concentration, poor in nutrients; low primary production and low phytoplankton biomass. Increasing oligotrophy from west to east; primary production in the open sea considered to be phosphorous limited, not nitrogen limited as is the case in most seas
- rich in biodiversity, especially in coastal zones with high rate of endemism
- biological invasions: main entry points: shipping ports; lagoons; and Suez Canal causes higher incidence of alien species in the eastern basin;

Source: EEA, 2006, p. 10

In addition to the above land-based uses associated with urbanization, tourism and industry, the sea is a major shipping route and base for capture fisheries and mariculture. There are 75 marine protected areas (MPA) in the region. The designation applies to specific unique or threatened resources, in need of protection such as *Posidonia oceanica*, sea grass beds and breeding and nesting sites for endangered species such as the loggerhead sea turtle (*Caretta caretta*). MPAs were also designated to encourage specific uses such as sustainable tourism and regenerating fish stocks (MEDPAN, 2007).

Aquaculture production in the region

Although INTAQ is very rare in the region, and therefore, data is scarce and often unavailable in the public sphere. Reasonable data is available for aquaculture in general. The statistics presented below, while not specific to INTAQ are the basis for inference as to potential future developments and patterns of growth in INTAQ.

The total production of all species in the Mediterranean Sea in 2006 was estimated at about 373 thousand tonnes (FAO-FishStat, 2008) with 14 percent growth from 2000 to 2006 (Table 1). The average rate conceals considerable variability ranging from a decrease of 17 percent between 2003 and 2004, and a 34 percent increase between 2004 and 2005. As Table 1 and Figure 4a show, although the industry has grown rapidly since 1950, production is variable, with variability increasing with growth rates. As in much of the world, the growth rate of Mediterranean Sea aquaculture has outpaced that of capture fisheries. Moreover, the interannual variability in aquaculture production is lower than in capture fisheries which have clearly reached a plateau in terms of annual

TABLE 1
Aquaculture production by country: 2000–2006 (by production volume in tonnes)

Country	2000	2001	2002	2003	2004	2005	2006
Italy	167 775	169 980	146 649	149 184	84 608	147 535	139 699
Greece	92 050	93 742	84 874	98 518	94 112	102 987	109 267
Turkey	35 646	29 730	26 868	39 726	50 335	70 963	72 331
France	21 414	30 499	26 149	29 907	26 903	28 324	30 753
Croatia	3 485	5 802	5 531	5 147	6 970	6 797	8 469
Israel	2 914	3 161	3 056	3 109	3 354	3 196	2 725
Cyprus	1 800	1 800	1 782	1 731	2 084	2 317	2 549
Albania	202	264	500	1 110	1 200	1 110	1 730
Tunisia	719	955	1 111	1 227	1 250	1 542	1 548
Spain	587	805	973	781	1 678	1 266	1 500
Malta	1 746	1 235	1 116	887	868	736	1 115
Ukraine	10	95	24	236	273	626	421
Libyan Arab Jamahiriya					278	378	378
Bosnia and Herzegovina			260	260	107	251	265
Bulgaria	10		55	15	118	171	228
Slovenia	117	154	120	206	273	228	193
Morocco	697	575	792	856	815	1 224	51
Algeria	47	64	65	23	14	14	16
Montenegro							11
Serbia and Montenegro	8	9	6	8	11	11	
TOTAL	**329 436**	**338 870**	**299 941**	**332 931**	**275 251**	**369 676**	**373 249**
% annual growth		2.9%	-11.5%	11.0%	- 17.3%	34.3%	1.0%
Average Growth							3.4%

Source: FAO FishStat, 2008.

harvest (Figure 4a); these issues may prove to be important considerations for business and policy decision-makers, especially, those concerned with food security, coastal communities and development.

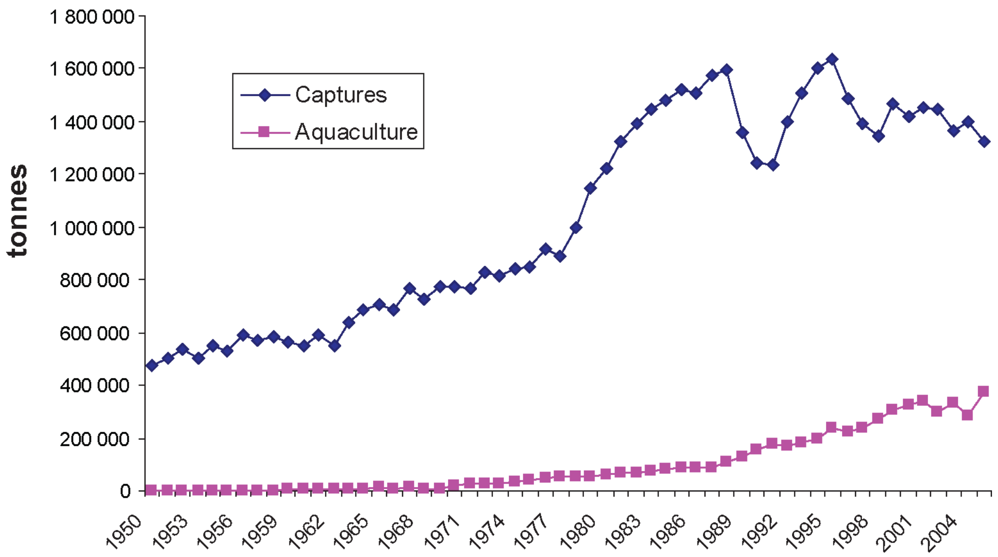
Within the aquaculture sector, the most striking feature of the physical production is the rate at which finfish have overtaken mussels as the dominant product. In 1990, finfish production accounted for less than 10 000 tonnes as compared to approximately 90 000 tonnes of mussels. In 2003, finfish production was in the range of 180 000 tonnes (49 percent) and mussels, 150 000 tonnes (40 percent). Clams and oysters had seven and two percent shares each. The main cultivated finfish species in the region are gilthead sea bream (*Sparus aurata*), European sea bass (*Dicentrarchus labrax*) and flathead grey mullet (*Mugil cephalus*). Given the rapid transformation in the industry, it is not surprising that production growth has outstripped the knowledge base and regulatory and social frameworks. Greece, Turkey and Italy were the three largest producers, with 86 percent of total production in 2006.

Key opportunities and bottlenecks for implementation and expansion of INTAQ in the Mediterranean Sea

The key opportunities for the expansion of INTAQ have much in common with the opportunities for mariculture as a whole, mainly, the stressed state of wild fish stocks and the capture fisheries (Figure 4a) and the increased demand for sea products. Both imply that the demand for the output from aquaculture, including INTAQ will continue to be high. Moreover the prospects for INTAQ to lead in the expansion of mariculture should be very good because of its better environmental potential compared to monoculture. In ecological terms, the lower effluent of INTAQ is preferred and with more experience and proper information dissemination this should lead to a higher level of public receptiveness and favourable regulatory provisions.

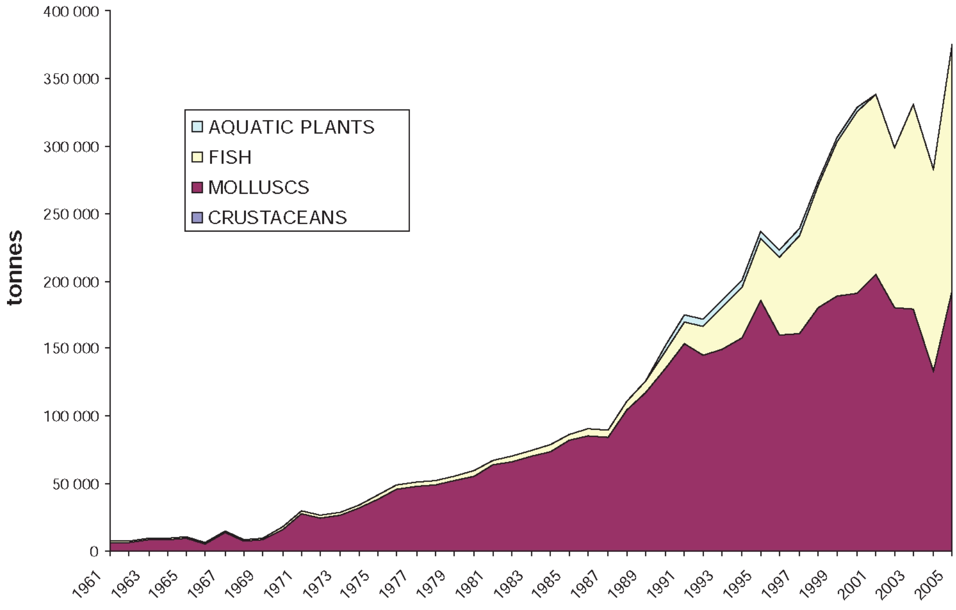
Similarly, at the investment level, the higher profit potential of INTAQ provides incentive for expansion. The main challenges, unique to INTAQ in the region are the oligotrophic conditions in much of the Mediterranean Sea. Even with the organic and inorganic effluents from fed species, the low baseline productivity may be insufficient to support the cultivation of other organisms. This implies that a careful examination

FIGURE 4a
Mediterranean Sea aquatic production from captures and aquaculture 1950-2006



Source: FAO FishStat, 2008

FIGURE 4b
Mediterranean Sea aquaculture production by product



Source: FAO FishStat, 2008.

of potential sites' baseline productivity and the contribution of aquaculture to nutrient loading are needed before conclusions can be made regarding implementation of INTAQ (Karakassis, Pitta and Krom, 2005). This leads us to the second major challenge for INTAQ and this is the general lack of experience in the Mediterranean Sea region. Though one of the reasons that there is less INTAQ in the Mediterranean Sea than in other areas of the world may be the sea's ecological carrying capacity, it may also be that INTAQ is relatively new. Even outside the region, commercial experience is limited and within the region, information on the practice is limited to a few experimental studies (e.g. Neori, Shpigel and Ben-Ezra, 2000; Neori *et al.*, 2004; 2007; Angel *et al.*, 2000a; 2002).

Other opportunities and challenges that INTAQ shares with mariculture as a whole in the region include, on the opportunity side, the potential for aquaculture operations to rejuvenate remote coastal communities, especially those formerly reliant on capture fisheries. Shared challenges include the competition for coastal space in more congested areas of the Mediterranean Sea region, poor public image and unfavourable regulatory conditions.

SYNTHESIS OF STUDIES AND REPORTS

In this synthesis, two elements are emphasized:

Description: It provides review of the current state of marine and brackish water INTAQ practices in the Mediterranean Sea including a classification of practices; an overview of production; an overview of current regulatory and legislative frameworks and guidelines; and a review of the technological requirements and site characteristics most conducive to the development or expansion of INTAQ.

Ecosystem approach: The ecosystem approach, described above is the lens through which the potential of INTAQ is assessed and compared with other methods of securing sea products; including finfish, crustaceans, bivalves, other invertebrates and macroalgae. The methods include monoculture aquaculture and capture fishery. It takes into account the multiple uses of coastal and marine resources (e.g. tourism, recreation, shipping, aquaculture), ecological impacts (e.g. water quality) stakeholder issues and social/political acceptability (e.g. social perceptions, public education, etc) as well as farm, investment and industry level issues.

Classification of INTAQ practices in the Mediterranean Sea

The most common design for an INTAQ system is based primarily on the needs of the main cultured species, usually fed finfish. Modifications are made to incorporate extractive species such as filterfeeders, detritivores and macro algae, but the basic design and engineering are tailored to the cage, tank or pond requirements of the finfish. A classical and well known example of such a system is a pilot project in the Bay of Fundy, on Canada's east coast where seaweed (*Laminaria saccharina* and *Alaria esculenta*), mussels (*Mytilus edulis*) and Atlantic salmon are grown together (Barrington, Chopin and Robinson, 2009; Ridler *et al.*, 2006; Chopin and Bastarache, 2004). In this case the salmon are the focus product. Experimental, pilot and small-scale commercial enterprises of this type can be found elsewhere in Canada, South Africa, Australia, the United Kingdom and, to a much more limited extent, in the Mediterranean Sea. A less common, and promising system that integrates salmon, scallops and oysters at the design stage is proposed by Cross (2004). The objective of this system is better integration that leads to lower operating costs. At present, it is at the theoretical and early experimental level.

As mentioned INTAQ at any scale is rare in the Mediterranean Sea and in this section, we present several isolated examples of advanced experimental and pilot/near commercial scale installations. All the examples are based on extensions of intensive cage or land-based (varying intensities) finfish culture. Land-based marine INTAQ takes place in man-made ponds, race-ways or tanks, usually in proximity to a marine water body (i.e. estuary or sea). Generally, each species is cultivated in a separate pond or tank (Neori *et al.,* 2004). Open water INTAQ may take place in floating cages or in net pens anchored to the sea bed in combination with other species reared using appropriate gear such as rafts, racks, and long-lines. The floating cages or net pens provide the growth environment for finfish and the other gear enables the cultivation of seaweed and/or mollusks, bivalves and other invertebrates. If shellfish and crustaceans are cultivated, specialized net cages, racks or trays may be used. INTAQ may also use artificial substrates/reefs. Further detail on the use of artificial reefs is given in the description of close-to-INTAQ methods below.

Country overviews

Egypt

Various species of mullet, sea bream, sea bass and shrimp are cultivated extensively in the saline Lake Quarun. Total production of all species is estimated at 23 000 tonnes, with a yield of 150 kg/ha per annum. Juvenile mullet are raised in earthen ponds adjacent to the lake and fertilizer and livestock waste is the main feed input. The source of fry for all species is wild stock and this is considered a serious non-sustainable practice, especially for mullet (ICES, 2005; El Gayar, 2003; Mega Pesca, 2001).

Spain (Andalucia) and Portugal

Several pond systems with different levels of intensity are being used to raise sea bream, sea bass, mullets, eel, sole and shrimp. A total of 67 000 tonnes per annum is produced; the bulk (60 percent) is sea bream in semi-intensive cultivation. Thirty-four percent of production is intensive and the remaining six percent is reared in extensive sole/mullet/shrimp/eel cultivation. The system employs recirculation of nutrient rich water from the intensive to the extensive ponds, where the organic content provides food for worms, the main food for sole and other prey fish (ICES, 2005).

Southern France

A low production, semi-intensive operation produces shrimp and oysters in the same pond. The oysters consume the phytobenthos re-suspended by shrimp foraging, providing added product and minor biofiltration benefits (ICES, 2005).

Israel

Several experimental and pilot facilities have been tested. Finfish (sea bream and sea bass), invertebrates (abalone or sea urchin) and macroalgae (*Ulva* sp. or *Gracilaria* sp.) are cultivated in separate, monoculture enclosures through which water is recirculated (see Figure 5). Primary inflow is used to raise abalone or urchin. The seabream, reared in intensive tanks using abalone or urchin effluent and the ulva is reared in raceways using sea bream effluent that has passed through a sedimentation tank. The ulva effluent can also be used to rear sea bream. In addition to its biofiltration function, the ulva is also used to feed the invertebrates (Shpigel, Neori and Marshall, 1996; Neori, Shpigel, and Ben-Ezra, 2000; Schuenhoff *et al.*, 2003). Other three-phylla, on-land systems have been designed to exploit the biofiltration capacity of seaweed, but without the "polishing" biological filter that minimises nutrient output in the final stage of the recirculating system (G. Shavit, pers. comm.).

