Exploratory analysis of the comparative environmental costs of shrimp farming and rice farming in coastal areas

John W. Gowing[1]
School of Agriculture, Food and Rural Development, Newcastle University, United Kingdom
Patricia Ocampo-Thomason
Developing Areas Research Network, Newcastle University, United Kingdom

Gowing, J. & Ocampo-Thomason, P. 2007. Exploratory analysis of the comparative environmental costs of shrimp farming and rice farming in coastal areas. 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. 201–220

ABSTRACT

In order to explore the possibility of using Material Flow Analysis (MFA) to evaluate comparatively the environmental cost of shrimp farming and rice farming in coastal areas, this exploratory report provides an overview of the different shrimp and rice farming systems currently use worldwide. Then, the most important environmental issues surrounding each system are presented in terms of material flows. Whilst the authors recognised that a comprehensive analysis of the rice or shrimp farming sectors should include the whole production chain, in this report the system boundary is the farm enterprise. The report shows that it is possible to adapt MFA methodology to provide quantitative data on environmentally relevant flows, but this in itself does not provide a measure of the impact of these flows on the environment. There are two inherent weaknesses of the method. Firstly, it is oriented towards material inputs and considers only a limited number of emissions. Secondly, it depends upon the notion that the resultant impact of all inputs and outputs can be deduced from their aggregate mass. This ignores obvious differences in the environmental impact of different materials. In order to make any meaningful comparison between shrimp and rice production systems there is a need to modify MFA methodology to allow for consideration of disaggregated data on environmentally relevant flows.

INTRODUCTION

The coastal zone is home to 40 percent of the world's population and supports much of the world's food production and industrial, transportation and recreation needs, while also delivering vitally important ecosystem services. The environment within this zone

---

[1] j.w.gowing@ncl.ac.uk

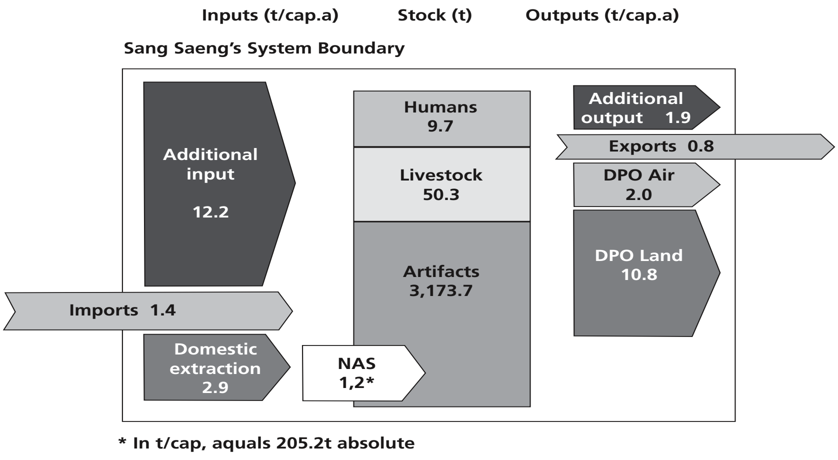
is under pressure and has undergone rapid change in recent times. Changes occurring in the state of the environment include altered nutrient, sediment and water fluxes; degradation of habitats and loss of biodiversity; pollution of soils, groundwater and surface water. These in turn affect human welfare through their effects on productivity, health and amenity. One of the key issues is land-use change; in particular the rapid growth of shrimp aquaculture. Natural habitats – principally mangrove forests and salt marshes – have been extensively cleared and converted to shrimp farming. However, it is important to recognise that recent expansion of shrimp farming has also encroached onto agricultural lands – principally paddy lands. Gowing, Tuong and Hoanh (2006) review the evidence of environmental and social impacts of this change and identify conflicts between agriculture, aquaculture and fishery interests within tropical coastal zones.

MATERIAL FLOW ANALYSIS

Material flow analysis (MFA) may have some merit in this context as a tool for evaluating environmental impacts of alternative resource use strategies. The analysis of material and energy flows can be traced back to the second half of the nineteenth century (Fischer-Kowalski, 1997), but current approaches rely on methods developed in the late 1960s and early 1970s (Ayres and Kneese, 1969; Boulding, 1973). The aim is to trace the physical flows of raw materials, products and wastes associated with particular economic activities. MFA can be applied on several spatial scales; the national level is most common and is most developed in terms of methodology (Eurostat, 2001; Mathews *et al.*, 2000). However, MFA can also be applied to supra-national entities such as the European Union (Eurostat, 2002) or to sub-national entities such as economic sectors, cities or regions (Brunner, Daxbech and Baccini, 1994).

Grunbuhel *et al.* (2003) use MFA to assess the environmental performance of a village in Thailand where rice is the dominant crop (see Figure 1). Natural resources extracted from the immediate environment (including timber from forests, crops from agricultural land and gardens, game from hunting and gathered products) represent the main inputs. These are aggregated as “domestic extraction”. “Imports” include all finished products and resources purchased in the market, either locally or outside the community. The third input category, labelled “additional inputs”, includes oxygen and water. Outputs to the immediate environment, either land or air, are aggregated as “domestic processed outputs”. DPO to air include CO_2 produced in combustion

FIGURE 1
Results of MFA in Sang Saeng village (Thailand) as determined by Grunbuhel *et al.* (2003)



* In t/cap, aquals 205.2t absolute

***t/cap.a= tonnes per person (capita) per year**

processes (fuel engines and wood burning) and respiration of humans and animals, and methane gas produced by domestic animals (water buffaloes and cattle). DPO to land consist mainly of faeces produced by both humans and animals, part of which is spread onto domestic fields as fertilizer. "Exports" include produce (mostly agricultural) extracted and processed in the community, and sold outside the community (mainly rice and livestock).

This example is typical of the general approach to MFA in which material flows are commonly calculated and presented in five main categories:

- Non-renewable raw materials such as minerals and fossil fuels;
- renewable raw materials such as plant biomass (cultivated and wild);
- soil;
- water;
- air (for combustion or as raw material).

The two inherent weaknesses of the method are apparent. Firstly, it is oriented towards material inputs and considers only a limited number of emissions (because of the complexity of the systems studied). Secondly, it depends upon the notion that the resultant impact of all inputs and outputs can be deduced from their aggregate mass. This ignores obvious differences in the environmental impact of different materials. In order to make any meaningful comparison between shrimp and rice production systems there is a need to modify MFA methodology to allow for consideration of disaggregated data on environmentally relevant flows.

A comprehensive analysis of the rice or shrimp farming sectors would include the whole production chain including upstream and downstream considerations. Upstream considerations would include activities producing inputs such as fertilizers and pesticides, while downstream considerations bring in activities of handling, storing and processing output. In this paper the system boundary is the farm enterprise, we also consider different levels of farming intensity, as each level will need and produce different material flows.

Shrimp farming systems

Shrimp farming is one of the most profitable and fastest-growing segments of the aquaculture industry (FAO, 2002; 2003). Latest estimates suggest there are now in the order of one billion consumers who purchase cultured shrimp, with the industry continuing to expand (World Bank *et al.,* 2002). However, its rapid expansion has been coupled with rising concerns over the environmental and social impacts of its development, and controversy associated with shrimp culture in shrimp producing and importing countries has been growing. As an integral part of the so called "blue revolution", shrimp farming has integrated coastal ecosystems into the global food production system, and, as in the earlier green revolution, there is mounting criticism over its social, economic and environmental consequences.

Shrimp farming is a sector with a very high degree of diversity, involving a wide range of species, farming systems and production practices, and farming locations. There are significant differences between and within countries regarding the levels of production intensity and yields, farm numbers and their sizes, and the various types of resources utilized (Barg *et al.,* 1999). Basically the level of intensification determines the classification of the systems, though Raux and Bailly (2002) propose a typology based on both technical criteria and on modes of organization. Globally, four grow-out production systems are generally recognized, which share some characteristics, but differ in other aspects; below the most common shrimp farming systems used in the current literature are described. However such classification of shrimp farming systems is difficult, and can be rather arbitrary, given that there are additional characteristics and different criteria and terminologies in use. Farms may also use monoculture or polyculture systems (polyculture systems are usually common with low input systems);

they may be operated as mixed systems (e.g. shrimp and mangrove farms); or by alternate cropping, involving one crop of shrimp followed by a harvest of another species or crop (eg rice-shrimp alternate cropping systems in Bangladesh, India, and Viet Nam). The size of farm is also very variable. In Asia, small-scale farms dominate shrimp farming in many countries, which is in contrast to many farms in the Western Hemisphere (i.e. Brazil, Ecuador, Mexico). Thus, an important consideration when discussing shrimp farming is the diversity of farming systems in operation as well as their location.

Extensive systems (including tambak)

Shrimp farms with low stocking densities, typically located in tropical water impoundments ranging from 2 ha to >100 ha and located along estuaries, bays, and coastal lagoons. Stocking densities are low, not over 25 000 postlarvae (PL) per ha that are normally collected in the wild. The tides provide a water exchange rate from 0percent to 5 percent per day (Rönnbäck, 2001). Shrimp feed on naturally occurring organisms, which may be encouraged with organic or chemical fertilizer. Lime may be applied if soils are acidic and, sometimes, animal manures or other organic materials are used to stimulate production of natural food for the shrimp. Construction and operating costs are typically low and production rarely surpasses 400 to 500 kg/ha in production cycles that last 100–140 days (Jory and Cabrera, 2003).

Semi-intensive systems

Shrimp farms that operate at medium stocking densities. In many cases ponds (2 to 30 ha) are built above the high-tide line and include a pumping station and water distribution canals and reservoirs, and use of formulated feeds. Pond preparation is more elaborate, with dry-out once or twice a year, tilling and liming and fertilization with N, P and Si compounds to promote natural production (Jory and Cabrera, 2003). Stocking rates range from 100 000 to 300 000 wild and/or hatchery produced postlarvae per ha. Water exchange rates typically used are 0 percent to 25 percent of pond volume per day. Formulated and pelleted feeds with 20 percent-40 percent crude protein are usually applied 1-3 times per day. Yields range from 500 to 5 000 kilograms (head-on) per hectare per year.

Intensive systems

Shrimp farms operate with high stocking densities (more than 300 000 PL per ha). Typical ponds are 0.1 to 2 ha, with preparation before stocking and more elaborate management with feed applied 6-8 times a day. Mechanical aeration is needed throughout the cycle, usually with increasing number of units and longer hours of operation as the cycle progresses. Generally 4-12 hp/ha is used, with the amount increasing as the biomass of shrimp increases. In Asia several chemicals, including calcium peroxide, burnt lime, zeolite, chlorine, iodine, formalin and bactericides, are applied to ponds to prevent water quality deterioration and disease (Jory and Cabrera, 2003). Sophisticated harvesting techniques and easy pond clean-up after harvest permit year-round production in tropical climates. Yields of 5 000 to 20 000 kg (head-on) per hectare per year are common.

Super-Intensive systems

Systems with very high stocking densities. These include the highest level of environmental control, to the point of some being located indoors in greenhouses and other structures. Annual production can reach 20-100 mt/ha and higher, but currently there are only a few of these farms, in Thailand, the United State of America, and possibly a few other countries (Rosenberry, 2001). Examples of these advanced farms and technology include the pioneer Belize Aquaculture Ltd (BAL) in Belize and the Ocean Boy Farms in Florida, United States of America (Burford *et al.,* 2003).

TABLE 1
Shrimp farming systems in four Asia countries

	Indonesia	Philippines	Taiwan Province of China	Thailand
Production (tonnes)	100 000	30 000	25 000	225 000
Farming area (ha)	300 000	50 000	7 000	80 000
Production (kg/ha)	333	6 000	3 571	2 813
No. of farms	6 000	1 000	2 000	20 000
percent extensive	80	35	0	5
percent semi-intensive	10	50	50	10
percent intensive	10	15	50	85

Source: adapted from Kongkeo, 1997

Pond management is based on zero water exchange, heavy aeration (up to 50 or more hp/ha) and the promotion of a bacteria-dominated and stable ecological system. At BAL, feeding rates have exceeded 350 kg/ha/day, which encourage bacterial flocs[2] to develop (Browdy *et al.*, 2001). The flocs remove nitrogenous waste products from the water and the shrimp feed on the flocs. These systems are believed by some experts to represent the future of shrimp farming (Rosenberry, 2001).

According to the latest estimates there are at approximately 1 251 450 hectares devoted to shrimp farming worldwide (Raux and Bailly, 2002). Indonesia, Viet Nam and China have the most land devoted to shrimp farms. In terms of percentages by intensification is very difficult to get information due to high degree of diversity, however GAA (1998) estimates that approximately 10 percent of the world farms are currently using intensive or super-intensive production strategies. There are some marked regional differences in Asia, for example Thailand presents an intensive nature (Barbier and Cox, 2004) while Viet Nam, India, Bangladesh and Indonesia are characterised by extensive development. Table 1 shows the percentage of extensive, semi-intensive and intensive systems in four Asian countries.

Rice farming systems

Rice is the largest irrigated crop and ranks second only to wheat as the most extensively grown crop in the world. Rice provides 23 percent of global human per capita energy and 16 percent of per capita protein. Rice is grown in four ecosystems, which are broadly defined on the basis of their water regime as: irrigated, rain-fed lowland, upland and flood-prone ecosystems. They cover 55 percent, 25 percent, 13 percent and 7 percent of the world's rice area respectively and account for 76 percent, 17 percent, 4 percent and 3 percent of the world's current rice production. Asia accounts for 90 percent of the world's rice area and over 90 percent of production. The distribution of rice land between these ecosystems for the main rice producing countries of Asia is summarized in Table 2.

Irrigated rice

This is grown in levelled and bunded[3] fields with an assured irrigation supply for one or more crops a year. Rice is transplanted or direct seeded into puddled[4] soil. Fields are flooded to shallow depth with anaerobic soil during crop growing season. Two sub-ecosystems are recognized: (i) are as served only by supplementary irrigation in the wet season; (ii) areas with wet season and dry season cropping.

Rain-fed lowland rice

This grows in bunded fields that are flooded for at least part of the cropping season to water depths that may exceed 50 cm for no more than 10 consecutive days. Rain-

---

[2] "floc": living microbial food organisms

[3] surrounded by a embankment

[4] soil particles pack together resulting in poor air movement and poor drainage

TABLE 2
Rice ecosystems in the main rice-producing countries in Asia (wet/dry season -WS/DS)

	Harvested area ('000 ha)						
	Irrigated		Rainfed lowland		Flood-prone	Upland	Total
	WS	DS	0-30	30-100			
India	15 537	4 123	11 985	4 447	1 364	5 060	42 516
China	20 490	9 146	1 990	0	0	499	32 125
Indonesia	2 963	2 963	2 872	1 006	2	1 209	11015
Bangladesh	351	2 267	3 271	2 873	1 220	697	10 679
Thailand	274	665	6 382	1 778	342	203	9 644
Viet Nam	1 630	1 630	1 963	651	177	322	6 373
Myanmar	1 812	1 386	2 033	478	362	214	6 285
Philippines	1 175	1 029	911	341	0	165	3 621
Pakistan	2 125	0	0	0	0	0	2 125
Cambodia	140	165	1069	349	152	24	1899
Nepal	706	24	406	166	118	68	1488
Korea, Rep.	776	0	326	0	0	1	1103
Sri Lanka	377	251	213	26	0	0	867
Total	49 211	24 003	34 056	12 131	3 737	8 853	131 991

WS/DS refers to Wet/dry season. 0-30/30-100 refers to depth of floodwater (cm).

Source: IRRI (2002). Rice Almanac, 3rd edition. Manila, International Rice Research Institute

fed lowland systems are characterized by lack of water control and have no access to irrigation. Fields are level to slightly sloping. Soils alternate at variable intervals between aerobic and anaerobic conditions. Four sub-ecosystems are recognized: (i) favourable rain-fed lowland; (ii) drought-prone; (iii) submergence-prone; (iv) drought -and submergence-prone.

Upland rice

It grows in fields where there is no attempt made to impound water and no natural flooding. It grows like any other upland crop under aerobic soil conditions and depends on rainfall. Landforms vary from flat to undulating and steeply sloping.

Flood-prone rice

It is subject to submergence of more than 10 consecutive days by standing (stagnant) water ranging in depth from 50 cm to more than 300 cm. Areas in coastal plains and deltas subject to tidal influence are also affected by salinity.

For the present purpose we need to consider the rice land area that offers the potential of conversion to shrimp aquaculture. All such land falls within either irrigated or flood-prone ecosystems. Land suitable for brackish water shrimp production lies within the coastal zone and is subject to tidal influence. Much of this land will be categorised as flood-prone eg Mekong Delta in Viet Nam and Cambodia, Chao-Phraya delta in Thailand and Ganges-Brahmaputra delta in Bangladesh. A special category is tidal swamp land where acid sulphate soils are widespread.