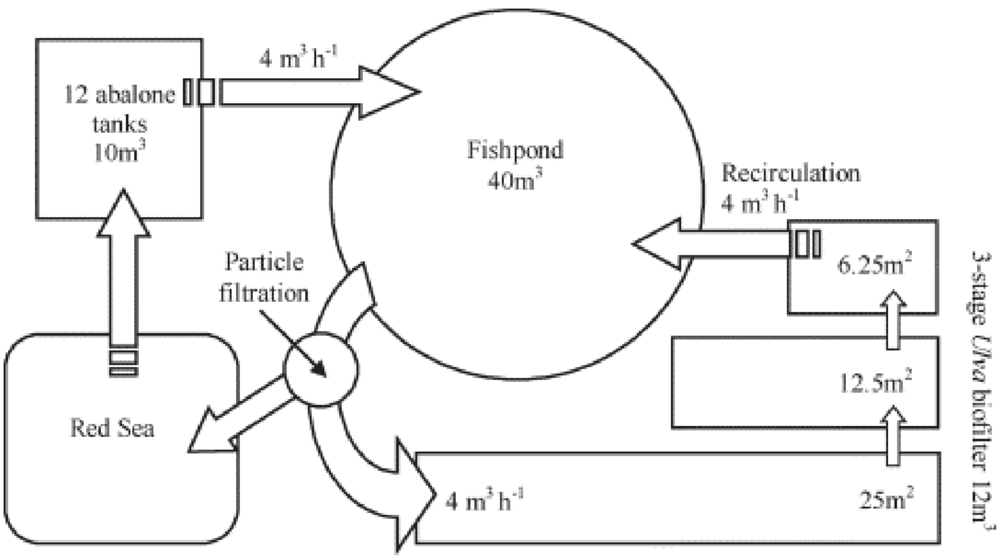
Porter *et al.* (1996), Katz *et al.* (2002) and Lupatsch, Katz and Angel (2003) documented a series of advanced experiments in the co-cultivation of sea bream and mullet in a system comprised of mullets in benthic enclosures below floating sea bream cages. These studies have found significant improvement in sediment quality alongside production of mullets without the need for additional of manufactured feed.

Other

In Croatia, advanced experimentation has been carried out for combinations of fed finfish and mussels. After ten months of growth, differences in size were observed for mussels growing at different distances from the fish cages (Perhada *et al.*, 2007). Mussels on lines located at a median distance showed higher growth than those closest to and furthest from the cages. The study also recorded seasonal differences

FIGURE 5

On-land pond, three-phylla recirculating system schematic



Source: Schuenhoff *et al.* (2003).

in growth rates and generally provides good indications for the potential for finfish-mussel culture in the eastern Adriatic Sea. There are several other more preliminary experimental INTAQ operations that we have been unable to fully document here. These include (but are not restricted to) the co-cultivation of sea bream and sponges in Turkey, sea bream with mussels in Greece and various higher trophic finfish species with mussels in Croatia.

Polyculture and other close-to-INTAQ systems in the Mediterranean Sea region

There are several practices that share some important characteristics with INTAQ, in particular, the co-cultivation of several species. We have not classified them as INTAQ as they lack one of more of INTAQ's defining features: That is, the use of manufactured feed for higher trophic species, joint production, deliberate design and/or intervention to achieve ecological integration and environmental benefit. Table 2 gives a summary classification and description of INTAQ and similar systems in the region.

Valliculture (Italy)

Valliculture is a traditional form of brackish water, extensive aquaculture, practised mainly in the Po River delta. Current production totals about 3 000 tonnes of mullet, 1 000 tonnes of sea bream and 1 000 tonnes of sea bass per annum in 43 000 hectares of extensive estuary ponds. Fry are captured from wild stock using a weir or other physical means of separating fish from the sea. Juvenile fish are able to pass through the weir during seasonal migrations and become trapped as their size increases. In some cases, sea bream and sea bass are stocked from hatcheries. The system has been adapted for detritivore species, such as mullet (Ghion, 1986). In addition to the stocking aspect, the systems may also alter the level of salinity in the area of cultivation (Ghion, 1986; Ardizzone, Cataudella and Rossi, 1988; Basurco, 2000). The techniques are *close-to-INTAQ* in the sense that they are multi trophic with elements of biofiltration provided by endemic species present in the enclosure. The high nutrient level in the enclosures is sufficient for both carnivorous species such as sea bream and sea bass and for detritivores such as mullet. The level of intervention is, however much lower than INTAQ, artificial feed is not used and the primary

TABLE 2
Classification of INTAQ and similar cultivation systems by prevalence, location and cultured species

Technique	Prevalence	Location	Focal species	Co-culture species	Stage
Cage/floating structures	rare	Greece, Turkey, Israel, Croatia,	Seabream, Seabass,	Mullet, Sea Cucumber, Sponge, Mussel,	Experimental, pilot
Land-based pond/tank	rare	Greece, Turkey, Israel, Croatia,	Seabream, Seabass,	Mullet, Mussel, abalone shrimp, Seaweed (Ulva and Gracilaria)	Experimental, Pilot, commercial
Lagoon/marine enclosure/Valliculture/ estuary/other brackish water	Traditional/ Regional	Italy (Po River Delta)	Seabream, Seabass, mullet,	Eel	Commercial, Artisanal
Benthic harvesting,	unknown	Vicinity of monoculture installations	various	Various benthic organisms (not cultured but attracted by biofouling and harvested)	unknown
Artificial Reefs combined with monoculture	Very rare	Spain, France Italy	Seabream Mussels	various pelagic organisms (not cultured but attracted by structures and biofouling and harvested)	Experimental

objective is finfish harvesting, not joint production though a small amount of eel (200 tonnes per annum) is harvested.

Harvesting increased benthic and pelagic production

A second type of "unplanned" INTAQ results from "spillovers" from monoculture to the surrounding environment. Benthic enrichment from sedimentation is an unintended consequence or spillover from monoculture. The enrichment from sediments attracts finfish, crustaceans and other species to the areas around fish cages. Similar phenomena have been observed around open water structures (e.g. artificial reefs), even without sedimentation. The increased abundance of the wild organisms in proximity to existing operations makes them relatively easy to harvest (Dempster *et al*., 2002; 2004; 2005; Dempster and Taquet, 2004). As in the case of valliculture, there is a very low level of control over the movement/migration of different species, their growth and final biomass as compared to INTAQ. However these organisms are using discharges from fish farms to produce additional biomass, creating the potential for an additional marketable harvest as shown in other regions (Soto and Jara, 2007). In the Mediterranean Sea the extent of the activity (i.e. production levels and values) is unknown at this time because it is largely unregulated. Also a management issue that needs to be explored is "access". Generally, a license to operate a fish farm grants exclusive rights to an area to a single operator. Unless the farmer harvests the migrating wild stocks or explicitly permits a fisherman to do so, the activity could be construed as illegal. Evidence from other regions, such as Chile (Soto and Jara, 2007), points to the need for further exploration of potential for increased benthic and pelagic production and institutional means of encouraging harvesting and other beneficial practices associated with these increases (Cataudella, Massa and Crosetti, 2005).

A similar phenomenon has been observed with respect to corals growing in proximity to cage farms in the Red Sea near Eilat and early stage experimentation with artificial reefs in Israel, Spain, France and Italy. Angel *et al.* (2000a) and Bongiorni *et al.* (2003) found that corals flourish around fish farms. This observation sparked the establishment of a coral nursery adjacent to the Eilat fish farms for broken corals retrieved from the Eilat coral reserve (Shafir, Van Rijn, and Rinkevich, 2006). The idea is also being adopted in several other research projects that focus on reef restoration in Indo Pacific and other tropical regions. Artificial reefs located near finfish cages in Spain, France and Israel and near mussel lines in Italy have acted as fish attracting devices with the migrating organisms consuming detritus from the farms.

There is preliminary evidence that spillovers may also be regional. Machias *et al.* (2005) and Giannoulaki *et al.* (2005) observe that aggregate regional fish landings in the Mediterranean Sea are positively correlated with the expansion of aquaculture although caution must be taken in interpreting this correlation since causation has not been established. Though the increase in certain wild pelagic stocks may be a result of increased nutrient levels caused by aquaculture, it could also be the result of recovery resulting from conservation efforts and lower dependence on capture fisheries as supplies of cultured fish become more dominant in the market. Moreover, even if causation can be shown, caution must be exercised. This is because, on one hand, the increase in wild fish stocks has positive aspects, especially for the capture fishery and communities' dependent on it and possibly in terms of biodiversity. At the same time, it can be taken as evidence that current mariculture practice is altering aspects of the ecology of the Mediterranean Sea ecosystem in uncertain and potentially irreversible ways. Until more is known about the interactions between aquaculture and changes in the Benthic and Pelagic levels, the Precautionary Principle favors practices such as INTAQ because of their potentially lower and better managed environmental impacts.

Formal regulations, legislation and guidelines governing the environmental impacts of aquaculture and potentially of INTAQ

The current legislative and regulatory context for INTAQ in the Mediterranean Sea region is largely the same as for aquaculture in general. Regulation of aquaculture is relatively new, having lagged behind the large scale and rapid growth in the industry. INTAQ is not singled out as a subcategory of aquaculture because it is so new. This means that INTAQ is subject to the same mix of international, European, regional, national and local geographic jurisdictions and mandates including fisheries, environment and coastal zone and marine management as aquaculture. Because regulation of aquaculture is underdeveloped and does not contain provisions specific to INTAQ, this review focuses on existing frameworks and where possible, their implications for INTAQ and provisions needed to encourage the expansion of INTAQ. In many cases such provisions are also relevant to the industry as a whole, since regulation tends to be rather restrictive. That is, INTAQ stands to benefit from many policies aimed at encouraging aquaculture. The review below, demonstrates that there is a clear need for comprehensive and consistent policy frameworks at all levels. Equally important, though somewhat beyond the scope of this review is improving knowledge of existing provisions that either inhibit or encourage INTAQ and identifying those that need to be incorporated into new policy. Anecdotal evidence from Turkey and northern Europe, provide several examples. In parts of Turkey, fish farms have been ordered to relocate to offshore sites because of stakeholder conflicts, especially with the tourist industry and generally negative public perceptions. Given current farming techniques, offshore positions restrict many INTAQ options, especially those involving seaweed culture. In a number of countries in northern Europe, certain kinds of INTAQ are not possible because of restrictions requiring large distances between installations for finfish, bivalves and shellfish because of concerns for pathogen transfer. The types of issues that need to be examined include those above as well as whether integrated operations will be bound by more regulation that monoculture. For instance, would a finfish-mussel farm need to comply with separate provisions for each species or would it be treated as an integrated entity subject somewhat different rules?

We have reviewed the main regional and where possible national legislation and regulation at both the formal and informal levels. Because there is a great deal more material available than that presented here, detailed references are included for readers who are interested. There are a number of comprehensive reviews of legal, institutional and regulatory frameworks as well as forms of self-regulation by professional membership organizations such as the Federation of European Aquaculture Producers (FEAP, 2000). This review draws heavily on the following sources:

- National Aquaculture Legislation Overview (NALO) of the Fisheries and Aquaculture Department of the FAO www.fao.org/fi/website/FIRetrieveAction.do?dom=collection&xml=nalo.xml
- Monitoring and Regulation of Marine Aquaculture (MARAQUA) 1999-2001 Project: www.lifesciences.napier.ac.uk/maraqua/
- Federation of European Aquaculture Producers, www.feap.info/feap/

Within the Mediterranean Sea, aquaculture is governed according to a hierarchy, at the top of which is legislation and laws, following by regulations that enact and enforce the laws at the operational level and finally self-regulation under guidelines and codes of conduct and practice. Legislation and regulation bind the producer to actions at all stages, from the site selection, size, construction and operation of the fish farm. They are the product of the political process and may be international, regional or local in origin. Violation of legal obligations results in sanctions and other penalties when proper monitoring and enforcement mechanisms are in place. In contrast, self regulation (or informal regulation) is not mandatory. To be effective, it must be in the spirit of the existing legal context but adherence to codes of self regulation is facilitated more by demonstrated mutual benefits and a clear understanding of the consequences of participation and cooperation that accompany adoption of given voluntary codes. Many of the international agreements, conventions and other events listed in the Appendix are relevant and in this presentation, their specific application to the EEA is highlighted. Table 4, at the end of this section provides a summary of relevant formal and informal/soft types of regulation.

Formal legislation and regulation

Most international regulation relevant to the Mediterranean Sea is also at the global and European Union (EU) levels. There are a range of international agreements to which many Mediterranean Sea countries are signatories. The ones having the most direct input into national level policies affecting mariculture are: United Nations Convention on the Law of the Sea (UNCLOS, 1982) and associated agreements; Article 9 of the FAO, Code of Conduct for Responsible Fisheries (FAO, 1995); UN Biological Diversity Convention[6] and the World Heritage Convention.[7] At the European level, the Common Fisheries Policy and eight EC directives directly impact the practice of mariculture. These directives range from those governing specific aspect of environmental and resource quality to system management as a whole. In addition, there are over fifty other directives that indirectly pertain to mariculture. Currently, the movement towards integrated coastal zone management (ICZM) and the application of various systems approaches, in particular the Ecosystem Approach in the EU and worldwide are the dominant paradigm for mariculture policies (Read and Fernandes, 2003; Fernandes, Miller and Read, 2000). Most of the EU directives incorporate provisions for specific local condition within Environmental quality Objectives (EQO) and Environmental Quality Standards (EQS). These facilitate the formulation of national policies within the context of the EU directive. They also recognize the complex interactions between the various uses of coastal and marine resources and the need to protect aquatic environment in order to safeguard aquaculture in the face of other potentially polluting activities (Eleftheriou and Eleftheriou, 2001). Many non-EU-member Mediterranean Sea countries use these directives as the basis of national policy. Read *et al.* (2001) provides a comprehensive review of international and EU agreements and directives that affect mariculture. Although not INTAQ specific, these provisions will be the basis for facilitating the expansion of INTAQ as agreements and directives on mariculture change in order to keep pace with development in the industry.

Policies at the national level reflect the international and regional level. That is, few countries have special legislation on aquaculture, though several began drafting special sets of rules in the early 2000's. These include Bulgaria, Croatia, Cyprus, Malta and Morocco (Van Houte, 2001). In most countries aquaculture falls under the auspices of the Ministry of Agriculture or Fisheries and is further subject to a range of environmental, water, zoning and other regulations.[8] Environmental Impact Assessment (EIA) provisions are becoming more and more common as part of the licensing process. There is also a tacit recognition by some that aquaculture is primarily

---

[6] www.cbd.in

[7] www.whc.unesco.org/en/conventiontext/

[8] van Houtte (2001) notes that traditional government bureaucracies tend to be organized along one of the following:

- use-specific lines – i.e. separate administrations responsible for water supply, land allocation, seed supply, import/export etc.;
- functional lines – separate administrations for water resources allocation, pollution control, disease control, etc.;
- types of water resources - freshwater, brackish water and sea water; or
- land resources - public lands, shore, lagoons, private land management, etc.

Aquaculture crosses all of these lines because of its dependence on several resource systems.

a business enterprise and funding of enterprise support tools as well as improved information on authorization processes and operational guidelines has been undertaken by some governments. This process dovetails with the trend toward stakeholder processes and greater public participation in resource planning as both aquaculturalists and non-aquaculturalists have better access to the same information.