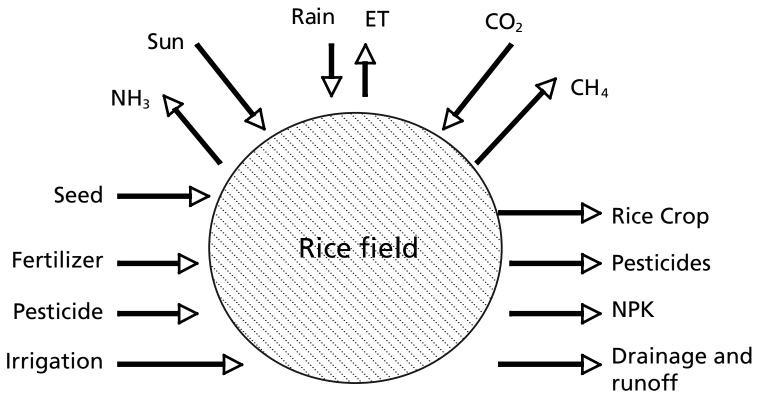
Material flows in rice production systems

At the scale of the individual rice farming enterprise we can identify the environmental issues which are readily presented in terms of material flows (Figure 2):

Water

Lowland rice is mostly transplanted or direct (wet)-seeded into puddled, bunded fields under flooded conditions. Water input (rain + irrigation) is required to match outflows due to evapotranspiration (ET) and drainage. Typical ET rates vary from 4 to 7 mm/day[5] (Tuong, 1999). Drainage includes seepage and percolation losses at rates

FIGURE 2
Material flows in rice farming systems



varying from 1 to 5 mm/day in clay soils up to 25 to 30 mm/day in sandy soils, together with runoff losses when pond depth exceeds overflow level. Runoff may also include controlled release of impounded water at certain times for crop management. For a typical 100 day season of modern high yielding rice, total water input varies from 700 to 5 300 mm, with 1 000 to 2 000 mm as a typical value (Tuong and Bouman, 2003).

Water 'losses' by seepage and percolation for a 100 day crop are typically in the range 100 mm to 3 000 mm while runoff is often closely matched to rainfall, reflecting inefficient use of this input. However, it should be recognised that analysis at the level of an individual field neglects to consider the possibility that water may be reused at another location. Reliable data on the scale effect are scarce (Tuong and Bouman, 2003), but in many river basins multiple reuses can occur and coastal zones may suffer severely from reduced flows due to upstream development (Atapattu and Molden, 2006). On the other hand, where the rice production system is located within the coastal zone, opportunities for reuse are very limited.

The relationship between the hydrology and chemistry of the flooded soil system has been described by many authors and is reviewed by Greenland (1997) and Kirk (2004). The majority of paddy fields are on alluvial fans and river terraces with well drained high-yielding paddy soils (pseudogleys). In these soils seepage and percolation losses are in the range of 500 to 1 500 mm. Within the coastal zone we are concerned with areas in lower parts of deltas and valley bottoms where soils are mostly stagnogleys and there is little or no vertical percolation. However, lateral seepage flows and surface runoff flows will still occur. In considering soil nutrient balance for sustainability analysis, Greenland (1997) neglects these flows on the assumption that inflows balance outflows and net loss is nil. We cannot ignore them as we are concerned with what he calls "boundary positions" from which there is a net loss to the wider environment.

Nutrients

Nutrient loading from diffuse agricultural pollution is a growing problem in water quality management. Nitrogen and phosphorus are of most concern because they can cause eutrophication in lakes and rivers. Nitrate seldom forms or persists in paddy soils because of reduced conditions and losses of N by leaching are generally in the form of ammonium and are lower than in upland soils. In contrast, losses of P are greater because solubility is increased in reduced conditions. Nevertheless, P concentration is generally an order of magnitude lower than N concentration.

In order to achieve a rice yield of 5 t/ha farmers typically apply 100 kg /ha of N (Greenland, 1997 p130; Fischer, 1998). Although N supply drives productivity, poor N fertilizer use efficiency is characteristic of irrigated rice systems with fertilizer N losses generally in the range from 10percent to 65 percent. Cassman *et al.* (1998); Cassman, Gines and Dizon (1996) and Cassman, Kropff and Gaunt (1993) reported apparent N fertilizer recovery rates at 36 percent to 39 percent in favourable conditions. With good management on research stations, it is possible to achieve recovery efficiency of 50 percent. Low efficiency is largely attributed to rapid losses of applied N from NH_3 volatilisation and denitrification.

Nutrient outputs from several studies in Japan and Korea, where fertilizer inputs are relatively high, were compared by Yoon, Ham and Jeon (2003) who showed that net output of N and P generally increased with rainfall amount. One of the important aspects of this study was to quantify the surface drainage of water, and export of nutrients, from rice fields treated with different fertilization rates. In all treatments, surface drainage constituted about half the total water loss. Fertilization rate itself did not affect nutrient loss by surface drainage. Saving water by limiting inflow could be a possible strategy to reduce surface drainage and nutrient losses. Bouman and Tuong (2001) reported that by reducing ponded water depth from 5–10 cm to the level of soil saturation did not reduce land productivity, and they found that 23 percent water savings caused only 6percent yield reductions. Less water inflow, however, needs careful field management because rainfall does not necessarily meet the water requirements for rice culture, and very accurate and timely water delivery would be required.

Agronomic practices can affect the effluent loads (Suspended Solids – SS, organic matter, nutrients, etc.). Cabangon *et al.* (2004) studied the effect of irrigation method and N-fertilizer management on rice yield, water productivity and nutrient-use efficiencies in typical lowland rice conditions in China. Alternate wetting and drying irrigation (AWD) has been reported to save water compared with continuous flooding (CF) in rice cultivation (Tuong and Bouman, 2003), but there was some concern that rice cultivation with AWD has very low fertilizer-use efficiency. Apparent Nitrogen Recovery (ANR) actually showed no significant difference between AWD and CF. Conditions in this experiment were typical of coastal zone with the soil in the root zone remaining moist most of the time and the perched water table seldom deeper than 20 cm.

The mechanisms of hydrology and water chemistry in paddy fields are rather complex and are modified by management practices. It is therefore difficult to generalise about nutrient flows and to make progress with MFA there is a strong case for adopting a modelling approach. Existing models can predict daily ponded-water depth, surface drainage flow, and nutrient concentrations (see for example GLEAMS, Chung, Kim and Kim, 2003 and PADDIMOD, Jeon *et al.,* 2004).

Pesticides

Greenland (1997) notes that uniform planting of modern high-yielding rice varieties combined with multiple cropping has led to increasing pest problems and increasing use of herbicides, fungicides and insecticides. Quantities used, and therefore amounts released into the environment, are much less than for nutrients, but they represent a more serious cause for concern (Greenland, 1997; p 215). Phuong, (2002) reports that pesticide use is the main cause of environmental pollution in the Mekong delta and most water samples there contain residues.

In recent years modelling has become an integral part of the pesticide registration process and efforts have been made to develop suitable models for risk assessment in rice areas (Miao *et al.*, 2003; Karpouzas, Capri and Papadopoulou-Mourkidou, 2005, 2006; Karpouzas *et al.*, 2005; Inao *et al.,* 2001, 2003). As with nutrients, such models offer a way forward with MFA for pesticides. Field scale models such as RICEWQ (Williams *et al.,* 1999) or PADDY (Inao and Kitamura, 1999) can be used to simulate pesticide concentration in water and soil, but local pesticide runoff is not reflected in the wider aquatic environment as a result of degradation and adsorption by sediment. This requires coupling a field-scale pesticide fate model to a transportation model.

Such coupled models have been successfully tested against data derived from surface water and groundwater monitoring, but, because of the diversity of compounds actually used, this can be done only for selected representative pesticides. The same problem arises with MFA for pesticides, although Phuong (2002) proposes aggregating different types on the basis of a toxicity scale.

Greenhouse gases

As well as carbon dioxide, the other major greenhouse gases (GHGs) are methane and nitrous oxide, both of which are emissions from flooded rice fields, although only methane in amounts considered significant for global warming (Neue *et al.*, 1995). Rice is the only agricultural crop that emits methane that is produced by the anaerobic decomposition of organic matter in the soil. The processes governing methane emissions from rice fields are described by Kirk (2004), who reports that estimates of the source strength improved greatly in the past decade. Initial estimates in the 1980's assumed emission rates very much higher than current estimates, which are accepted by Intergovernmental Panel on Climate Change – IPCC (1997) as 200 kg CH_4 per hectare per season for "irrigated and continuously flooded lowland rice ecosystems". IPCC (1997) proposes scaling factors for drought-prone and flood-prone rice ecosystems of 0.4 and 0.8, respectively.

Wassman *et al.* (2000) reported a coordinated programme to collect field measurements on methane emissions from rice fields in five Asian countries. Even under identical treatment conditions of continuous flooding and no organic fertilizers, emission rates varied from 15 to 200 kg CH_4 per hectare per season, thus reflecting the influence of other environmental and management variables. Soil type, temperature, recycling of crop residues, cultivation practices and water management all influence methane emission rates.

Several models have been developed in recent years to estimate emission rates under specified conditions. Early models (Anastasi, Dowding and Simpson, 1992; Huang, Sass and Fisher, 1998) used tool pools to represent soil organic matter with differing potential decomposition rates and modified them to represent the influence of soil texture and temperature. Matthews, Wassman and Arah (2000) and Matthews *et al* (2000a, 2000b) developed the mechanistic MERES model based on CERES-Rice model. The DNDC model (Li, Aber and Stange, 2000) is a generic model of carbon and nitrogen biogeochemistry in agricultural ecosystems, which has been validated against field data from China, Japan and Thailand. As with other aspects of MFA such models offer the best prospect of achieving a differentiated picture of environmental impact of rice production systems.

Material flows in shrimp production systems

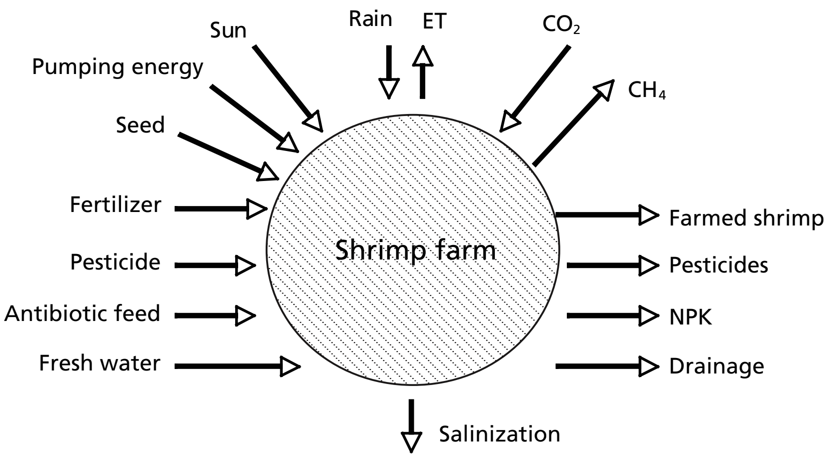
The shrimp farming production process has different types of environmental impacts that arise from the consumption of natural resources (land, water, seed and feed) and the subsequent release into the environment of waste products, chemical residues, parasites and feral animals (Beveridge, Phillips and Macintosh, 1997; Kautsky *et al.*, 2000). Effects may be direct, through release of toxic chemicals, the transfer of diseases and parasites to wild stock, and the introduction of exotic and genetic material into the environment, or indirect through loss of habitat and changes in food webs (Rönnbäck, 2001).

At the scale of the individual shrimp farming enterprise we can identify the environmental issues that are readily presented in terms of material flows (Figure 3):

Water use

Shrimp farming requires large amounts of clean water to support the farmed animals, replenish oxygen and remove wastes; each tonne of shrimp produced in intensive farms

FIGURE 3
Material flows in shrimp farming systems



requires about 50 to 60 million litres of water (Gujja and Finger-Stich, 1996). However, there is still a notion that water is a relatively free good. For example water use in the industry is always presented in percentage of exchange rate and, with the exception of a few cases, the amount of water is never related to production; as Clay (2001) reflects, we never hear about water conversion ratios in the shrimp farming literature. There is also the added issue in shrimp farming of the use of freshwater to reduce salinity; this water is then mixed with saline water and discharged as brackish water; in this case we can argue that this freshwater is totally consumed by the system. As argued by Brummet (2007) aquaculture systems differ from agriculture in that the water necessary to fuel the production system is not completely consumed by the system and, in some cases, the quality of water released is good and readily available for other uses. However, in the specific case of shrimp farming we can argue that is this is not the case. The use of earthen ponds increases evaporation and seepage. For example, ponds in sand/loam soils or under high temperatures have a very high evaporation and seepage; as much as 1 percent-3 percent of the pond volume may be lost per day (Kautsky *et al.,* 2000). Water loss by seepage and evaporation in Thailand averages 23 cm in the final month of the crop, compared with 103 cm for Indonesia and 58 cm in the Philippines (Kongkeo, 1997).

According to the experts the general trend around the world is to reduce water exchange rates. In Asia some operations use three percent or less water exchange per day and in Latin America five percent or less a day, down from 15 percent or more which was common in the past. BMP advised a 2 percent-3 percent exchange per day for traditional systems and 67 percent exchange per 130-day cycle in closed systems (Boyd, 2003) and also to base water exchange on objective reasons.

Super-intensive systems, such as Belize Aquaculture Ltd. – BAL (see page 9) are reported to be very water-efficient. There is no water exchange and most water is recycled. McIntosh *et al.* (1999) estimate that about 2 m^3 of water are required per kilogram of shrimp produced. Boyd and Clay (2002) support this figure; they observed a harvest of 22 675 kg of shrimp from a 1.6 ha pond. The pond was 2 m deep and had been filled 1.6 times. So a total of 51 200 m^3 of water was used, working out to 2.26 m^3 of water per kilogram of shrimp. This contrasts with water use in semi-intensive farms in Madagascar where Boyd *et al.* (2006) found that 94 318 m^3 of water was required for each tonne of shrimp produced; so 94.5 m^3 of water is needed for each kilo of shrimp produced.

In terms of freshwater use we know that in Taiwan Province of China (Taiwan PC), for example, 90 percent of pond water supply is mixed open sea water with underground freshwater; pond salinity is kept constant at 10-15 ppt pumping underground water

(Kongkeo, 1997). Other countries such as Indonesia, Philippines and Thailand also mix sea water with freshwater, although not in the proportions of Taiwan PC (46, 10 and 4 respectively). According to Barraclough and Finger-Stich (1996) in a Thailand district an average 33 m^3 of fresh-water per day is pumped in for each tonne of shrimp produced.

Nutrient and solid budget

Nutrient loading from shrimp farming effluent is widely seen as a key environmental management problem in semi-intensive and intensive ponds. Two components of shrimp farm discharges have particular potential to cause environmental degradation: nitrogen (N) and phosphorus (P). The main inputs of N and P are fertilizers and feeds that are applied to ponds to promote shrimp production (Boyd, 2003).

In a study of intensive shrimp farms in Thailand, Briggs and Funge-Smith (1994) found that 95 percent of the nitrogen and 71 percent of the phosphorus applied to the ponds was in the form of feed and fertilizers and only 24 percent of the nitrogen and 13 percent of the phosphorus was incorporated into the shrimp harvested. The remainder N and P was retained in the pond and ultimately exported to the surrounding environment. The authors report that effluent water contained 35 percent of the nitrogen and 10 percent of the phosphorus discharged and that a major portion of the nitrogen (31 percent) and most of the phosphorus (84 percent) was retained in the sediments.

Nitrogen waste presents particular problems because some dissolved N components are toxic to aquatic animals and must be maintained at low concentrations in the production pond itself (Lorenzen, 1999). N locked into sediments may be re-suspended and discharged when the pond is drained for harvesting. In the case of phosphorus waste there are concerns because phosphorus enrichment of surface waters may lead to eutrophication (Naylor *et al.,* 2000).

Several studies show that discharge loads are affected by many factors including water exchange rates, intake loads, management style and expertise, and farm design (Boyd, 2003; Jackson, Preston and Thompson, 2004; Teichert-Coddington, Martinez and Ramirez, N/D). There are also large seasonal differences for nutrient budgets. For example, Teichert-Coddintong, Martinez and Ramirez (ND) found in semi-intensive farms in Honduras that production was significantly higher during the wet than dry season, even though the total quantity of feed added to ponds was not different between the seasons. They concluded that the conversion of feed and protein to shrimp flesh was significantly more efficient during the wet season.

They also found, that nitrogen conversion ratios were directly correlated with feed conversion ratios. Nitrogen discharge from ponds increased linearly with increasing feed conversion ratios. The nitrogen conversion ratio was also correlated with percentage of nitrogen in the feed. The authors argued that nitrogen conversion is less efficient with increasing protein content of feed. In their study higher protein levels in shrimp feeds did not result in better feed conversion efficiency either.