The specific provisions for enforcing legislation tend overwhelmingly toward physical regulation and command and control measures, with well-defined penalties for violations including revocation of licenses, imposition of fines and criminal prosecution. The design of these measures is meant to provide, in the first instance, deterrents to unauthorized, inappropriate or dangerous practices. If they fail as a deterrent, they are intended as punishment and a means of stopping the undesirable activity once it has begun in order to remediate environmental damage. As is the case at the executive/legislative level, implementation and enforcement of regulations is marked by overlapping authorities. In many African countries, including those with Mediterranean Sea shores, responsibility for aquaculture may be assigned to several ministries without any coordinating framework. In general the complicated regulation structure does not seem to facilitate the sustainability of aquaculture but the opposite and a wide implementation of INTAQ may require reviewing and adapting at least some parts of the existing regulations. The possibility of creating incentives for the implementation of INTAQ deserves careful review.

Self-regulation

In Europe, the Federation of European Aquaculture Producers (FEAP) is the main membership-based, self-regulating body. Since 2000, the FEAP Code of Conduct governing environmental quality has been in place (Hough, 2001). It has 28 signatories and covers:

- water use and quality
- abstraction and discharge
- site selection
- site management
- escapes
- therapeutic actions

National producer associations also exist. Table 3 gives a national review of the dominant national associations in the region.

Codes of practice generally detail guidelines for day to day operations of fish farms. They may be developed under formal regulation, codes of conduct or both. In the Mediterranean Sea, the last option is common in countries that have national plans for aquaculture. Greece is the first country to have had a national plan for aquaculture and Code of Practice to which 50 percent of producers adhere (Christofilogiannis, 2001). Other Mediterranean Sea countries with national aquaculture plans include Cyprus, Egypt, Israel, Turkey, Italy, Malta, Spain, France, Morocco and Tunisia. Codes and other voluntary guidelines are enforced by measures such as suspension of certification or of membership in professional bodies. As in the case of formal regulation, a thorough investigation of the codes is needed in order to identify their orientation with respect to INTAQ and to identify aspects that need to be incorporated in order to facilitate it.

Technological requirements and general investment range for a variety of systems

Commercial-scale INTAQ is rare in the Mediterranean Sea, but experimental, pilot and early commercial stage evidence, both from the Mediterranean Sea and elsewhere (west and east coasts of Canada; New Hampshire, United States of America; western Scotland and southern Chile), can provide the basis for inferences as to the technical

TABLE 3
Federations of aquaculture producers in the Mediterranean Sea (in 2001)

CROATIA (1) The Aquaculture Group **CYPRUS (3)** Cyprus Mariculture Association; CYFISH; Yalos **FRANCE (5)** FFA - Federation Francaise D'Aquaculture; Syndicat Francais des Aquaculture Marins; Syndicat des Selectioneurs Avicoles et Aquacoles Francais; Comite National de la Conchyliculture; Sections Regionales de la Conchyliculture **GREECE (12)** FGM - Federation of Greek Maricultures; Greek Aquaculture Producers Union; Fish Farmers Union of the Northern Aegean Sea; Fish Farmers of Dodecanese; Aquaculture Producers Association of Northern Greece; Panhellenic Confederation of Agricultural Cooperatives Unions; Fisheries Cooperative Chalastra; Fisheries Cooperative Eilikrineai; Fisheries Cooperative of Kymina-Malgara; Greek Mussel farmers- Mollusc farmers Association; Mussel farmers Association of Pieria Prefecture; Mollusc culture Cooperative of Makrygialos **TUNISIA(1)** Union Tunisienne de L'agriculture et de la PTA **ROMANIA (0)**	**MOROCCO (1)** Association Marocaine de l'Aquaculture **ITALY (1)** API - Associazione Piscicoltori Italiani **MALTA (1)** Malta Aquaculture Producers Association **SPAIN (2)** APROMAR - Asociacion Empresarial De Productores De Cultivos Marinos; OPAC - Orrganisacion De Productores De Acuicultura Continental **TURKEY (4)** Turkish Aegean Aquaculture Association; Bodrum Fisheries Society; Fisheries Society (SUDER); Turkish Fisheries Foundation (TURKSU) **ISRAEL (3)** Fish Breeders Association; Tnuva; Fish Breeders Organisation **EGYPT (7)** Damietta; Amryaa; Fayum; Sharkia; Al-Tyna Plain **BULGARIA (2)** Bulgarian Fishing Association (1998);Bulgarian Fish Producers Association

Source: FEAP* and Christofilogiannis (2001).

* www.feap.info/feap/

requirements for INTAQ systems in the Mediterranean Sea. The focus is on cage mariculture, rather than on-land, for two reasons. First, it is the most common form of mariculture in the Mediterranean Sea (Mathe *et al.*, 2006) and therefore the most likely model for INTAQ to follow. Second, on-land INTAQ systems tend to be customized from the design stage, not adapted from existing operations and the range of design and engineering options for both joint production and effluent treatment is quite large (e.g.: polyculture ponds; monoculture ponds with water recirculation through various stages, etc.). Also, in the case of in-sea installations, the environmental issues are quite specific and the options for design are more limited, especially for effluent treatment. Therefore, the following discussion extends applications of temperate zone, cage INTAQ to the Mediterranean Sea, notwithstanding the fact that in some cases considerable adaptation will be required to implement such systems locally.

Considering technological requirements, the parameters for investment and operations vary considerable. On-land mono-culture installations are generally more expensive to construct and have lower returns on investment than do cage systems. For example, Lisac and Muir (2000) compared sea bream culture in 1 000–2 000 m^3 rearing volume concrete tanks with 2 500–3 500 m^3 rearing volume open sea cage systems. They found that investment requirements for the land-based systems were on average 1.5 times higher than the open sea systems and operating capital was 1.2 percent higher. The average internal rate of return (IRR) for land based systems was two percent, considerably lower than the 16 percent IRR for the sea cage systems. Recirculating land-based systems, in-particular may be quite expensive to construct and maintain. Pro-forma comparisons of the performance of INTAQ systems with monoculture finfish counterparts have shown that financially, the former have distinct advantages. Preliminary results from a case study based on an experiment of integrated sea bream – mullet cultivation in Israel (Angel and Freeman in prep.) show that for a range of assumptions, the INTAQ installation has distinct environmental

TABLE 4
Formal and self-regulation of environmental impacts of aquaculture

Jurisdiction	Detail	Sponsor, type (guideline, law, directive) and title
International	Provides a basic framework for comprehensive ocean governance.	United Nations Convention on the Law of the Sea (UNCLOS,1982) and associated agreements
International	Aquaculture Development and responsible aquaculture at production level *"9.1.1 States should establish, maintain and develop an appropriate legal and administrative framework which facilitates the development of responsible aquaculture."*	FAO; Code of conduct; Code of conduct for Responsible Fisheries (CCRF), Article 9
International	Of particular relevance, UNEP, 1998: Ecosystem approach under the Convention on Biological Diversity. Information Document No. 9 (UNEP/CBD/COP/4/Inf.9), 4th Conference of the Parties to the CBD to be held in Bratislava, Slovakia from 4 to 15 May 1998	1992 Biological Diversity Convention (1992); World Heritage Convention (1972).
International - EU	Primary policy framework for European fisheries sector	Common Fisheries Policy (CFP)
International - EU	EC directives are implemented at the national level by EU member states through national legislation and regulations and other restrictions.	Eight EC Directives directly governing environmental impacts of mariculture: • Dangerous Substances Directive • Quality of Shellfish Growing Waters Directive • Shellfish Directive • Environmental Impact Assessment (EIA) Directive • Strategic Environmental Assessment Directive (SEA) • Species and Habitats Directive • Wild Birds Directive • Water Framework Directive. More than fifty Directives, Decisions and Regulations indirectly affecting the monitoring and regulation of marine aquaculture (Read *et al.*, 2001).
Mediterranean Sea	Provides Best Available Technology (BAT) and Best Environmental Practice (BEP) designed to limit the pollution from fish farms in the Baltic Sea and in adjacent coastal areas where discharges enter the Baltic Sea.	Helsinki Convention (HELCOM) for the Protection of the Marine Environment of the Baltic Sea Area The Barcelona Convention for the Protection of the Mediterranean Sea against Pollution. General Fisheries Commission for the Mediterranean Sea
Professional Association	Strong self-regulation and enforcement by members through codes of practice, Management Schemes, Quality Schemes, and labelling and certification schemes	Federation of European Aquaculture Producers (FEAP); Voluntary Code of Conduct; FEAP Code of Conduct
Other	PARCOM Recommendation 94/6 on "Best Environmental Practice for the Reduction of Inputs of Potentially Toxic Chemicals from Aquaculture Use" is a benchmark for best practice beyond North East Atlantic	OSPAR; International Convention; Convention for the Protection of the Marine Environment of the North East Atlantic

and production/economic advantages over its sea bream monoculture counterpart. On the production side, the experimentation described in Porter *et al.* (1996), Katz *et al.* (2002) and Lupatsch, Katz and Angel (2003) showed that detritus from sea bream cages was sufficient to support mullet culture in enclosures beneath the sea bream cages. This contrasted with enclosures located 100 metres away from the cages, inside which the mullet could not survive solely on ambient nutrients. When the experimental production results were fed into an economic model, return to the investment and profits for the integrated farm was found to be on a par or slightly better than for monoculture as long as the price of sea bream was stable. The market price of mullet is much lower than that of sea bream and the level of production for this experiment was rather low. That is, the price of the primary species drives the profitability in this case.

The conclusions at this stage are that although the production benefits from integration were marginal, there is clear evidence that discharges into the environment can be lowered with no losses to the farmer and this speaks in favour of INTAQ. Moreover, this experimental evidence clearly indicates that with more intensive culture of the secondary species and in particular, the choice of more profitable species the overall production and economic benefits could be much larger.

The "classic" coastal INTAQ system could consist of a net cage or net pen fish farm and shellfish (usually mussels) and/or macroalgae (usually kelp). In practically all cases fish farms are designed as "monoculture" farms where all gear and moorings serve the fish cages/pens.[9] INTAQ components are usually added on afterwards in an attempt to reduce ecological effects and to increase and/or diversify aquaculture production without adding manufactured pellet fish feed (the most costly operating input) provided to the system. In such cases, baskets with shellfish and/or longlines with shellfish and/or macroalgae are either moored separately (as in Figure 1) or are attached to the existing fish farm mooring lines and structures.

However, a well-planned fish farm will consider features such as bathymetry, prevailing wave and wind and current directions and intensities to minimize risk of damage to the structures and to the health of the fish stocks. It is likely that the addition of INTAQ components to the system will affect aspects such as the structural integrity of the farm, circulation and water quality inside the net pens. Also the best design to obtain the highest benefits from the INTAQ production requires effective planning therefore this is highly recommended at the design and engineering stages. This needs to be done together with simulations of the effect of variable physical conditions on the integrity of the farm structures and to modeling of the effects of the INTAQ system on water quality inside and around the farm. It has been shown that an action as simple as rotating (swiveling) the orientation of aquaculture cages or shellfish longlines relative to the direction of the prevailing current can dramatically improve water circulation and quality inside the cages (Richardson, 2003; Newell and Richardson, 2004). Moreover, redistribution or aggregation of the INTAQ components relative to the fish cages or to one another may also improve water flow (and thereby water quality) through the cages. Ultimately a comparison of the performance of these various options will determine whether the INTAQ option is viable.

A variation on the classic scheme has been proposed by Cross (2004) in western Canada. His design incorporates shellfish and seaweeds within the farm rather than at the perimeter of the farm. By integrating the shellfish components within the physical structure of the finfish net pen farm, rather than on the outside, there is considerable reduction in moorings and other infrastructure required to stabilize the system. Moreover, by proper planning and timing of shellfish and finfish stocking, maintenance, handling and harvesting of each of the cultivated stocks may be done more efficiently by a small team at the farm.

In addition to the considerations for coastal mariculture, mention needs to be made of technical requirements for offshore or deepwater mariculture. One of the challenges that faces both monoculture and integrated aquaculture farmers is the growing acceptance that further expansion of coastal aquaculture is limited by physical space constraints and the ever increasing pressure by multiple stakeholders on the already overloaded coastal zone. Already, some Mediterranean Sea monoculture farms are choosing to move to offshore locations. One of the main challenges posed by open ocean aquaculture is the economic feasibility of the operation considering added expenses involved in such aspects as deep water mooring, special structures that can withstand open ocean conditions, travel costs from shore to the farm site for daily maintenance, harvesting, etc. Because the INTAQ components have requirements

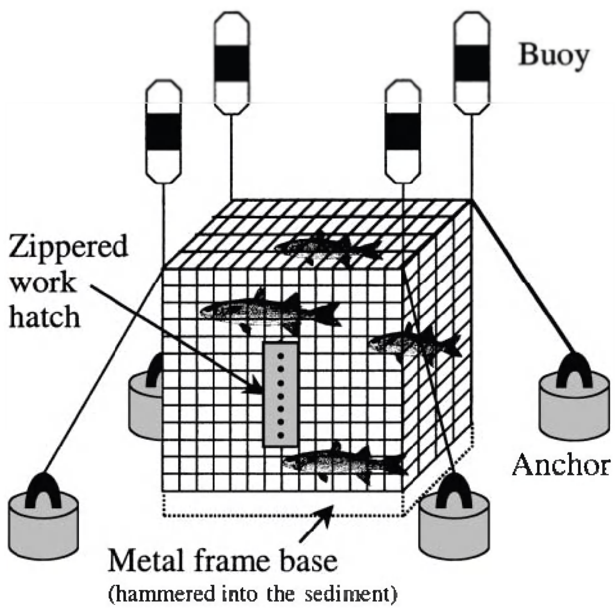
[9] Beveridge (1996) provides a very good reference for design and construction specifications.

that are not identical to those of the finfish, transition to an open ocean site may require special engineering solutions and, potentially, added costs to the farm that may detract from the joint-production benefits of co-cultivation. Another important consideration is the environmental benefits of reduced effluent from INTAQ practices. These are probably highest in the coastal areas where pollution levels are highest because of lower water circulation and congestion. Therefore, there is a strong case to be made for encouraging INTAQ in coastal areas as an alternative to monoculture. Given the prevailing negative attitudes towards aquaculture, information, information dissemination and public education will be critical components in the process of improving acceptance of INTAQ practices.

A variety of INTAQ systems have been considered to enhance the sustainability of finfish aquaculture in the Red Sea and the eastern Mediterranean Sea and a few of these will be briefly described below.

Seabream – mullet INTAQ. In the series of experimental-scale trials mentioned in the Israel country overview, Porter *et al.* (1996), Katz *et al.* (2002) and Lupatsch, Katz and Angel (2003) found that grey mullets placed in benthic enclosures (that were open to the underlying sediments) below a commercial sea bream/sea bass fish farm effectively removed organic carbon, nitrogen and phosphorus from the organically enriched sediments and grew at a rate equivalent to that of mullets reared in brackish water ponds on land. Scaling up such INTAQ systems to a pilot or commercial scale operation would involve construction of large bottom enclosures for deployment of mullets or other detritivore fishes (or invertebrates) using systems similar to those used for rearing of such bottom-feeding flatfishes as sole and flounder.