To investigate the impact of farming intensity and water management on nitrogen dynamics Lorenzen, Struve and Cowan (1997) tested a conceptual mathematical model. The model was applied to Thai commercial shrimp farms and they found that assimilation by phytoplankton with subsequent sedimentation or discharge is the principal process of ammonia removal. When inputs of ammonia exceed the algal assimilation capacity, nitrification and volatilization of excess ammonia become significant. In terms of intensity the model shows that in low density farms (43 PL/m^2) almost all dissolved nitrogen (87 percent) is assimilated by phytoplankton and is either sedimented or discharged in particulate form. In high density farms (98 PL/m^2) total ammonia nitrogen (TAN) exceeds the capacity of phytoplankton for assimilation (only 54 percent is removed) and volatization and discharged dissolve nitrogen become an important removal process.

Antibiotic use

Recent studies have found that large number of antibiotics are used in the shrimp farming industry not only to treat diseases but also as prophylaxis (Gräslund, Holmström and Wahlström, 2003). Traces of antibiotics above European, Canadian and US permissible levels have been found in farmed shrimp since 1990 (Rönnbäck, 2002), but the most publicized case has been the detection in 2001 of chloramphenicol in farmed shrimp from China, Viet Nam and Southeast Asia imported into the European Union. This find prompted a food safety scare and product recall (SNI, 2005).

According to Holmström *et al.* (2003) a large number of antibiotics are used in Thai shrimp farming. The study found that 56 percent of the farmers interviewed used antibiotics, 86percent of them as a preventive measure and 27 percent as an antiviral. The study also found that several of the antibiotics used are antibiotics used in human medicine, a factor that can contribute to the risk of resistance development.

Le and Munekage (2004) surveying residues of antibiotics such as trimethoprim (TMP), sulfamethoxazole (SMX), norfloxacin (NFXC) and oxolinic acid (OXLA) in water and mud in shrimp ponds on mangrove areas in Viet Nam, found these antibiotics in all samples of both shrimp ponds and surrounding canals. Their results show antibiotics concentration varied widely between the water and the bottom mud. They found that the highest concentrations occurred in the mud (wet weight). Table 3 illustrates the difference in concentrations between water column and bottom mud.

Interestingly they also found that there is only a slight difference in the antibiotic concentrations between improved extensive ponds and intensive ponds. This is, according to the authors, an indication that the potential pollution by antibiotics in both types of shrimp ponds varies little. This is also the case in other studied locations where concentrations were quite high and do not vary much.

In a similar study (also in Viet Nam), Quan, Thanh and Van-Ha (2003) found much smaller concentrations of antibiotics, the results of this study however showed that only in the intensive system there is a clear difference in antibiotics concentration between water and mud. In the improved extensive system there was no clear difference in antibiotic concentration between water and mud. Authors' findings also showed two very important aspects, that antibiotic residues can be found not only in shrimp ponds but also in the surrounding areas and that antibiotic concentrations may vary greatly between water and mud.

It is also important to note that only 20-30 percent of antibiotics are absorbed by shrimp (Quan, Thanh and Van-Ha, 2003); so, a big percentage of antibiotics applied are released into the environment. Some types of antibiotics are able to stimulate growth of plankton and continue to be gradually accumulated through nutrient chains. Most antibiotics can exist for a long time in residues, leading to the development of some antibiotic resistant bacteria (Rönnbäck, 2002).

Energy use

Energy requirements and use in the shrimp farming industry are not very well documented. Normally the issue is addressed as an economic factor and the data

TABLE 3

Levels of antibiotic residues (ppm) in shrimp ponds water and mud,Viet Nam

Antibiotic	Water (surface layer)		Water (bottom layer)		Wet bottom mud (depth 5 cm)	
	Minimal level	Maximum level	Minimal level	Maximum level	Minimal level	Maximum level
TMP	0.08	1.04	0.08	2.03	9.02	734.61
SMX	0.04	2.39	0.04	5.57	4.77	820.49
NFXC	0.06	6.06	0.08	4.04	6.51	2 615.96
OXLA	0.01	2.5	0.01	2.31	1.81	426.31

(Adapted from Le and Munekage, 2004)

is presented as dollars spend on fuel (diesel) per crop (see for example: Valderrama and Engle, 2002), however authors such as Larsson, Folke and Kaustky (1994), Kausky *et al.* (1998) and Troell, (1997) give a good insight of the direct industrial energy requirements shrimp culture, these authors also describe other indirect energy requirements such as the fossil fuel energy needed to produce feed and fertilizer and to transport it to the shrimp farm. For example Larsson, Folke and Kaustky (1994) found that the total industry energy use of semi-intensive shrimp farm in Colombia was 669 GJ per ha of pond. According to this study the industrial energy input per J of edible protein is 40.3; the direct fuel energy per J edible protein is 13.9. This is comparable with other food production systems such as mussel culture (10) or vegetable crops 2-4 (Larsson, Folke and Kaustky, 1994, page 672)

We also know that every ton of shrimp harvested requires approximately 1.5 times as much industrial energy to rear as an equivalent amount of cage-cultured salmon (129-205 GJ/t) compared with 97-107 GJ/tonne of salmon (Folke and Aneer, 1988). For each kilogram (wet weight) of shrimp produced about 1.5 litre of diesel fuel is required, mainly to power the pumping of freshwater into the cultivation ponds (Larsson, Folke and Kaustky, 1994, p 671). To produce 1 J of edible shrimp protein requires GPP of 295 J, whereas 1 J of farmed salmon requires a solar energy subsidy as large as 1204 (Folke and Aneer, 1988).

According to Tyedmers and Pelletier, 2007 (this report) energy dependence of culture systems varies with intensity; this is typically a direct consequence of the high energy cost of providing feed inputs to intensive culture systems. Results from a super-intensive farm in Belize, however, show a different picture. According to Boyd and Clay (2002) the electricity required to produced 13 600 kg/ha/crop is 59 227.5 kWh/crop; so electricity for aeration will amount to 4.35 kW/h per kilogram of shrimp. The authors compare this number with their previous estimate for intensive farms in Thailand where the average production rate was 5 000 or 6 000 kg/ha, and electricity was about 4.5 kWh per kilogram of shrimp. These authors also reflect on the fact that pumping costs for the Belize Aquaculture production system were much less than for traditional shrimp aquaculture systems that use water exchange and that energy use for vehicles is much less per unit of shrimp production than for large semi-intensive ponds because much shorter travel distances are involved. With these considerations, the authors concluded that, it is likely that the intensive Belize Aquaculture production system uses less energy per kilogram of shrimp produced than the semi-intensive systems that are common throughout Latin America (Boyd and Clay, 2002). It is important to note here that these authors' results are specifically on the energy use for aeration and do not consider energy inputs needed to produce the feed; if these are considered the most likely outcome is that the super-intensive farm in Belize is using the same or more energy as used by intensive and semi-intensive systems.

DISCUSSION

A summary analysis of material flows in rice and shrimp production systems is presented in Table 4. Given the degree of variability within each of these systems, this should be seen as indicative and is presented here as a basis for comparing their environmental impacts. It can be seen that material flows do not differ greatly, but it should be noted that shrimp value is approximately 20x rice value (a tonne of shrimp vs a tonne of rice). Key points to emerge are:

- Due to the greater storage volume and need for regular exchange of stored water, shrimp systems use more water. However, only part is drawn from freshwater resources and if this component is considered alone, then water use is comparable with rice systems.
- Release of nutrients (N and P) into the wider environment is an issue only for more intensive systems and is much the same for both shrimp and rice production.

TABLE 4
Indicative material flows[6] (per season)

Material	Shrimp		Rice	
	Low intensity	High intensity	Low intensity	High intensity
Yield kg/ha	500 – 2 000	3 000 – 6 000	1 000 – 2 000	3 000 – 5 000
Water use[7] m^3/ha	50 000 – 100 000	150 000 – 300 000	10 000 – 50 000	10 000 – 50 000
Nutrients kg/ha	-	N 50-250 P 20-200	-	N 50-60 P 5-10
Bioactive[8] chemicals	-	?	-	?
GHG	?	?	200 kg/ha	200 kg/ha
Energy use	-	4.5 kWh per kg	-	-

- Release of bio-active chemicals is also an issue that affects only the more intensive systems. The nature of these chemicals differs between rice (pesticides) and shrimp (antibiotics). Quantities involved are much less than for nutrients and data on actual amounts released is problematic, but it seems likely that the two systems are broadly comparable.
- Release of greenhouse gases, particularly methane, is a significant issue for rice which has received considerable attention in the last decade such that good estimates of emissions are available. Equivalent data for shrimp systems is not readily available.
- Energy for pumping and aeration is an issue for more intensive shrimp systems. Energy use in rice production is closely related to the level of mechanisation of farm operations and therefore also tends to increase with intensity of the system.

The analysis presented here and summarised in Table 4 relates to the environmental performance of rice and shrimp production systems at the level of an individual farm enterprise. A comparative analysis of rice and shrimp farming sectors at a higher level of aggregation (regional or national) would include consideration of the whole production chain. Upstream considerations would include activities producing inputs such as fertilizers for rice and feed for shrimp. Downstream considerations would include activities of handling, storing and processing output. Such life-cycle analysis (LCA) may well change the comparative performance of the two systems. Mungkung *et al.* (2006) has shown that there are very important upstream and downstream issues in the shrimp production chain. In areas where shrimp farms depend on the capture of wild seed, the high mortality provoked in the by-catch species, can have a major consequences for biodiversity and capture fisheries production. For example in India and Bangladesh where the collection of wild *Penaeus monodon* seed supports the shrimp farming industry, up to 1 000 fish larvae and other shrimp fry are discharged for every penaid shrimp collected. Given that a yearly seed collection of one billion *P. monodon* in Southeast Bangladesh, the amount of by-catch destroyed is staggering (Primavera, 1998).

We have shown that it is possible to adapt MFA methodology to provide quantitative data on environmentally relevant flows, but this in itself does not provide a measure of the impact of these flows on the environment and also the associated environmental cost. Where guideline figures have been agreed, as in the case of nitrate levels in drinking water, then a basis exists against which performance can be judged. However, MFA does not provide a direct measure of degradation of the environment.

---

[6] Values are presented on area basis but yields are broadly similar for shrimp and rice production systems so conversion from basis of per hectare to per kg is the same for both.

[7] For shrimp production only part is fresh water (assume 25 percent)

[8] Antibiotics for shrimp production; pesticides for rice production.

The impacts of both rice and shrimp production on biodiversity are numerous from the alteration of wild fish and crustacean habitats due to modified water flows and quality, to the introduction of pathogens and parasites and the transfer of alien species. The sensitivity of environmental receptors and environmental risks should be considered alongside data derived from MFA in order to allow informed judgement of likely impact. Methodologies exist to assess assimilative capacity of the environment (Gowing, Tuong and Hoanh, 2006).

While the analysis has been presented here in comparative terms, it should be noted that we are not dealing with a simple either/or analysis. Both production systems exist in coastal zones but they exhibit distinctly different environmental requirements. Rice production systems occur within a fresh water environment, while shrimp production systems occur within saline/brackish environments, therefore they are not necessarily competing activities. Seasonal variation in the fresh/brackish interface within estuarine and deltaic environments may allow for alternating rice/shrimp co-production systems. Otherwise, conversion between the two alternative production systems will require environmental manipulation as in the case of the Mekong delta in Viet Nam. It then becomes important to consider both social and environmental impacts (Gowing *et al.*, 2006) since different stakeholders are likely to be affected differently. Poor people, whose livelihoods are at least in part dependent on access to common property resources, may well be disadvantaged by such change.

In presenting a comparative analysis, we have not considered prior land use, but one of the most widely reported environmental concerns of shrimp farming is the siting of ponds on fragile ecosystems such as mangroves According to some reports, globally, shrimp farming may be responsible for up to 25 percent of the mangrove clearance that has taken place since 1960 (Clay, 1996). In regions where shrimp farming has become important it is estimated that up to 50 percent of the mangrove destruction is due to shrimp aquaculture (FAO/NACA, 1995). Mangrove loss and its degradation has become one of the battlegrounds between local communities, environmentalists and the defenders of the shrimp farming industry.

CONCLUSIONS

The achievement of sustainable development in coastal zones will depend upon adoption of appropriate evidence-based policy particularly regarding land-use planning. The decision whether to promote rice and/or shrimp production systems will depend at least in part on an assessment of their environmental impacts. Material flow analysis (MFA) may have some merit in this context but two inherent weaknesses of the standard method are apparent. Firstly it considers only a limited number of materials and emissions. Secondly it depends upon the notion that the resultant impact of all inputs and outputs can be deduced from their aggregate mass. This ignores obvious differences in the environmental impact of different materials.

In order to make a meaningful comparison between shrimp and rice production systems, there is a need to modify MFA methodology to allow for consideration of disaggregated data on environmentally relevant flows. We have shown that this is achievable and much relevant information is available in published sources. A preliminary evaluation based on this information indicates that in general shrimp and rice production systems exhibit broadly similar material flows when considered at the level of the farm enterprise.

As proposed by Eriksson, Elmquist and Nybrant (2005), there is a need to adopt a systems analysis approach based on material flow models, which offer the best prospect of achieving a differentiated picture of variable production systems. Since the flows of resources and emissions depend greatly on environmental and management variables, there is no merit in attempting a generalised comparison of rice versus shrimp production systems. There is a strong case for an initiative to assemble a consistent set of models for this purpose and to test them against appropriate field data particularly referring to environmental effects and associated costs

REFERENCES

Anastasi, C., Dowding, M. & Simpson, V.J. 1992. Future CH4 emissions from rice production. *Journal of geophysical research–atmospheres,* 97 (D7): 7521-7525.

Atapattu, S. & Molden, D. 2006. Achieving food and environmental security: better river basin management for healthy coastal zones. In Hoanh, C.T.; Tuong, T.P.; Gowing, J.W. & B. Hardy (eds) *Environment and livelihoods in tropical coastal zones.* CABI, Wallingford, United Kingdom. pp 293-301.

Ayres, R.U. & Kneese, A.V. 1969. Production, consumption and externalities. *American Economic Review* 59: 282.

Barbier, E.B. & Cox, M. 2004. An economic analysis of shrimp farm expansion and mangrove conversion in Thailand. *Land Economics,* 80: 389-407.

Barg, U., Subasinghe, R.P., Willmann, R., Rana, K. & Martinez, M. 1999. Towards Sustainable Shrimp Culture Development: Implementing the FAO Code of Conduct for Responsible Fisheries (CCRF). In B.W. Green, H.C. Clifford, M. McNamara, & G.M. Montaño (eds) *V Central American Symposium on Aquaculture.* 18-20 August 1999, San Pedro Sula, Honduras Asociación Nacional de Acuicultores de Honduras (ANDAH), Latin American Chapter of the World Aquaculture Society (WAS), and Pond Dynamics/Aquaculture Collaborative Research Support Program (CRSP). Honduras, pp. 64-81.

Barraclough, S. & Finger-Stich, A. 1996. *Some ecological and social implications of commercial shrimp farming in Asia.* UNRISD, WWF Discussion Paper, Geneva, 71p.

Beveridge, H.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,* 228: 797-808.

Boulding, K.E. 1973. The economics of the coming spaceship earth. In H.E. Daly (ed.). *Towards a steady state economy.* Freeman, San Francisco, United States of America. pp. 3-14.

Bouman, B.A.M. & Tuong, T.P. 2001. Field water management to save water and increase its productivity in irrigated lowland rice. *Agricultural Water Management.* 49:11-30.

Boyd, C.E. 2003. Guidelines for aquaculture effluent management at farm-level. *Aquaculture,* 2 *226*: 101-112.

Boyd, C. E. & Clay, J. 2002. *Evaluation of Belize Aquaculture, Ltd: a superintensive shrimp aquaculture system.* World Bank, NACA, WWF and FAO Consortium Program on Shrimp Farming and the Environment, 17p.

Boyd, C.E., Corpron, K., Bernard, E. & Pengsang, P. 1994. *A nutrient budget of some intensive marine shrimp ponds in Thailand.* Aquaculture and Fisheries Management, 25: 789-811.

Boyd, C.E., Corpron, K., Bernard, E. & Pengsang, P. 2006. Estimates of bottom soil and effuent load of phosphorus at a semi-intensive marine shrimp farm. *Journal of the World Aquaculture Society,* 37: 41-47.

Browdy, C. L., Bratvold, D., Stokes, A. D. & McIntosh, R. P. 2001. Perspectives on the application of closed shrimp culture systems. In C.L. Browdy, & D.E Jory (eds) *The New Wave, Proceedings of the Special Session on Sustainable Shrimp Culture, Aquaculture* 2001. The World Aquaculture Society, Baton Rouge, United States of America, pp. 20–34.