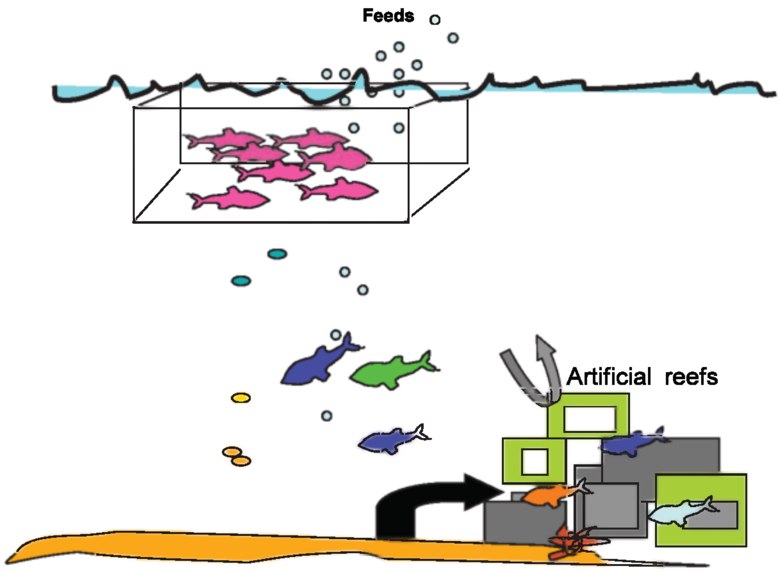
FIGURE 6
Sketch of a 1 m^3 (1 m width, 1 m height) benthic enclosure stocked with mullets



Source: Katz, *et al.* (2002).

Seabream – artificial reefs. Artificial structures placed around and/or below commercial fish farms serve as substrates for the development of natural fouling communities which may absorb some of the fish farm effluents, thereby enhancing the sustainability of the farms. We have observed that such structures may provide benefits that are similar to the more traditional INTAQ systems. Specifically, they may have the environmental benefits required by INTAQ, but the production/economic benefits accrue to a wider public than in the case of a fully integrated farm or several farms working in conjunction with each other. As a result, there are a number of property rights issues that influence incentive for the development of artificial reef systems; these include the rights to harvest migrating organisms and other activities in the vicinity of the reefs. The underwater structures boost local biodiversity as they attract benthic, demersal and pelagic fishes and invertebrates (Angel *et al.*, 2002) which trap and absorb particles released from the fish cages (Lojen *et al.*, 2005) thereby reducing impacts on the surrounding ecosystem (Figure 7). In addition to increasing biodiversity in the vicinity of the fish farms, the communities that develop on the artificial structures may serve as underwater attractions for tourism. The designs of the underwater artificial structures may be extremely diverse in terms of material, shape, etc. Several small scale deployments have been tested next to fish farms in the Red Sea, in Hong Kong and in Spain but none of these have been scaled up to larger structures. Although such systems show promise, there is a need for further research on issues such as size of structures, depth of deployment, orientation relative to the fish cages, optimal materials, effectiveness of biofiltration and economic feasibility.

FIGURE 7
Schematic for an artificial reef adjacent to fish cages



Environmental considerations

We consider the environmental impacts of INTAQ from two perspectives. The first is the overall environmental context of the Mediterranean Sea region and environmental issues of primary concern in the region. The issues are relevant to the aquaculture sector as a whole, not just INTAQ. Since public perceptions about aquaculture and regulatory attitudes towards it are often heavily influenced by these environmental concerns, they are relevant when considering the potential for expanding any aquaculture practice, including INTAQ. The second perspective is comparative, examining the potential environmental benefits of INTAQ over monoculture. The comparison and assessment relies on the perspective of the ecosystem approach and uses the conceptual tools discussed in the Introduction as a frame. When possible, quantitative measures are provided. Because INTAQ is so rare in the Mediterranean Sea region much of our data has come from the aquaculture sector in general (Soto and Crosetti, 2005), experimental results and evidence from non-Mediterranean Sea experience with INTAQ.

The Mediterranean Sea environment and environmental concerns: overview

EEA (2006) lists the following as the main issues of environmental concern:

- sewage and urban run-off
- solid waste
- industrial effluent
- urbanization
- eutrophication
- sand erosion
- marine transport
- biological invasions
- harmful algal blooms (HABs)
- exploitation of marine resources
- expansion of aquaculture
- natural hazards

This rather long list highlights not only the range of stressors affecting the Mediterranean Sea ecosystem, but also previews potential stakeholder conflicts and environmental challenges facing aquaculture and the opportunities for the expansion of INTAQ. Significantly for INTAQ, the expansion of aquaculture was highlighted as one of five emerging environmental threats in two major reports (EEA, 1999; 2002). This is extremely important for INTAQ. First, it reveals the extent to which negative attitudes towards aquaculture prevail. If these attitudes dominate policy decision-making, then the expansion of the industry, including INTAQ could be difficult. At the same time, INTAQ's environmental advantages directly answer some of the concerns about aquaculture and this may be an important opportunity. If INTAQ is shown to be more sustainable than monoculture, then it could become the leading edge for practices promoted by industry and policy makers. In addition, mariculture, including INTAQ has been a partial solution to the problem of stressed wild fish stocks, reductions in landings and increased consumer demand for marine products. It also has been instrumental the creation or maintenance of jobs and other economic opportunities in places traditionally dependent on capture fisheries. Therefore, in the wider context of the ecosystem, that includes ecological systems, fish resources and human communities, INTAQ could well be part of a sustainable solution (EEA, 2006; Jensen, 2001; Commission of the European Communities, 2002).

Environment and public image: potential benefits of INTAQ over monoculture

Rapid expansion is the defining characteristic of the mariculture sector in the Mediterranean Sea. In 2005, it produced nearly twenty times the tonnage that was produced in 1970 (375 560 tonnes vs. 19 997 tonnes), with most of the increase taking place after 1988 (EEA, 2006). Based on Fischler's (1999) estimate and given the sector's growth, aquaculture employs more than 70 000 people. It also has attracted considerable negative attention. Aquaculture's poor public image is in part due to observed adverse environmental impacts. During the period of rapid growth, farms proliferated and there were instances of poor management and accidents. Issues such as pollution, contamination of wild stocks from disease or fish escaping from cages and depletion of wild stocks for the production of manufactured feed and capture of fry have attracted widespread public attention and contributed to the poor image (Black, 2001; Basurco, 2000; Gowen and Bradbury, 1987; Hargrave, 2005; Heinig, 2001; ICES, 2005; Mazur, Aslin and Byron, 2005; Tlusty *et al.*, 2001; Naylor *et al.*, 2001). Often, the public's introduction to aquaculture is in the form of very negative media reports and in the absence of other information, negative opinions are formed. Thus, a second contributing factor to the image of aquaculture is the lack of knowledge and a degree of uncertainty. The process of developing understanding and creating an information base is ongoing and will take time to develop. A third important factor in the formation of public opinion is the fact that often, aquaculture installations compete with other stakeholder activities in the coastal zone. This will not change as the zone has multiple legitimate uses and an important part of policy is equitable and efficient allocation. Thus the image of aquaculture and public attitudes toward it can be influenced by good information and public education but also by policy development processes that accommodate various stakeholders, local, national and regional priorities.

Ecological effects at the farm level have received the most study but it has been difficult to generalize them or extrapolate the results up to the ecosystem level because of multiple and complex interactions between the farm and its larger environment. Even at the farm level, it has been difficult to determine standards for acceptable and unacceptable impacts in terms of degree and spatial extent (Heinig, 2001). Another issue in the Mediterranean Sea context is that much of the research has been conducted outside the region and may or may not be applicable. The fact that there is perceived impact and that conflicts exist is sufficient cause for a closer examination of the impact of aquaculture on the human and physical environment. (GESAMP, 1991; UNEP/MAP/MEDPOL, 2004).

Given the relatively short history of large-scale commercial aquaculture in the Mediterranean Sea, its integration in multiple management systems (e.g. fisheries, coastal zone, environment, marine resources, etc.) and the newness of system approaches applied to environmental/ecosystem management, it is not surprising that comprehensive ecosystem models of aquaculture are unavailable. Nevertheless, heuristic observation is possible and offers important indications for continued research. Referring to the list of main environmental concerns in the previous sections, all four carrying capacities are evident. Public image and competition among stakeholders in the coastal zone are clearly within the realm of social *carrying capacity*. Moreover, the better public image potential for INTAQ means that *its social carrying capacity* may be higher than that of monoculture. The specialized technical specification of integrated farms may limit the *productive carrying capacity* of open water sites for INTAQ while the integration of multiple species should increase the *productive carrying* capacity of more sheltered coastal sites. The lower effluent inherent in INTAQ poses less of a challenge to *ecological carrying capacities* and this may provide a wider scope for site selection, including areas that might otherwise be too sensitive to accommodate monoculture, resilient enough for INTAQ. In each of these examples, the importance of the *physical carrying capacity* is evident. For instance currents determine both the rates at which sediment is dispersed and the technical requirements of the farm. Water temperature determines growth rates of cultured organisms and absorption of effluent within the farm's zones of influence and the extent to which a particular site stands to benefit from INTAQ.

Table 5 summarizes the main ecological spillovers for which INTAQ practices may offer improvements in the Mediterranean Sea. The list in the table is a subset of aquaculture related issues raised by many research and policy bodies. The following section provides a detailed discussion of the potential improvements from an ecological standpoint.

Farm effluent and changes in diversity: comparing monoculture and INTAQ

While theoretical, experimental and pilot level evidence points to INTAQ as a lower emission process than monoculture, an optimal analysis of the environmental benefits of INTAQ requires at the very least, accurate data on the:

- uptake of dissolved and particulate matter by seaweed and detritivore species;
- amount that the uptake represents (in absolute and percentage terms) of baseline effluent from the monoculture counterpart;
- difference in terms of primary ecological impacts caused by the changes in effluent levels (dose-response differentials).

TABLE 5
Ecological spillover: comparing monoculture and INTAQ

	Monoculture	INTAQ	
		IMTA (3 trophic taxa)	artificial reefs + finfish cages
Effluent I – uneaten food and detritus causes particulate accumulation in the water column (nutrification/ Eutrophication/turbidity of water column) and sedimentation	High	**Medium** Most uneaten food waste is contained within the system but faeces and excretory waste is discharged	Probably **Medium** but needs further study Discharge from cages is as for monoculture BUT an unknown portion is taken up by migrating species
Effluent II – excretory waste causes accumulation of dissolved nitrogen and phosphorous in the water column	High	**None** Wastes in solution absorbed by macro algae	**As above**
Effluent III – pharmaceutical and chemical contamination of water and sediments	Low-Medium	**Medium** May be higher than for monoculture if there is a risk of pathogen transfer between cultured species	**As for monoculture**
Ecosystem health – changes in diversity and risk; e.g. migration of wild detritivore species to vicinity of cages a secondary effect of sedimentation (Effluent I)	High	Low	**As for monoculture** but impact may be mitigated by harvesting

Main Sources: EEA, 2006; FAO, 2007; GESAMP, 2001; 1997; 1996.

Partial information on the first two items above is available both in the Mediterranean Sea and other regions. Little if any of the dose-response time data exists. In addition, there are wide variations over different co-cultured species and from region to region in levels of effluent, uptake and primary, secondary and tertiary impacts. For example, Angel *et al.* (1992) found that organic matter decomposition rate in sediments under fish cages in the Red Sea may be greater than in temperate climates by as much as a factor of four. Moreover, ICES (2005) cites evidence that proper physical farm structures and operating practices can greatly reduce effluent, leaving open the possibility that the engineering and design of systems will be at least as important as the choice and integration of species.

Filter feeding invertebrates, especially mussels, have been used to take up particulate organic effluents from fish farms whereas dissolved inorganic nutrients are preferentially absorbed by macroalgae. The authors of the various studies report nutrient uptake dynamics using a variety of different flux rates. This is a challenge for comparing results; nevertheless, the results provide an estimate of the potential for the mitigation of environmental impacts. In one of the few figures published regarding net pen INTAQ, the AquaNet project has shown that mussels and other filter feeders may remove as much as 20 percent of the particulate effluents released by salmon, equivalent to around 240 kg particulate C per day for a 1 000 ton farm at peak production (AquaNet Project)[10]. In the same study, it was estimated that a kelp cultivation system mounted on long-lines adjacent to the salmon farm could assimilate at least one third of the dissolved nitrogen load (mostly ammonia) released by the caged fish, equivalent to around 150 kg dissolved nitrogen per day for a 1 000 ton farm at peak production. Most of the quantitative studies of INTAQ systems were land-based experimental recirculation units which suggest that inorganic N and P recovery of dissolved fish effluents may range from 35 percent to 100 percent (Troell *et al.*, 2003). In experiments using juvenile salmon and freshwater mussels, phosphorous and chlorophyll concentrations in tanks were reduced by orders of magnitude of one and two compared to tanks containing only salmon. The presence of bivalves effectively

[10] www.aquanet.ca

converted a hypereutrophic environment to an oligotrophic one (Soto and Mena, 1999). In order to predict the benefit to the environment from reduced particulate effluents following integration of mussels with salmon in British Columbia (Canada), Cross (unpublished) used the particle tracking model DEPOMOD (Cromey, Nickell and Black, 2002) to compare the footprint of an INTAQ salmon farm to a monoculture farm and found an order of magnitude reduction in organically-enriched sediments (ICES, 2005). Soto and Jara (2007), studying both marine and freshwater salmon farming INTAQ-type approaches, note that in addition to direct uptake of nutrients by wild bivalves, the bioturbation produced by these moving mollusks reduced the impact of nutrient accumulation in the sediments underneath fish cages.

In addition to the environmental benefit of mopping up effluents, proponents of the "integrated" approach point out the economic benefits and advantages of INTAQ over monoculture. It is noteworthy that some studies show no significant differences in mussel growth rates when comparing between a deployment near commercial fish farms vs. reference sites, but these are generally the result of poor choice of shellfish deployment station since the deposit feeders must be close enough to the particulate effluent load in order to absorb and remove it. When properly sited, workers in the AquaNet project have reported increased growth rates of both mussels and kelp by as much as 50 percent over the growth rates of these biofiltering organisms at nearby reference sites (ICES, 2005). A rare Mediterranean Sea example is that provided by Peharda *et al.* (2007) in the Eastern Adriatic Sea. They find mussels' growth in a suboptimal area adjacent to aquaculture cages was as good as mussels grown in isolation in areas considered to be more suited to mussel culture. This example highlights the need for more geographically focuses study. Parts of the Adriatic have the highest level of primary production in the Mediterranean Sea region. For this reason, they are suited to monoculture mussel production and could also be well suited to forms of INTAQ.

In considering the scale of improvement the effect of aquaculture on sediments is much easier to measure and monitor than the effect of aquaculture on water column properties, such as dissolved nitrogen or phosphorous concentrations. Particulate matter falls to the seafloor below the net cages forming a benthic footprint, whereas dissolved compounds released from fish farms are dispersed by water motion and rapidly assimilated by micro and macroalgae in the water column making them more elusive. Moreover, suspended solids and dissolved effluents released from fish farms may have "far-field" effects (Milligan and Law, 2005) that are not detected within close proximity to the farms. As a result, sediments have been monitored more closely and benthic impacts have been copiously described and identified as a local problem. Particulate organic matter, mainly faeces and uneaten feed, settles underneath fish cages leading to high sediment oxygen demand and eventually anoxia (Black, 2001). The benthic effects are localized and the severity depends on a large number of factors that determine the organic matter decomposition rate and the extent to which deposits from the farms are dispersed, including bathymetry of underlying seafloor, hydrodynamics, nature of the sediment particles, water depth, temperature, etc. (Beveridge, 1996; Black, 2001). Organic matter accumulations are problematic because they can lead to changes in benthic flora and fauna (EEA, 2006) and may lead to loss of certain ecosystem services. Dispersal, while it may seem to be a solution to the immediate area around the farm may have implications for water quality (e.g. turbidity and oxygen levels) on a larger scale, with negative or potentially positive consequences (e.g. if enhancing production of wild organisms). This is an important consideration for areas that currently have many farms and for the future as the number of farms increases.

One of the observed consequences of organic enrichment has been the migration (attraction) of wild fish and invertebrates from surrounding areas to the proximity of the farms (McDougall and Black, 1999; Angel *et al.* 2002; Eden, Katz and Angel, 2003), thereby changing local diversity. INTAQ combines pellet fed species with invertebrate scavengers and plant biofilters, mimicking the natural fouling community observed around monoculture farms. By limiting the dispersal of particulate and dissolved effluents to the area close to the farm, environmental impacts on the surrounding area are reduced and agencies such as the Scottish Environmental Protection Agency have developed the concept of *Allowable Zone of Effect* (AZE) to regulate the spatial extent of such local impacts (SEPA, 2004; PROFET Policy, 2001).

With respect to diversity, the concern is that, at least locally, discharges from monoculture aquaculture cause an undesired or uncertain change. This has been amply documented with respect to macrofauna and meiofauna (Weston, 1990; Angel *et al.*, 2000b; Hargrave, 2005). The Pearson and Rosenberg model of macrofauna succession with respect to organic enrichment (Pearson and Rosenberg, 1978) is a widely accepted dogma regarding benthic impacts of mariculture (Black, 2001; Hargrave, 2005) which predicts a sharp drop in biodiversity with increasing organic enrichment. EEA (2006) cites mortality of benthic fauna, deterioration of sea grass meadows and changes in the trophic status resulting from aquaculture impacts. A well known case is that of the *Posidonia oceanica* sea grass meadows. These sea grasses are important habitat and food sources for a range of invertebrates, fish and birds as well as a buffer against coastal erosion and concerns about aquaculture impacts on them are the most frequently cited (Soto and Crosetti, 2005). In Fornells Bay, Menorca they were totally eliminated in areas around fish farms (Cancemi, De Falco and Pergent, 2000). Though they recovered following cessation of aquaculture, it took at least three years before any recovery became apparent (Delgado *et al.*, 1999). In the case of overall ecosystem function, EEA (2006) conclude that monoculture, probably has detrimental impacts but the evidence is somewhat mixed and further studies are required.

Ecosystem issues common to monoculture and INTAQ

The previous section focused on production and environmental improvements offered by INTAQ. These are significant improvement from an ecological standpoint and should contribute to improved public perceptions and regulatory provisions that could facilitate the expansion of INTAQ. There are, however a number of other concerns that INTAQ shares with monoculture and though we do not discuss them in detail in this report, we do list them briefly in Box 2, because they are also significant and must be addressed in any aquaculture forum, including INTAQ. The list includes both potential negative spillovers from aquaculture to the environment and the effects of the surrounding environment on aquaculture operations. It also includes potential benefits of aquaculture as a whole.

Geographical areas and coastal zones most commonly used: where is INTAQ most likely to occur?

The expansion of INTAQ will depend on a combination of ecological factors, the current state of development of aquaculture in different places and the policy environment. In the near to medium term INTAQ is most likely to occur or expand in places where it already operates on experimental, pilot or commercial levels. Countries that already have a well developed mariculture industry with the physical and regulatory infrastructure, market support mechanisms and human capital that it entails will be the leaders. Greece, Turkey, Italy, Spain and Israel can therefore be expected to be early leaders in the expansion of INTAQ. They have the requisite infrastructure, financial, research and development base. In the longer term, follower countries will be those who have smaller industrial scale mariculture and who stand to benefit from adopting more mature INTAQ technologies, rather than developing them. Most countries in the southern Mediterranean Sea will fall into this category, with the possible exception of Egypt and Morocco which have relatively well developed aquaculture sectors. The benefits they stand to gain from the adoption of INTAQ are in the area of food

BOX 2

Main impacts and interactions relevant to Mediterranean Sea mariculture practice

Potential negative spillovers from aquaculture to the environment

1. **Impact on wild stocks I** – transfer of parasites and diseases
2. **Impact on wild stocks II** – escaped fish
3. **Impact on wild stocks III** – fry capture from wild stocks
4. **Impact on birds and marine mammals**
5. **Food safety**
6. **Stakeholder conflicts I** – farm sites inhibit other uses (e.g. tourism and recreation in the vicinity of farms)
7. **Stakeholder conflicts II** – spillovers among coexisting uses (pollution and hazards)

Effect of surrounding environment on aquaculture

1. **Effluent IV** – point and non-point source pollution from other users (e.g. sewage, industrial pollution, agricultural runoff, accidental spills)
2. **Stakeholder conflict I** – siting of the farm inhibited by other uses (e.g. existing urban and industrial installations may require off-coast sitings of farms.)
3. **Stakeholder conflict II** – e.g. risk to deep water farms from shipping and capture fisheries vessels
4. **Weather** – mainly the impact of severe weather on installations
5. **Wild animals** – usually cause damage to pens and cages; may involve predation
6. **Poaching**

Potentially positive impacts of aquaculture

1. **Business** (decreased cost, increased production)
2. **Employment maintenance and creation**
3. **Community integrity** in places dependent on fisheries (e.g. communities dependent on fish processing, transport, marketing, etc.)
4. **Creation of new economic opportunities** (e.g. hatcheries, non-conventional markets)
5. **Food Security** (maintaining sources of sea products in the face of stressed wild fish stocks)
6. **Improved management of fishery resources** (e.g. potential for aquaculture to relieve pressure on stressed wild fish stock)

Main Sources: EEA, 2006; FAO, 2005; GESAMP, 2001; 1997; 1996; Andersen, 2002.

security with lower environmental impact than monoculture. If INTAQ proves to be cost effective, then it may be the first stage of significant mariculture development in these countries, not so much replacing monoculture, but bypassing it entirely. Key issues of concern for these countries will be the cost of installations, training and other elements of developing human capital and property rights (Poynton, 2006; Ahmed, 2004). However INTAQ could be much more helpful and successful in countries and regions with fewer economic resources it is amenable to a variety of level of technological sophistication. If well guided and planned, it could provide benefits for a wide array of people of different social and economic levels. For example, the potential for setting mussel lines close to existing fish farms should be investigated, since mussel farming does not require complicated technology or expensive gear. Peharda *et al.* (2007) provide good evidence for the potential of such practices.

Places in which close-to-INTAQ production already takes place may also be locations in which practices can be formalized and expanded to fully realize the potential of integration. Instances of polyculture or collectivities of farms culturing different trophic species in close proximity are candidates. For example, in Olbia, Italy, there has been a rapid growth in finfish and mussel farms. The bay depicted in Figure 8 had virtually no aquaculture in 2005. Within two years, it was full of finfish cages and mussel lines.

From the standpoint of the social carrying capacity, areas in which INTAQ may be encouraged or adopted include offshore and more remote areas where competition for space is less intense than most coastlines. New offshore installations will have engineering requirements that will allow them to withstand rougher physical conditions in open water but will probably face less opposition from other stakeholders. Similarly, social acceptability of coastal aquaculture may be higher if the environmental advantages of INTAQ are understood and this may be another route to expanding the practice, notwithstanding congestion in the coastal zone. Moreover, rural support and development programmes in the entire region may benefit from INTAQ because of its environmental advantages and potential for business development and job creation in localities experiencing net outflows of population.

Since low primary production in many parts of the Mediterranean Sea has been cited as a constraint for INTAQ practices, we can also expect to see higher prevalence in the western basin and in areas such as the eastern and northern Adriatic Sea. Certain types of culture have specific nutritional or physical requirements, so from the standpoint of productive carrying capacities, consideration must be given to the feasibility of macroalgae and certain species of shellfish and their co-culture. Y. Karakassis (pers. comm.) points to ecological limitations affecting INTAQ in Greece where finfish and shellfish cultivation are physically separate. Specifically, the oligotrophic status of the water in the vicinity of many finfish farms in the eastern Mediterranean Sea is a limiting factor for introducing filter feeders to finfish cage environments as the low concentration of phytoplankton and detritus is probably insufficient for prolific mussel or other shellfish cultivation. The balance between low nutrient levels (specifically phosphates and ammonia) and low turbidity/high light penetration (Soto and Crosetti, 2005) may be the key to successful macroalgae co-cultivation. The former is a constraint while the latter may actually favour cultivation at depths not possible in other more nutrient rich ecosystems. Seaweeds also require a large area of fairly calm waters, characteristic of

FIGURE 8
Finfish cages and mussel farms in Olbia, Sardinia

inshore and land-based installations as turbulent physical conditions may cause algae to break off of the artificial supports near the fish cages used to cultivate these plants. The large areas needed may however be difficult to find in inshore waters.

Information requirements for better understanding of current practices and realization of major opportunities

INTAQ in the Mediterranean Sea is in its infancy and as such information on the practice, its consequences and potential is at a premium. At present, none of the major stakeholders and decision-makers, farmers, industry, lawmakers or the public at large have enough up-to-date, accurate information to fully understand the potential of INTAQ. The baseline characteristics of the physical and ecological carrying capacities of the region are reasonably well understood and the environmental concerns detailed in numerous reports give clear indications of the social carrying capacity. There is much less information on the productive carrying capacity for INTAQ. Some information on non-Mediterranean Sea experience, mainly from advanced experimental and pilot projects, can provide guidance, especially on the requirements for engineering, up-front investment and profit potential. To a lesser extent, these can also provide relevant information on the primary ecological impacts of INTAQ, for example, the potential nutrient uptake by detritivores and macro-algae. Specific information on the oligotrophic properties of the Mediterranean Sea and the challenges and opportunities it poses for INTAQ is probably the most critical gap that exists. We simply do not know what the implications are because there is so little experience. Another important gap is on the potential for new negative spillovers from INTAQ, for example, the transfer of disease among co-cultured species. Again more practical experience will contribute to fill such information gaps.

In addition to the creation of information, dissemination and outreach is also a key factor in determining the potential for INTAQ. This means that channels for transferring information from generators to users is important. In particular, education as a means of informing the public at large and influencing decision-makers will be an important element in promoting the social acceptability of INTAQ.

Finally, at the enterprise and market level, not enough is known about the production risks of INTAQ compared with other practices. Ridler *et al.* (2007) notes that the diversification of production may lower both production and market risk. For example, by cultivating two or more species, farmers could be exposed to less risk if the economic return one crop is compromised either by production failure (e.g. due to disease) or by significant drop in price. Only time and experience will provide information on these variables.

General evaluation of the major opportunities and constraints for INTAQ

As the preceding discussions indicate, INTAQ is potentially attractive in terms of both production and profitability and environmental sustainability. Nevertheless, very little of the practice is seen globally in marine and coastal environments. This is especially true of the Mediterranean Sea basin. Thus the focus of this section is the question: Why, given its apparent advantages has INTAQ not been adopted on a larger scale? In answering the question, we focus on two factors:

- the perspective of the operator given their awareness of the potential of INTAQ and expectations of returns on investment in INTAQ; and
- factors external to the operator that enhance or constrain the adoption of INTAQ.

Ridler *et al.* (2006) note that unless they are profitable, in the long run, INTAQ practices will not be adopted by farmers. It's expansion offers potential opportunities in three areas: (1) increased profitability at the farm level as a result of reduced feed and maintenance cost and increased production; (2) upstream diversification into non-traditional products (Chopin *et al.*, 2004) and reduction of market risk; (3) downstream business and employment opportunities such as the development of hatcheries and maintenance of existing processing, transport and marketing activities. The first two are of most interest to operators and the third to other businesses and local and regional planners concerned with communities that rely on the sector.

In assessing the profit potential of INTAQ, operators will need to be convinced, not only of its baseline potential in comparison to monoculture but also its potential in the face of existing and expected regulatory restrictions and other incentive instruments (e.g. taxes and subsidies, direct regulation, public image and consumer acceptance, etc.). For example, monoculture farmers are increasingly being required to pay for the environmental damage caused by their farms. This may be in the form of fines or installation of costly measures to prevent or treat effluent. In other cases, licensing may become more difficult for certain "undesirable" culture techniques or farms in certain areas. The Turkish fish farmers forced to move offshore because of the perceived impacts in the coastal zone and potential damage to tourism industry is a good example. Stricter regulation and enforcement of the practice of aquaculture may in fact be a source of opportunity for INTAQ if, because it is more acceptable, it becomes easier to license and/or less expensive to operate when the costs of regulation are added in to the profit calculation. Still, if farmers believe that changes in regulation such as in Turkey, will compromise their business, they will be less likely to risk the increased up-front investment required in setting up INTAQ operations.

INTAQ, as a new, untried technology presents both upside and downside risks, many of which will be resolved if enough experience is accumulated. For example, the risks to monoculture aquaculture over large periods with declining prices, such as those of 2001–2002, are well known (University of Stirling, 2004). The potential of diversified production to hedge against these risks is a potential incentive for the adoption of INTAQ but must be weighed against other negative productive carrying capacity risks such as unknown but possibly increased incidence of production losses due to cross-species contamination as a result of proximity.

In terms of factors external to the operator, most are in the realm of political and social acceptability and priorities of decision-makers. If the relevant stakeholders are convinced of INTAQ's advantages, there is a higher likelihood that it will be promoted both locally and regionally. The two advantages that are key in facilitating this promotion are in INTAQ's environmental sustainability and its potential for enhancing economic viability of farms and communities. The first has been discussed in considerable detail in the sections above. The second is reviewed here.

If INTAQ proves to be a viable means enhancing local economic activity, then rural communities in general and developing countries in particular, stand to benefit from more sustainable sources of enterprise, job creation and food security. Many Mediterranean Sea fishing communities are rural. In the absence of job opportunities, young people increasingly leave and communities are threatened. The experience in fishing areas in the north of Scotland points to the potential for INTAQ to help maintain their Mediterranean Sea counterparts. In Scotland, the development of aquaculture has been responsible for job creation and invigoration of local businesses in several communities under stress due to the decline in the capture fisheries. Jobs in the farms and local processing plants have reversed an outflow of young people from their communities (Commission of the European Communities, 2002). Similar opportunities have been observed in small Island communities in the Mediterranean Sea region. In these locations, there may be added advantages of food security, self-sufficiency, less competition and environmental pressure from industrial and urban sources than on mainland coastlines (Paquotte and Lacroix, 1997). A variety of incentive systems are needed to encourage the adoption of INTAQ practices in order to obtain benefits of these sorts. These include government support for small businesses, subsidies for new INTAQ farms and provisions to encourage collaboration among growers and harvesters of different species; for example, permitting mussel and finfish farms to locate in close proximity to one another and establishing legal frameworks that would permit more benthic harvesting.