Brummett, R.E. 2007. Comparative analysis of the environmental costs of fish farming and crop production in arid areas. 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. 221–228

Brunner, P.H., Daxbeck, H. & Baccini, P. 1994. Industrial metabolism at the regional and local level: a case-study on a Swiss region. In R.U. Ayres, & U.E. Simonis (eds) *Industrial Metabolism. Restructuring for Sustainable Development*. United Nations University Press, Tokyo, New York, Paris. pp. 163–193.

Burford, M.A.,Thompson, P.J., McIntosh, R.P., Bauman, R.H. & Pearson, D.C. 2003. Nutrient and microbial dynamics in high-density, zero-exchange shrimp ponds in Belize. *Aquaculture,* 219: 393-411.

Cabangon, R.J., Tuong T.P., Castillo, E.G., Bao, L.X., Lu, G., Wang, G., Cui, Y., Bouman, B.A.M., Li, Y., Chen, C. & Wang, J. 2004. Effect of irrigation method and N-fertilizer management on rice yield, water productivity and nutrient-use efficiencies in typical lowland rice conditions in China. *Paddy Water Environment.* 2(4): 195-206.

Cassman, K.G., Kropff, M.J. & Gaunt, J. 1993. Nitrogen use efficiency of rice reconsidered – what are the key constraints? *Plant and Soil.* 156: 359-362.

Cassman, K.G., Gines, G.C. & Dizon, M.A. 1996. Nitrogen-use efficiency in tropical lowland rice systems: Contributions from indigenous and applied nitrogen. *Field Crops Research* 47 (1):1-12.

Cassman, K.G., Peng, S., Olk, D.C., Reichardt, W., Doberman, A. & Singh, U. 1998. Opportunities for increased nitrogen use efficiency from improved resource management in irrigated rice systems. *Field Crops Research* 56: 7-39.

Chung, S.O., Kim, H.S. and Kim, J.S. (2003) Model development for nutrient loading from paddy rice fields. *Agricultural Water Management.* 62(1): 1-17.

Clay, J. 2001 *Aquaculture's environmental footprint. Some findings research on shrimp farming* Vancouver, pp.10.

Clay, J.C. 1996. *Market potential for redressing the environmental impact of wild captured and pond produced shrimp.* World Wildlife Fund, Washington,

Eriksson, I.S., Elmquist, H. & Nybrant, T. 2005. SALSA: a simulation tool to assess ecological sustainability of agricultural production. *Ambio.* 34 (4-5): 388-392.

Eurostat. 2001. Economy-wide material flow accounts and derived indicators. A methodological guide. Office for Official Publications of the European Communities, Luxembourg.

Eurostat. 2002. Material use in the European Union 1980–2000: Indicators and analysis. Office for Official Publications of the European Communities, Luxembourg.

FAO. 2002. *The state of world fisheries and aquaculture (SOFIA 2002).* FAO, Rome 150p.

FAO. 2003. *Review of the state of world aquaculture.* Inland Water Resources and Aquaculture Service FAO, Rome, 95p.

FAO/NACA. 1995. *Regional Study and Workshop on the Environmental Assessment and Management of Aquaculture Development (TCP/RAS/2253).* NACA Environmental and Aquaculture Development Series No. 1, Network of Aquaculture Centres in Asia-Pacific, Bangkok, Thailand., http://www.fao.org/docrep/field/003/AC279E/AC279E00.htm#TOCp.

Fischer, K.S. 1998. Toward increasing nutrient-use efficiency in rice cropping systems. *Field Crops Research* 56: 1-6.

Fischer-Kowalski, M. 1997. Society's metabolism, on the childhood and adolescence of a rising conceptual star. In Redclift, M. & G. Woodgate (eds) *The International Handbook of Environmental Sociology*, Edward Elgar, Cheltenham. pp. 119-137.

Folke, C. & Aneer, G. 1988. *Estimations of solar and fossil energy flows in Atlantic salmon (Salmo solar) aquaculture in the Baltic.* University of Stockholm, Stockholm, Sweden,

GAA. 1998 *Code of Practice for responsible shrimp farming (http://www.gaalliance.org/book.html).*

Gowing, J.W., Tuong, T.P. & Hoanh, C.T. 2006. Land and water management in coastal zones: dealing with agriculture-aquaculture-fishery conflicts. In C.T Hoanh, T.P. Tuong, J.W. Gowing, & B. Hardy (eds) *Environment and livelihoods in tropical coastal zones.* CABI, Wallingford, United Kingdom. pp1-16.

Gowing, J.W., Tuong, T.P., Hoanh, C.T. & Khiem, N.T. 2006. Social and environmental impact of rapid change in the coastal zone of Viet Nam: an assessment of sustainability issues. In C.T Hoanh, T.P. Tuong, J.W. Gowing, & B. Hardy (eds) *Environment and livelihoods in tropical coastal zones.* CABI, Wallingford, United Kingdom. pp. 48-60.

Gräslund, S., Holmström, K. & Wahlström, A. 2003. *A field survey of chemicals and biological products used in shrimp farming. Marine Pollution Bulletin,* 46: 81-90.

Greenland, D.J. 1997. *The sustainability of rice farming.* CABI, Wallingford, United Kingdom.

Grunbuhel, C.M., Haberl, H., Schandl, H. & Winiwarter, V. 2003. Socio-economic metabolism and colonization of natural processes in Sang Saeng village, Thailand. *Human Ecology* 31: 53-86.

Gujja, B. & Finger-Stich, A. 1996. *What price prawn? -Shrimp cultivation in Asia.* Environment, 38: 12-39.

Holmström, K., Gräslund, S., Wahlström, A., Poundshompoo, S., Bengtsson, B.-E. & Kaustky, N. 2003. *Antibiotic use in shrimp farming and implications for environmental impacts and human health.* International Journal of Food Science and Technology, 38: 255-266.

Huang, Y., Sass, R.L. & Fisher, F.M. 1998. A semi-empirical model of methane emission from flooded rice paddy soils. *Global Change Biology* 4: 247-268.

Inao, K. & Kitamura, Y. 1999. Pesticide paddy field model for predicting pesticide concentrations in water and soil in paddy fields. *Pesticide Science* 55: 38-46.

Inao, K., Ishii, Y., Kobara, Y. & Kitamura, Y. 2001. Prediction of pesticide behaviour in paddy field by water balance on the water management using pesticide paddy field model (PADDY) *Journal of Pesticide Science* 26: 229-235.

Inao, K., Ishii, Y., Kobara, Y. & Kitamura, Y. 2003. Landscape scale simulation of pesticide behaviour in river basin due to runoff from paddy fields pesticide paddy field model (PADDY) *Journal of Pesticide Science* 28: 24-32.

IPCC. Intergovernmental Panel on Climate Change. 1997. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, J.T. Houghton *et al.* IPCC/OECD/IEA, Paris, France.

IRRI. 2002. Rice Almanac, 3rd edition. Manila, International Rice Research Institute.

Jackson, C., Preston, N. & Thompson, P. J. 2004. *Intake and discharge nutrient loads at three intensive shrimp farms.* Aquaculture Research, 35: 1053-1061.

Jeon, J.H., Yoon, C.G., Ham, J.H. & Jung, K.W. 2004. Model development for nutrient loading estimates from paddy rice fields in Korea. *Journal of Environmental Science and Health Part B—Pesticides, Food Contaminants, and Agricultural Wastes.* B39 (5–6): pp. 845–860.

Jory, D. & Cabrera, T. 2003. *Marine Shrimp (chapter 19).* In J. Lucas & P.C. Southgate (eds) *Aquaculture: farming Aquatic Animals and Plants.* Blackwell Publishing, London, pp. 382-419.

Kaneki, R. 2003. Reduction of effluent nitrogen and phosphorus from paddy fields. *Paddy Water and Environment.* 1: 133–138.

Karpouzas, D.G., Ferrero, A., Vidotto, F. & Capri. E. 2005. Application of the RICEWQ-VADOFT model for simulating the environmental fate of pretilachlor in rice paddies *Environmental Toxicology and Chemistry.* 24 (4): 1007-1017.

Karpouzas, D.G., Capri, E. & Papadopoulou-Mourkidou, E. 2005. Application of the RICEWQ-VADOFT model to simulate leaching of propanil in rice paddies in Greece *Agronomy for Sustainable Development.* 25 (1): 35-44.