Food security and the potential of INTAQ to contribute to economic development is a particularly important consideration for the southern Mediterranean Sea. Developing countries, mostly in Pacific Asia now supply most of the world's farmed fish. Aquaculture output is an important supply of animal protein for domestic consumption in these countries and a major export product. Though the anticipated rise in demand for fish and fish products and in aquaculture as a primary means of production has mixed potential benefits for the poor, the link between aquaculture and rural livelihoods as means of sustainable resource exploitation and diversification is considered part of development strategy (Ahmed, 2004). INTAQ, if it proves to be technologically appropriate and economically feasible could be an important component of such strategy.

Notwithstanding these potential benefits, public awareness of INTAQ is low, and in the few cases where there is awareness, INTAQ is not always differentiated from monoculture and suffers from a poor public image. Without better information, information dissemination and direct education of the public, such attitudes will continue to be a major obstacle to the expansion of the practice of INTAQ in the Mediterranean Sea region.

Major requirements for the expansion of this practice

In order to better understand the requirements for expanding INTAQ practice in the Mediterranean Sea region, it is necessary to carefully examine the few instances of INTAQ and near-INTAQ operations in the region and to look for examples outside the region that may be instructive. The focus of this section is to outline the conditions under which INTAQ is feasible and attractive. This section is more normative/prescriptive than the previous ones and focuses on maximizing benefit to all relevant stakeholders; the fish farm as a business; the industry, other users of coastal and marine resources, and regulators and quality of the environment. There is significant site specificity in terms of the needs of a given farm site. The Mediterranean Sea is a large ecosystem and both the physical and ecological carrying capacities vary from place to place making it impossible to provide a "general prescription" type of guideline for technical requirements and day to day operations. Since INTAQ in the region is rare and information scarce and often difficult to obtain, it is also not feasible to prepare a meaningful profile of specific sites and farms. For this reason we proceed with a set of principles and a framework for procedures that will help us to understand the current state of development in INTAQ and the pre-requisites for expanding the practice. In doing so, we distinguish between IMTA and other forms of INTAQ. Such is the case of benthic and pelagic harvesting in the vicinity of farms, cage – artificial reefs combinations and individual farms operating in the proximity of another. This is because, while all forms of INTAQ may have similar environmental benefits, IMTA more often involves a single operator who controls all aspects of investment and production and operates under well defined private property rules. The others may have multiple operators and several types of property rule: for example, two private owners of separate farms; a single private owner operating alongside a public property regime that allows common access to recreational users. In order to fully benefit from the potential of INTAQ, these differences must be considered.

IMTA

Beginning with the experience of IMTA in North America, the lack of commercial application has been attributed to a combination of lack of experience and reluctance on the part of business people to make large-scale commitments in the face of technological, political and economic uncertainty (Taylor, 2004). This belies the relatively high level of interest in the fin- and shellfish monoculture sectors on both coasts of the continent. S. Cross (pers. comm.) is developing a small scale commercial system using private funds and has a business plan for a large-scale, multi-site INTAQ operation. Both systems have generated industry interest but as yet, no commitment. Various others in the field have stressed the challenge of potentially high and variable costs of constructing and operating INTAQ farms as a specific deterrent (M. Ben Yami [Israel], G. Shavit [Israel], S. Cross [Canada], Y. Karakassis [Greece], pers. comm.). S. Cross (pers. comm.) further comments that there may be trade-offs between the investment and operating costs, citing the example of high capital costs of setting up his more "intensive" INTAQ system that requires modifying a steel net-cage salmon system to accommodate shellfish in a system that has a cost-effective automated product handling (grading, harvest and seed deployment). The pilot site is designed to produce approximately 125 tonnes of sablefish, 60 tonnes scallops, 60 tonnes mussels and 20 tonnes of kelp per year. He compares this to the more conventional raft or longline approach used in another three species system in eastern Canada and contends that though less capital cost intensive, it may have higher operating costs. Positive evidence from pilot projects and a clear understanding of the cost and production possibilities are indicated as important steps towards encouraging entry of enterprises. On the production side, the background ecology of the Mediterranean Sea must also be considered and more information is needed on the suitable co-cultivation options in oligotrophic waters in order to allow operators to make informed decisions on diversification at the trophic level.

Facilities that encourage diversification in the market will also encourage diversification in production. Industry and market level initiatives that enable access to many markets will encourage participation at the farm level. Chopin (2006) and Robinson and Chopin (2004) indicate that marine farm products need not compete exclusively with traditional fishery products (46.2 percent molluscs; 44 percent seaweeds; 8.7 percent finfish; 1.0 percent crustaceans and 0.1 percent other animals) and should be seen as a potential source of an array of "bioactive compounds of marine origin" (e.g. pharmaceuticals, nutraceuticals, functional foods, cosmeceuticals, botanicals, pigments, agrichemicals, biostimulants, etc). The European experience points to the need for diversification. Market saturation for common species (salmon, sea bass, and sea bream) is frequent (Fishing in Europe, 2004).

Even if INTAQ is shown to be more profitable and less risky at the market level than monoculture, without a stable, appropriate, well understood regulatory environment, farmers may be reluctant to adopt INTAQ. In the first instance, while the production benefits of INTAQ are of clear interest to farmers, the environmental benefits may not be. One of the reasons that mariculture businesses do not fully recognize the environmental benefits associated with biofiltration is that they accrue in the public sphere. Similarly, the environmental damages caused by monoculture are not considered by firms because they generally have no impact on farms' operations, productivity and profit. Internalizing these environmental costs will provide stronger incentives to marine farmers to adopt practices such as INTAQ. Appropriate regulation should therefore incorporate incentives that recognize the benefits of combining fed and extractive species and encourages practices that do so (Neori *et al.*, 2007).

Second, there is a high degree of uncertainty about INTAQ and its acceptability to regulators. Unless farmers can be reasonably certain that their investment in INTAQ will not be penalized at some future date by new regulation, they will be less likely to adopt it. There is ample evidence from other resource-based sectors showing that operators delay or fail to adopt practices and technologies that are both environmentally preferable and more profitable than conventional practices. Olmstead (1998) documented California farmers' reluctance to invest in water conserving technologies because of skepticism over the water regulator's commitment to supply and price controls. Similarly, Canadian timber producers have been reluctant to commit to practices that while allowing them increased freedom to choose the timing and size of harvests require considerable up-front investment in silviculture. The firms indicate that notwithstanding the expected positive return on their investment, they are uncertain as to whether the policy will remain in place until the growth stock reaches a harvestable age (Freeman, 2003). Given the complicated nature of formal and soft regulation governing aquaculture, the issue needs to be addressed.

Finally, unless INTAQ has a broad base of social acceptance, it will be difficult to foster its expansion, whether by creating an appropriate regulatory framework, or at the grass-roots level. Information dissemination and public education will be the key tools in fostering acceptance. Ridler *et al.* (2007), found favorable attitudes toward INTAQ when survey respondents were informed of its environmental advantages. Robinson and Chopin (2004) in Canada, Whitmarsh (2006) in Scotland and Mazur, Aslin, and Byron (2005) in Australia as well as others have found that environmental impacts are among the major public concerns related to aquaculture. Heuristic evidence from the Mediterranean Sea region points to similar concerns particularly because there is wide use of coastline for tourism activities and therefore, it is possible that an informed public will be more accepting of INTAQ than of other forms of mariculture.

Non-IMTA forms of INTAQ

As soon as there is more than one owner/operator/user, especially when more than one property rights regime is involved, a much wider set of incentives must be considered. In the case of several monoculture farms such as in Olbia, there must be regulatory provisions and techniques that allow for farms to operate in close enough proximity to each other so that detritus from the fed finfish can reach the lower trophic taxa. Examples where this is not the case point to rapid decline in integration benefits. The experiments involving mullets is instructive (Katz *et al.*, 2002) as is evidence from corals which show much higher growth over a limited distance from the fish cage but return to their baseline growth rate at large distances (Bongiorni *et al.*, 2003). This may require specialized design and engineering so that various structures in different farms do not interfere with each other.

Benthic or pelagic harvesting in close proximity to fish cages, especially if it is on the farm site by someone other than the farm owner may also require special provisions such as licenses and agreements with the farmer. More open access activities characteristic of tourism and recreation (e.g. diving around artificial reefs) may be even more complicated. Farmers need to be confident of the security of their site, public officials need to have the safety of other users in mind and depending on the nature of the complementary INTAQ activity and its proximity to the fish farm, the two may be in conflict and creative solutions will be required to ensure that the benefits of INTAQ can be achieved.

CONCLUSIONS AND RECOMMENDATIONS

This report has reviewed the theory and current practice of INTAQ in the Mediterranean Sea. It has used a combination of research, government and professional reports together with direct consultation with researchers and practitioners in the field. The report's objectives were to: describe the current practice of INTAQ in the region and the main factors influencing it; assess INTAQ's strengths and weaknesses in comparison to monoculture using the ecosystem approach and indicate the technological, regulatory, business and other parameters needed to implement INTAQ on a larger scale. The report reviews in detail current practice, relevant industry structures, regulation, environmental issues and information requirements. Because INTAQ is rare in the Mediterranean Sea, we have used, as appropriate, experience from other regions. For the same reasons, we have referred extensively to mariculture and fisheries in general in the discussions of environmental concern and regulation. INTAQ is part of a continuum of practices that exploit marine resources and its impacts on the environment and the fish resource base, and the opportunities it offers for business, industry and communities are best understood in this context.

With respect to several important characteristics, INTAQ compares favorably to monoculture. In terms of ecological carrying capacity, INTAQ's potential for reducing effluent is a significant advantage over monoculture. For the same reason, INTAQ may have a higher degree of social acceptability. INTAQ also offers favorable options for bivalve aquaculture (or other filter feeders) when the vicinity to fish cages provides more food. At the enterprise level, the increase in production together with opportunities for diversification represent important sources of profit and the potential for risk reduction. Feed costs per unit biomass production are lower in INTAQ and there may be operating synergies that lower overall operating costs per unit biomass. The investment required and in particular, the return on investment is difficult to assess, though preliminary case studies have had favorable results.

At the same time, many of the same environmental concerns for monoculture apply to INTAQ as well and these are significant. Also, INTAQ may introduce other risks, such as increased incidence of disease because of the proximity of several species.

Because INTAQ is new and because the environment in which it operates is complex and dynamic, there are many unknowns that need to be resolved in order to confidently assess its potential. Our recommendations below are aimed at this resolution.

Recommendations:

- Establish a metric for comparing various forms INTAQ to other alternatives. This report has provided heuristics but more rigorous comparisons of different types of INTAQ with different types of monoculture that are relevant for the Mediterranean Sea region.
- Increase research at the pilot commercial (rather than theoretical) level to examine the carrying capacity for INTAQ. The research needs to be wide ranging, with specific attention given to the oligotrophic conditions of the Mediterranean Sea and the implications for species selection and nutritional strategies; juvenile production; and overall environmental impact.
- Establish the basis for economic viability and technical feasibility of INTAQ projects in different areas of the Mediterranean Sea.
- Improve information dissemination and in particular public education in order to decrease public opposition to aquaculture in general and to increase understanding of INTAQ in particular.
- Examine the regulatory conditions (formal and soft) suited to the promotion of INTAQ as one of the options for sustainable aquaculture (i.e. incorporating sustainable resource use, economic viability and public benefit). Implement appropriate measures at the regional, national and local levels. Attention to initiatives at the national and local level will be important as these are the levels at which INTAQ takes place, at which opposition occurs and at which direct incentives will be most effective.

ACKNOWLEDGEMENTS

Without the help of a number of people, this report could not have been prepared. We are grateful for direct consultation with Menachem Ben-Yami who shared both his experience and extensive library, and to Guy Shavit and Ardag Ltd. We would also like to thank the following people: Y. Karakassis, K. Black, S. Sadek, G. Yucel, S. Cross, I. Okumus; F. Rad, A. Conides, Y. Avnimelech and A. Wainberg. This work also benefited from input from the ECASA project and the FAO workshop, *Building an Ecosystem Approach to Aquaculture (EAA): Initial Steps for Guidelines* in May 2007.

Finally, we are grateful to the Fisheries and Aquaculture Department of the FAO and in particular to D. Soto for the opportunity to prepare this report.

REFERENCES

Adamowicz, W.L. & Veeman, T.S. 1998. Forest Policy and the Environment: Changing Paradigms. *Canadian Public Policy,* vol. xxiv, supplement.

Ahmed, M. 2004. Outlook for Fish 2020: A Win-Win-Win for Oceans, Fisheries and the Poor? *In* A.G. Brown ed. *Fish, Aquaculture and Food Security Sustaining Fish as a Food Supply*. Record of a conference conducted by the ATSE Crawford Fund, Canberra, Australia, 11 August, 2004.

AMEC. 2002. Aquaculture information review - an evaluation of known effects and mitigations on fish and fish habitat in Newfoundland and Labrador. Canadian Technical Report of Fisheries and Aquatic Sciences 2434 vii + 47 p.

Andersen, J.L. 2002. Aquaculture and the Future: Why Fisheries Economists Should Care. *Marine Resources Economics.* 17: 133-141.

Angel, D.L., Krost, P., Zuber, D. & Neori, A. 1992. Microbial Mats Mediate the Benthic Turnover of Organic Matter in Polluted Sediments in the Gulf of Aqaba. Proceedings of the U.S-Israel Workshop on Mariculture and the Environment, pp. 66-73. Eilat, Israel - June 8 - 10, 1992

Angel, D.L., Katz, T., Eden, N., Gada, D., Stamper, G., Tzuker, A. & Gordin, H. 2000a. Why are scleractinian corals found in the relatively eutrophic waters around a commercial fish farm in the Gulf of Aqaba? *Annual Report (2000) of the National Center for Mariculture, Israel Oceanographic and Limnological Research Ltd.*

Angel, D.L., Verghese, S., Lee, J.J., Saleh, A.M., Zuber, D., Lindell, D. & Symons, A. 2000b. Impact of a net cage fish farm on the distribution of benthic foraminifera in the northern Gulf of Eilat (Aqaba, Red Sea). *Journal of Foraminiferal Research* 30: 54-65.

Angel, D.L., Eden, N., Breitstein, S., Yurman, A., Katz, T., & Spanier, E. 2002. In situ biofiltration: a means to limit the dispersal of effluents from marine finfish cage aquaculture. *Hydrobiologia* 469:1-10

Ardizzone, G.D., Cataudella, S. & Rossi, R. 1988. *Management of coastal lagoon fisheries and aquaculture in Italy*. FAO Fisheries Technical Paper, No. 293. Rome, FAO. 103 pp.

Barrington, K., T. Chopin & Robinson, S. 2009. Integrated multi-trophic aquaculture (IMTA) in marine temperate waters. In D. Soto (ed.). Integrated mariculture: a global review. FAO Fisheries and Aquaculture Technical Paper. Rome, FAO. pp.

Basurco, B. 2000. Mediterranean Sea Fish Farming Production Systems. *In* B. Basurco. *Mediterranean Sea Aquaculture: Marine Fish Farming Development,* (Chapter 2). CIHEAM, International Centre for Advanced Mediterranean Sea Agronomic Studies. www.medobs.org/themes/aquaculture/

Beveridge, M.C.M. 1996. Cage Aquaculture. 2nd edition. Fishing News Books, Oxford: 346 pp.

Black, K.D. (ed). 2001. *Environmental Impacts of Aquaculture.* Sheffield: Sheffield Academic Press.

Bongiorni, L., Shafir, S., Angel, D. & Rinkevich, B. 2003. Survival, growth and reproduction of two hermatypic corals subjected to *in situ* fish farm nutrient enrichment. *Marine Ecology Progress Series* 253. pp.137–144

Cancemi, G., De Falco, G. & Pergent, G. 2000. Impact of a fish farming facility on a *Posidonia oceanica* meadow. *Biologia Marina Mediterranea* 7. pp. 341-344.

Cataudella, S., Massa, F. & Crosetti, D. (eds). 2005. Interactions between aquaculture and capture fisheries: a methodological perspective. *In* Studies and Reviews - General Fisheries Commission for the Mediterranean Sea (FAO), no. 78 / FAO, Rome: General Fisheries Commission for the Mediterranean Sea.

Choo, P.S. 2001. Environmental Effect of Warm Water Culture in Ponds/Lagoons. *In* K.D. Black (ed) *Environmental Impacts of Aquaculture.* Sheffield: Sheffield Academic Press.

Chopin, T. 2006. Commentary: Integrated Multi-Trophic Aquaculture, What it is, and Why You Should Care… and Don't Confuse it with Polyculture. *Northern Aquaculture*. July/August 2006.

Chopin, T. & Bastarache, S. 2004. Mariculture in Canada: finfish, shellfish and seaweed. *World Aquaculture* 35. pp. 37-41.

Chopin, T., Robinson, S., Sawhney, M., Bastarache, S., Belyea, E., Shea, R., Armstrong, W., Stewart, I., & Fitzgerald, P. 2004. The AquaNet Integrated Multi-Trophic Aquaculture Project: Rationale of the Project and Development of Kelp Cultivation as the Inorganic Extractive Component of the System. *Bulletin of the Aquaculture Association Canada* 104. pp. 11-18.

Christofilogiannis, P. 2001. Codes of Practice in Southern Europe. Report of the MARAQUA Project. www.lifesciences.napier.ac.uk/maraqua/christo.htm

Commission of the European Communities, 2002. Communication from the commission to the council and the European Parliament: A Strategy for the Sustainable Development of European Aquaculture (COM(2002) 511 final) Brussels, 19.9.2002

Cromey, C.J., Nickell, T.D. & Black, K.D. 2002. DEPOMOD - Modeling the Deposition and Biological Effects of Waste Solids from Marine Cage Farms. Aquaculture 214: 211-239.

Cross, S.F. 2004. Marine Finfish & Suspended Shellfish Aquaculture: *Water Quality Interactions and the Potential for Integrated Aquaculture.* Doctoral Thesis, University of Stirling, Scotland. 312 pp.

Delgado, O., Ruiz, M., Perez, J., Romero, J. & Ballesteros, E. 1999. Effects of Fish Farming on Seagrass (*Posidonia Oceanica*) in a Mediterranean Sea Bay: Seagrass Decline after Organic Loading Cessation. *Oceanologica Acta*, 22: 1 pp. 109-117.

Dempster, T. & Taquet, M. 2004. Fish Aggregation Device (FAD) Research: Gaps in Current Knowledge and Directions for Further Ecological Studies. *Reviews in Fish Biology and Fisheries,* 14:1, 21–42 pp.

Dempster, T., Sanchez-Jerez, P.J., Bayle-Sempere, T., Gimenez-Casalduero, F. & Valle, C. 2002. Attraction of Wild Fish to Sea-Cage Fish Faros in the South-Western Mediterranean Sea: Spatial and Short-Term Temporal Variability. *Marine Ecology Progress Series* 242: 237–252 pp.

Dempster, T., Sanchez-Jerez, P.J., Bayle-Sempere, T. & Kingsford, M. 2004. Extensive Aggregations of Wild Fish at Coastal Sea-Cage Farms. *Hydrobiologia* 525: 245–248 pp.

Dempster, T., Fernandez-Jover, D., Sanchez-Jerez, P., Tuya, F., Bayle-Sempere, J.T., Boyra, A. & Haroun, R.J. 2005. Vertical Variability of Wild Fish Assemblages Around Sea-Cage Fish Faros: Implications for Management. *Marine Ecology Progress Series,* 314: 309–310 pp.

Eden, N., Katz, T. & Angel, D.L.. 2003. The impact of net cage fish farms on *Nassarius* (Niotha) *sinusigerus* distribution in the Gulf of Eilat (Aqaba), Red Sea. *Marine Ecology Progress Series* 263: 139-147

EEA. 1999. State and Pressures of the Marine and Coastal MediterraneanMediterranean Sea Environment. E. Papathanassiou and G. P. Gabrielidis (eds). European Environment Agency, Environmental assessment series No 5, pp. 137. (www.reports.eea.eu.int/ENVSERIES05/en/envissue05.pdf).

EEA. 2002. *Europe's Biodiversity — Biogeographical Regions and Seas.* Environmental issue report Published by EEA (European Environment Agency) Copenhagen 2002. (www.reports.eea.eu.int/report_2002_0524_154909/en).

EEA. 2006. Priority Issues in the Mediterranean Sea Environment. EEA Report n°4/2006. Copenhagen: European Environment Agency.

Eleftheriou, A. & Eleftheriou, M. 2001. Legal and Regulatory Background to Best Environmental Practice. *In* P.A. Read, T.F. Fernandes, K.L. Miller, A. Eleftheriou, M. Eleftheriou, I.M. Davies, & G.K. Rodger eds. (2001). The Implications of Directives, Conventions and Codes of Practice on the Monitoring and Regulation of Marine Aquaculture in Europe. Proceedings of the Second MARAQUA Workshop, 20– 22 March 2000, Institute of Marine Biology, Crete. Scottish Executive, Aberdeen, UK. 114 pp.

El Gayar, O.F. 2003. Aquaculture in Egypt and Issues for Sustainable Development. *Aquaculture and Economic Management.*, 7: *137-154.*

Falkenmark, M. & Tropp, H. 2005. Ecosystem Approach and Governance: Contrasting Interpretations. Stockholm International Water Institute. www.siwi.org/downloads/WF%20Articles/WF4-05_Ecosystem_Approach%20.pdf

FAO. 1995. Code of Conduct for Responsible Fisheries. Rome, FAO. 41 p.
www.fao.org/docrep/005/v9878e/v9878e00.htm#9

FAO. 2005. General Fisheries Commission for the Mediterranean Sea, Report of the Experts Meeting for the Re-Establishment of the GFCM Committee on Aquaculture Network on Environment and Aquaculture in the Mediterranean Sea, Rome, 7-9, December, 2005, FAO Fisheries Report No. 791 (FIRI/R791)

FAO. 2007. State of World Fisheries and Aquaculture 2006. Rome, FAO Fisheries and Aquaculture Department.

FAO. 2009. State of World Fisheries and Aquaculture 2008. Rome, FAO Fisheries and Aquaculture Department.

FAO Fishstat. 2008. www.fao.org/fi/statist/FISOFT/FISHPLUS

FEAP. 2000. A code of conduct for European Aquaculture. Version 1, Federation of European Aquaculture Producers, Secretariat. 8pp. www.feap.info/FileLibrary/6/FEAP%20Code%20of%20Conduct.pdf

Fernandes, T.F., Miller, K.L. & Read, P.A. 2000. Monitoring and Regulation of Marine Aquaculture in Europe. *Journal of Applied Ichthyology*. 16 (4–5), pp.138– 143.

Fischler, F. 1999. The Future of Aquaculture in Europe. 3rd Annual Conference PESCA, Santiago de Compostela.

Fishing in Europe. 2004. Editorial. Special Issue on Promoting Sustainable Aquaculture. December 2004, No. 24. pp.3-4. (www.ec.europa.eu/fisheries/publications/magaz/fishing/mag24_en.pdf)

Freeman, F. 2003. Economics of Forest Risk Management. Report to the meeting of the Forest Research Partnership, Mattawa, Ontario, October, 2003.

Garcia, S.M., Zerbi, A., Aliaume, C., Do, Chi, T. & Lasserre, G. 2003. The Ecosystem Approach to Fisheries. Issues, Terminology, Principles, Institutional Foundations, Implementation and Outlook. *FAO Fisheries Technical Paper*. No. 443. Rome, FAO. 71 p.

GESAMP (IMO/FAO/UNESCO-IOC/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). 1991. Reducing environmental impacts of coastal aquaculture. Rome, FAO. Reports and Studies. GESAMP 47. 35 pp.

GESAMP (IMO/FAO/UNESCO-IOC/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). 1996. Monitoring the Ecological Effects of Coastal Aquaculture Wastes. Scientific Aspects of Marine Environmental Protection. Rome, FAO. Reports and Studies. GESAMP 57. 38 p.

GESAMP (IMO/FAO/UNESCO-IOC/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). 1997._Towards Safe and Effective Use of Chemicals in Coastal Aquaculture. Reports and Studies. GESAMP 65. 40 p.

GESAMP (IMO/FAO/UNESCO-IOC/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). 2001. Planning and Management for Sustainable Coastal Aquaculture Development. Rome, FAO. Reports and Studies. GESAMP 68. 90 p.

Ghion, F. 1986. Intensive Rearing of Mullet. In Mediterranean Sea Regional Aquaculture Project: Technics Used for Intensive Rearing and Alimentation of Fish and Shellfish. FAO Fisheries and Aquaculture Department.

Giannoulaki M., Machias, A., Somarakis, S. & Karakassis, I. 2005. Wild Fish Spatial Structure in Response to Presence of Fish Farms. *Journal of Marine Biological Association of the United Kingdom,* 85: 1271-1277.

Gowen R.J. & Bradbury, N.B. 1987. The ecological impact of salmonid farming in coastal waters: a review. Oceanogr Mar Biol Annu Rev 25:563–575.

Hargrave B.T. (ed.), 2005 *Environmental Effects of Marine Finfish Aquaculture, Handbook of Environmental Chemistry, Springer*, Berlin Heidelberg New York.

Heinig, C. 2001. The Impacts of Salmon Aquaculture: The Difficulties ofEstablishing Acceptability Standards. *In* M. Tlusty, D. Bengston, H.O Halvorson, S. Otkay, J. Pearce & R.b. Rheault, Jr (eds). Marine Aquaculture and the Environment: A Meeting for Stakeholders in the Northeast. Falmouth, Mass.: Cape Cod Press. pp. 41-68.

Hough, C., 2001. Codes of Conduct and Aquaculture. *In* P.A. Read, T.F. Fernandes, K.L. Miller, A. Eleftheriou, M. Eleftheriou, I.M. Davies & G.K. Rodger, eds. *The Implications of Directives, Conventions and Codes of Practice on the Monitoring and Regulation of Marine Aquaculture in Europe*. Proceedings of the Second MARAQUA Workshop, 20–22 March 2000, Institute of Marine Biology, Crete. Scottish Executive, Aberdeen, UK, pp. 12–23.

ICES. 2005. Report of the Working Group on Environmental Interactions of Mariculture (WGEIM), 11-15 April 2005, Ottawa, Canada, CM 2005/F:04, 112 p.

Inglis, G.J., Hayden, B.J. & Ross, A.H. 2000. An Overview of Factors Affecting the Carrying Capacity of Coastal Embayments for Mussel Culture. NIWA, Christchurch, Client Report. CH00/69 vi, 31 p.

Jensen, G. 2001. The JSA Aquaculture Task Force Approach – Lessons Learned. *In* M. Tlusty, D. Bengston, H.O Halvorson, S. Otkay, J. Pearce & R.B. Rheault, Jr. (eds). *Marine Aquaculture and the Environment: A Meeting for Stakeholders in the Northeast.* Falmouth, Mass.: Cape Cod Press: 9-13.

Karakassis, I., Pitta P., & Krom, M.D. 2005. Contribution of Fish Farming to the Nutrient Loading of the Mediterranean Sea *Scientia Marina*, 69: 313-321.

Katz, T., Herut, B., Genin, A. & Angel, D.L. 2002. Grey Mullets Ameliorate Organically-Enriched Sediments Below a Fish Farm in the Oligotrophic Gulf of Aqaba (Red Sea). *Marine Ecology Progress Series* 234: 205-214.

Kimball, L. A. 2001. International ocean governance. Using International Law and Organizations to Manage Marine Resources Sustainably. Gland, Switzerland, and Cambridge, UK, The World Conservation Union, 123 p.

Lackey, R.T. 1998. Seven Pillars of Ecosystem Management. *Landscape and Urban Planning*, 40(1/3): 21-30.

Lisac, D. & Muir, J. 2000. Comparative Economics of Offshore and Mariculture Facilities, *Mediterranean Sea Offshore Mariculture, CIHEAM, Serie B, Etudes et Recherches, Numero 30,* Zarragoza.

Lojen, S., Spanier, E., Tsemel, A., Katz, T., Eden, N. & Angel, D.L. 2005. $\delta^{15}N$ As a Natural Tracer of Particulate Nitrogen Effluents Released from Marine Aquaculture. *Marine Biology* 148: 87-96.

Lupatsch, I., Katz, T. & Angel, D.L. 2003. Removal of Fish Farm Effluents by Grey Mullets: a Nutritional Approach. *Aquatic Living Resources* 34: 1367-1377.

Machias A., Karakassis, I., Somarakis, S., Giannoulaki, M., Papadopoulou, K.N. & Smith, C. 2005. The Response of Demersal Fish Communities to the Presence of Fish Farms. *Marine Ecology Progress Series.* 288: 241-250.

Mathe, S., Rey-Valette, H., Brunel, O., Clement, O., F. Rene, F & Blancheton, J-P. 2006. Analysis of the Standards and Indicators for Sustainable Development of Aquaculture. (IUCN/Centre D'Etudes de Projects, Copy for Consultation).

Mazur, N., Aslin, H. & Byron, I. 2005. Community Perceptions of Aquaculture: Final Report. Canberra, Australia: Social Sciences Program, Bureau of Rural Sciences.

Mc Kindsey, C.W., Thetmeyer, H., Landry, T. & Silvert, W. 2006. Review of Recent Carrying Capacity Models for Bivalve Culture and Recommendations for Research and Management. *Aquaculture*, 261: 451-62.

McDougall, N. & Black, K.D. 1999. Determining Sediment Properties Around a Marine Cage Farm Using Acoustic Ground Discrimination: RoxAnnTM. *Aquaculture Resources.*, 30: 451-458.

MEDPAN. 2007. The Network of Managers of Marine Protected Areas in the Mediterranean Sea. www.medpan.org.il

Mega Pesca. 2001. Marine Aquaculture in Egypt. Consultant Report.

Milligan T.G. & Law, B.A. 2005. The effect of marine aquaculture on fine sediment dynamics in coastal inlets., In B.T. Hargrave (ed.), *Environmental Effects of Marine Finfish Aquaculture, Handbook of Environmental Chemistry, Springer*, Berlin Heidelberg New York, Chapter 12.

Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M., Clay, J., Folke, C., Lubchenco, J., Mooney, M. & Troell, M. 2001. Effect of Aquaculture on World Fish Supplies. *Nature*, 405: 1017-24.

Neori, A. Shpigel, M., & Ben-Ezra, D. 2000. A sustainable Integrated System for Culture of Fish, Seaweed and Abalone. *Aquaculture.* 186: 279-291.