Karpouzas, D.G. , Capri, E. & Papadopoulou-Mourkidou, E. 2006. Basin-scale risk assessment in rice paddies: An example based on the Axios river basin in Greece. *Vadose Zone Journal* 5 (1): 273-282.

Kaustky, N., Folke, C., Rönnbäck, P. & Troell, M. 1998. The ecological footprint. A tool for assessing resource use and development limitations in aquaculture. *Dossier Echoes of Expo'98,* 11: 5-7.

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

Kautsky, N., Beveridge, M., Folke, C., Primavera, J. H., Rönnbäck, P. & Troell, M. 2000. Aquaculture and biodiversity. In S. Levin (ed.) *Encyclopaedia of Biodiversity*, Vol. 1 Academic Press, London, pp.185-198.

Kirk, G. 2004. *The Biogeochemistry of Submerged Soils.* John Wiley & Sons, Chichester, United Kingdom.

Kongkeo, H. 1997. Comparison of intensive shrimp farming systems in Indonesia, Philippines, Taiwan and Thailand. *Aquaculture Research,* 28: 789-796.

Larsson, J., Folke, C. & Kaustky, N. 1994. Ecological limitations and appropriation of ecosystem support by shrimp farming in Colombia. *Environmental management,* 18: 663-676.

Le, T.X. & Munekage, Y. 2004. Residues of selected antibiotics in water and mud from shrimp ponds in mangrove areas in Viet Nam. *Marine Pollution Bulletin,* 49: 922-929.

Li, C.S., Aber, J. & Stange, F. 2000. A process-oriented model of N2O and NO emissions from forest soils. *Journal of Geophysical Research – atmospheres,* 105: 4369-4384.

Li, C.S., Frolking, S., Xiao, X.M., Moore, B., Boles, S., Qiu, J.J., Huang, Y., Salas, W. & Sass, R. 2005. Modelling impacts of farming management alternatives on CO_2, CH_4 and N_2O emissions. *Global Geochemical Cycles.* 19(3): Art. No. GB3010.

Lorenzen, K. 1999. Nitrogen recovery from shrimp pond effluent: dissolved nitrogen removals has greater overall potential than particulate nitrogen removal, but requires higher rates of water exchange than presently used. *Aquaculture Research,* 30: 923-927.

Lorenzen, K., Struve, J. & Cowan, V. J. 1997. Impact of farming intensity and water management on nitrogen dynamics in intensive pond culture: a mathematical model applied to Thai commercial shrimp farms. *Aquaculture Research,* 28: 493-507.

Matthews, E., Amann, C., Fischer-Kowalski, M., Huttler, W., Kleijn, R., Moriguchi, Y., Ottke, C., Rodenburg, E., Rogich, D., Schandl, H., Schutz, H., Voet, E.V.D. & Weisz, H. 2000. The Weight of Nations, Material Outflows From Industrial Economies. World Resources Institute, Washington, DC, United States of America.

Matthews, R.B., Wassman, R. & Arah, J. 2000. Using a crop/soil simulation model and GIS techniques to assess methane emissions from rice fields in Asia. I. Model development. *Nutrient Cycling in Agroecosystems* 58: 141-159.

Matthews, R.B., Wassman, R., Buendia, L.V. & Knox, J. 2000a. Using a crop/soil simulation model and GIS techniques to assess methane emissions from rice fields in Asia. II. Model validation and sensitivity analysis. *Nutrient Cycling in Agroecosystems* 58: 161-177.

Matthews, R.B., Wassman, R., Knox, J.W. & Buendia, L.V. 2000b. Using a crop/soil simulation model and GIS techniques to assess methane emissions from rice fields in Asia. IV. Upscaling of crop management scenarios to national levels. *Nutrient Cycling in Agroecosystems,* 58: 201-217.

McIntosh, R.P., Drennan, D.P. & Bowen, B.M. 1999. Belize Aquaculture: Development of an intensive, sustainable, environmentally friendly shrimp farm in Belize. In Green, B.W. (ed.) *Acuacultura y Ambiente, juntos Hacia el nuevo milenio* pp.85-98.

Miao, Z., Padovani, L., Riparbelli, C., Ritter, A.M., Trevisan, M. & Capri, E. 2003. Prediction of the environmental concentration of pesticide in paddy field and surrounding surface water bodies. *Paddy Water Environ* 1:121–132.

Mungkung, R.T., de Haes, H.A.U. & Clift, R. 2006. Potentials and limitations of life cycle assessment in setting ecolabelling criteria: A case study of Thai shrimp aquaculture product. *International Journal of Life Cycle Assessment,* 11: 55-59.

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

Neue, H.U., Ziska, L.H., Matthews, R.B. & Dai, Q. 1995. Reducing global warming – the role of rice. *Geojournal* 35: 351-362.

Phuong, D.M. 2002. The impacts of pesticide use in rice production on aquaculture in the Mekong delta: a dynamic model. Report to economy and environment program for Southeast Asia (EEPSEA)

Primavera, J. H. 1998. Tropical shrimp farming and its sustainability. In S. de Silva, (ed.) *Tropical Mariculture*. Academic Press, London, pp.257-289.

Quan, T.Q.D., Thanh, N.K. & Van-Ha, M. 2003. Assessment of water quality change in shrimp farming ponds in the mangrove area of proposed Biosphere Reserve in the Red River Delta – A case study in Giao Lac Commune, Giao Thuy District, Nam Dinh Province.

Raux, P. & Bailly, D. 2002. Literature review on world shrimp farming. Individual partner report for the project: Policy research for sustainable shrimp farming in Asia. European Commission *INCO-DEV Project No. IC4-2001-10042.* CEMARE, University of Portsmouth, United Kingdom and CEDEM, Brest, France, 46p.

Rönnbäck, P. 2001. *Shrimp aquaculture - State of the Art.* Swedish EIA Centre, Swedish University of Agricultural Sciences (SLU), Uppsala, 58p.

Rönnbäck, P. 2002. *Environmentally sustainable shrimp farming.* Swedish Society for Nature Conservation, Stockholm, 25p.

Rosenberry, B. 2001. *World Shrimp Farming 2001.* Shrimp News International, San Diego, CA.

SNI. 2005. *http://www.shrimpnews.com/Chloramphenicol.html.* Vol. 2005 Shrimp News International. The Rise and Fall of Chloramphenicol.

Teichert-Coddington, D., Martinez, D. & Ramirez, E. (N/D) Characterization of shrimp farm effluents in Honduras and chemical budget of selected nutrients. Oregon State University, Oregon, 15p.

Troell, M. 1997. Searching for footprints. The concept of footprint is worthwhile tool for analysing different aquaculture production systems. *Samudra,* March: 26-28.

Tuong, T.P. & Bhuiyan, S.I. 1999. Increasing water-use efficiency in rice production: farm-level perspectives. *Agricultural water Management* 40 (1): 117-122.

Tuong, T.P & Bouman, B.A.M. 2003. Rice production in water-scarce environments. In J.W Kijne, R. Barker & D. Molden (eds) *Water productivity in agriculture: limits and opportunities for improvement.* CABI, Wallingford, United Kingdom. pp. 53-67.

Tyedmers, P. & Pelletier, N. 2007. Biophysical accounting in aquaculture: Insights from current practice and the need for methodological development. 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. 229–241

Valderrama, D. & Engle, C.R. 2002. *Economics of Better Management Practices (BMP) for semi-intensive shrimp farms in Honduras and shrimp cooperatives in Nicaragua.* World Bank, NACA, WWF and FAO, 53p.

Wassman, R., Buendia, L.V., Lantin, R.S., Bueno, C.S., Lubigan, L.A., Umali, A., Nocon, N.N., Javellana, A.M. & Neue, H.U. 2000. Mechanisms of crop management impact on methane emissions from rice fields in Los Banos, Philippines. *Nutrient Cycling in Agroecosystems* 58: 107-119.

Williams, W.M., Ritter, A.M., Cheplick, J. M. & Zdinak, C.E. 1999. RICEWQ: pesticide runoff model for rice crops, users manual and program documentation version 1.6.1. Waterborne Environmental, S. E. Leesburg, VA, United States of America.

World Bank, NACA,WWF & FAO. 2002. *Shrimp farming and the environment. A World Bank, NACA, WWF and FAO Consortium Program. To analyze and share experiences on the better management of shrimp aquaculture in coastal areas.* Published by the Consortium, 119p.

Yoon, C.G., Ham, J. & Jeon, J. 2003. Mass balance analysis in Korean paddy rice culture. *Paddy and Water Environment* 1: 99–106.