Neori A., Chopin T., Troell M., Buschmann A.H., Kraemer G.P., Halling C., Shpigel M., & Yarish, C. 2004. Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture**.** *Aquaculture* 231**:** 361-391.

Neori, A., Troell, M., Chopin, T., Yarish, C., Critchley, A., & Buschmann, A.H. 2007. The Need for a Balanced Ecosystem Approach to Blue Revolution Aquaculture. *Environment.* 49: 36-43.

Newell, C. & Richardson, J.E. 2004. Shellfish Carrying Capacity and Site Optimization. *Aquaculture Ireland – The Journal of the Irish Aquaculture Association*, April/May 2004.

Nybakken, J.W. 1982. *Marine Biology: an ecological approach.* New York. Harper and Row.

Odum, E.P. 1975. *Ecology*. New York. Rinehardt and Wilson.

Olmstead, J.M. 1998. Emerging Markets in Water: Investments in Institutional and Technological Change. Doctoral Dissertation, University of California, Berkeley.

Paquotte, P. & Lacroix, D. 1997. Aquaculture and Economic Development in Mediterranean Sea Islands. Paper presented at the EAFE 9th Annual Conference, Quimper France 28-30 April, 1997.

Pearson, T.H. & Black, K.D. 2001. The Environmental Impacts of Marine Fish Cage Culture. *In* K.D. Black ed. *Environmental Impacts of Aquaculture.* Sheffield: Sheffield Academic Press.

Pearson, T.H. & Rosenberg, R. 1978. Macrobenthic Succession in Relation to Organic Enrichment and Pollution of the Marine Environment. *Oceanography and Marine Biology Annual Review* 16: 229–311.

Peharda, M., Župan, I., Bavčević, L., Frankić, A. & Klanjšček, T. 2007. Growth and Condition Index of Mussel *Mytilus Galloprovincialis* in Experimental Integrated Aquaculture. *Aquaculture Research* 38(16): 1714-1720.

Porter, C.P., Krost, P., Gordin, H. & Angel, D.L. 1996. Grey Mullet (*Mugil cephalus*) as a Forager of Organically Enriched Sediments Below Marine Fish Farms. *The Israel Journal of Aquaculture - Bamidgeh* 48: 47-55.

Poynton, S.L. 2006. Regional Review on Aquaculture Development 2. Near East and North Africa 2005**.** *FAO Fisheries Circular No.* 1017/2 FIRI/C1017/2. Rome: FAO

PROFET Policy. 2001. "MERAMED" A tool to monitor the environmental impact of marine fish cage farms in the Mediterranean Sea. Technical Leaflet-Policy-relevant issues in Aquaculture & Fisheries Reference No. AA-FI-ENV-01.

Read, P. & Fernandes, T. 2003. Management of Environmental Impacts of Marine Aquaculture in Europe. *Aquaculture* 226: 139–163.

Read, P.A., Fernandes, T.F., Miller, K.L., Eleftheriou, A., Eleftheriou, M., Davies, I.M. & Rodger, G.K. eds. 2001. The Implications of Directives, Conventions and Codes of Practice on the Monitoring and Regulation of Marine Aquaculture in Europe. Proceedings of the Second MARAQUA Workshop, 20–22 March 2000, Institute of Marine Biology, Crete. Scottish Executive, Aberdeen, UK. 114 p.

Richardson, J.E. 2003. Productive Capacity Study of Shellfish Aquaculture Farm. *Alden Research Laboratory Report No.* 322-03/N1080F, Holden, MA.

Ridler, N., Robinson, B., Chopin, T., Robinson, S. & Page, F. 2006. Development of Integrated Multi-Trophic Aquaculture in the Bay of Fundy, Canada: A Socio-Economic Case Study. *World Aquaculture.* September. pp. 43-48.

Ridler, N., Wowchuk, M., Robinson, B., Barrington, K., Chopin, T., Robinson, S., Page, F. & Haya, K. 2007. Integrated Multi-Trophic Aquaculture (IMTA): A Potential Strategic Choice for Farmers. (unpublished draft)

Robinson, M.C. & Chopin, T. 2004. Defining the Appropriate Regulatory and Policy Framework for the Development of Multi-Trophic Aquaculture Practices: Introduction to the Workshop and Positioning of Issues. *Bulletin of the Aquaculture Association Canada* 104: 4-10.

Schuenhoff, M. Shpigel, M., Lupatsch, I., Ashkenazi, A., Msuya, F.E. & Neori, A. 2003. A semi-recirculating, integrated system for the culture of fish and seaweed. *Aquaculture* 221: 167–181.

Scialabba, N. 1998. Integrated coastal area management and agriculture, forestry and fisheries. *FAO Guidelines.* Rome, FAO. 256 pp.

SEPA. 2004. Improving The Regulation Of Environmental Impacts From Marine Caged Fish Farms: Revised Methodology to Assess Impacts in Marine Sediments and Derive Consent Limits on Maximum Fish Biomass. 21 December 2004. Scottish Environmental Protection Agency. www.sepa.org.uk/pdf/aquaculture/projects/mod_aze/part1.pdf.

Shafir, S., Van Rijn, J., & Rinkevich B. 2006. Steps in the Construction of an Underwater Coral Nursery, an Essential Component in Reef Restoration Acts. *Marine Biology* 149: 679-687.

Shpigel, M., Neori, A. & Marshall, A. 1996. The Suitability of Several Introduced Species of Abalone (Gastgropda; Haliotidae) for Land-Based Culture with Pond-Grown Seaweed in Israel. *Israeli Journal of Aquaculture, Bamidgeh*, 48: 192-200.

Soto, D. &. Mena, G.P. 1999. Filter Feeding by the Freshwater Mussel *Diplodon Chilensis* as a Biocontrol of Salmon Farming Eutrophication. *Aquaculture* 171: 65–81.

Soto, D. & Crosetti, D. 2005. The Environmental Situation of Aquaculture in the Mediterranean Sea. *In* General Fisheries Commission for the Mediterranean Sea, Report of the Experts Meeting for the Re-Establishment of the GFCM Committee on Aquaculture Network on Environment and Aquaculture in the Mediterranean Sea, Rome, 7-9, December, 2005, FAO Fisheries Report No. 791 (FIRI/R791).

Soto, D. & Jara, F. 2007. Using Ecosystem Services to Diminish Salmon-Farming Footprints in Southern Chile. In T.M. Bert (ed.) *Ecological and Genetic Implications of Aquaculture Activities* Vol. 6 *Methods and Technologies in Fish Biology and Fisheries* Series. Springer, Netherlands.

Soto, D., Aguilar-Manjarrez, J. & Hishamunda N. (eds). 2008. *Building an ecosystem approach to aquaculture*. FAO/ Universitat de les Illes Balears Expert Workshop. 7–11 May 2007, Mallorca Spain. FAO Fisheries Proceedings. No 14. Rome, FAO. pp. 15-35.

Taylor, J. 2004. Defining the appropriate regulatory and policy Framework for the development of integrated multitrophic aquaculture Practices: the department of Fisheries and Oceans perspective. Bull Aquacul. Assoc. Canada 104: 68-70.

Tett, P. 2007. Presentation at the ECASA Stakeholders Meeting Presentation. Heraklion, Crete, September 2007.

Tlusty, M., Bengston, D., Halvorson, H.O., Otkay, S., Pearce, J. & Rheault, Jr., R.B. 2001. Marine Aquaculture and the Environment: A Meeting for Stakeholders in the Northeast. Falmouth, Mass.: Cape Cod Press.

Troell, M. 2009. Integrated Marine and Brackishwater Aquaculture in tropical regions research, implementation and Prospects. In D. Soto (ed.). Integrated mariculture: a global review. FAO Fisheries and Aquaculture Technical Paper. FAO, Rome. pp. 47–131.

Troell, M., Halling, C., Neori, A., Chopin, T., Buschmann, A.H., Kautsky, N. & Yarish, C. 2003. Integrated mariculture: asking the right questions. *Aquaculture* 226. pp. 69–90.

UNEP/MAP/MEDPOL. 2004. Mariculture in the Mediterranean Sea. *MAP Technical Reports Series*. No. 140. UNEP/MAP, Athens. 80 p.

University of Stirling. 2004. Study of the Market for Aquaculture Produced Seabass and Seabream Species. Final Report 23April 2004. Report to the European Commission DG Fisheries. Unversity of Stirling, Department of Marketing and Institute of Aquaculture.

Van Houtte, A. 2001. Establishing Legal, Institutional and Regulatory Framework for Aquaculture Development and Management In R.P. Subasinghe, P. Bueno, M.J. Phillips, C. Hough, S.E. McGladdery & J.E. Arthur, (eds). Aquaculture in the Third Millennium. Technical Proceedings of the Conference on Aquaculture in the Third Millennium, Bangkok, Thailand, 20-25 February 2000. NACA, Bangkok and FAO, Rome.

Weston, D.P. 1990. Quantitative examination of macrobenthic community changes along an organic enrichment gradient. *Marine. Ecology Progress Series* 61: 233–24.

Whitmarsh, D.J. 2006. Public Attitudes Towards the Environmental Impact of Salmon Aquaculture in Scotland. *European Environment,* 16.

Appendix

KEY EVENTS IN THE EVOLUTION OF ECOSYSTEM MANAGEMENT RELEVANT FOR AQUACULTURE

1900-1980 (6 events)		1981-1989 (13 events)		1990-present (21 events)	
1902	Charter of the International Council for the Exploration of the Sea. Revised 1964, 1970.	1981	Convention for Cooperation in the Protection and Development of the Marine and Coastal Environment of the West and Central African Region	1989-91	UN General Assembly Resolutions on Large-Scale Pelagic Driftnet Fishing and its Impacts on the Living Marine Resources of the World's Oceans and Seas
1910	International Commission for the Scientific Exploration of the Mediterranean Sea (ICSEM)	1981	Convention for the Protection of the Marine Environment and Coastal Areas of the South East Pacific.	1990	• Regional Seas Caribbean Protocol on Specially Protected Areas and Species • Convention for a North Pacific Marine Science Organization (PISCES)
1969	Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP)	1982	UN Convention on the Law of the Sea. The comprehensive framework for marine environmental protection and resources conservation.	1991	MARPOL Guidelines for the Designation of Particularly Sensitive Sea Areas (PSSAs)
1971	Convention on Wetlands of International Importance, Especially for Waterfowl (Wetlands or Ramsar Convention). Its "wise use" principle anticipates the concept of sustainable development. Led to the development of the protected areas concept	1982	Protocol on Specially Protected Areas	1992	• UNCED Declaration and Agenda 21 • Convention on Biological Diversity • Convention for the Protection of the Marine Environment of the North East Atlantic • Convention on the Protection of the Marine Environment of the Baltic Sea Area • Convention on the Protection of the Black Sea Against Pollution. Followed by the Black Sea Environment Programme (BSEP) in 1994.
1971	Man and Biosphere Programme (MAB), launched as a program of UNESCO. Contributed to the development of protected areas.	1983	Convention for the Protection and Development of the Marine Environment of the Wider Caribbean Region	1994	• Code of Practice on the Introductions and Transfers of Marine Organisms. Supersedes earlier versions of 1973, 1979 and 1990 • Establishment of the Antarctic whale sanctuary
1972	Stockholm Conference on Human Environment. Defined the right of mankind to a healthy environment.	1984	Action Plan for Biosphere Reserves (MAB Programme of IOC) Commission on Environment and Development.	1995	• Global Programme of Action on Protection of the Marine Environment from Land-Based Activities (GPA) • Agreement Relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks (Fish Stocks Agreement or FSA) • FAO Code of Conduct for Responsible Fisheries • UNESCO Seville Strategy and the Statutory Framework for the World Network of Biosphere Reserves • Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean Sea. Call for protected areas. Supersedes the 1976 Convention.

KEY EVENTS IN THE EVOLUTION OF ECOSYSTEM MANAGEMENT RELEVANT FOR AQUACULTURE

1900-1980 (6 events)		1981-1989 (13 events)		1990-present (21 events)	
1972	Convention Concerning the Protection of the World Cultural and Natural Heritage (World Heritage Convention). Covers both natural and cultural areas of outstanding value.	1984 -87	World Commission on Environment and Development	1997	• International Guidelines for the Control and Management of Ships' Ballast Water to Minimize the Transfer of Harmful Aquatic Organisms and Pathogens
1972	Convention for the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention)	1985	International Wildlife Coalition moratorium on whaling	1999	• ITLOS decision regarding Pacific Southern Bluefin Tuna • FAO International Plans of Action (IPOAs) : (1) To reduce the incidental catch of seabirds in long-line fisheries; (2) For the conservation and management of sharks;(3) For the manage-ment of fishing capacity.
1973	Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). Embodies an eco-system-based approach.	1985	Regional Convention for the Conservation of the Marine Environment of the Red Sea and the Gulf of Aden Environment	2001	• FAO International Plan of Action to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing • Reykjavik Declaration on Responsible Fisheries in the Marine Ecosystem
1973	FAO Technical Conference on Fisheries Management and Development: stressed overfishing, overcapitaliza-tion, environmental degrada-tion (as a risk higher than fishing!) and the need for precautionary, anticipatory and experimental fisheries management. Proposed to frame fisheries management into ocean management	1985	Convention for the Protection, Management and Development of the Marine and Coastal Environment of the Eastern African Region	2002	• Plan of Implementation of the World Summit on Sustainable Development
1979	Convention on the Conservation of Migratory Species of Wild Animals (CMS or Bonn Convention). Priority work on marine turtles and small cetaceans.	1986	Convention for the Protection and Development of Natural Resources and Environment of the South Pacific Region	2006	General Fisheries Commission for the Mediterranean Sea recommends adoption of Ecosystem Approach to Aquaculture (EAA)
1979	Indian Ocean whale sanctuary	1987	Publication of the Brundlandt Report (Our Common Future). A report of the World	2007	Ecosystem Approach to Aquaculture: Worksop on Definition, Principles and Guidelines, Mallorca, Spain
1980	Commission on the Conservation of Antarctic Marine Living Resources (CCAMLR)	1989	Exxon Valdez oil spill		

Source: mainly Kimball (2001) in Garcia *et al*. (2003).

This technical paper provides a comprehensive review of current integrated mariculture practices around the world in three papers covering temperate zones, tropical zones and one semi enclosed ecosystem, the Mediterranean Sea. Integrated mariculture includes a diverse range of co-culture/farming practices, from integrated multitrophic aquaculture to the more specialized integration of mangrove planting with aquaculture, called aquasilviculture. Modern integrated mariculture systems must be developed in order to assist sustainable expansion of the sector in coastal and marine ecosystems thus responding to the global increase for seafood demand but with a new paradigm of more efficient food production systems. Successful integrated mariculture operations must consider all relevant stakeholders into its development plan, there is also a need to facilitate commercialization and promote effective legislation for the support and inclusion of integrated mariculture through adequate incentives particularly considering the reduction of environmental costs associated to monoculture farming. Bioremediation of fed aquaculture impacts through integrated mariculture is a core benefit but the increase of production, more diverse and secure business and larger profits should not be underestimated as additional advantages.

ISBN 978-92-5-106387-3 ISSN 2070-7010

9 789251 063873

I1092E/1/10.09/1600