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Aquaculture Development and Global Carbon Budgets: Emissions, Sequestration and Management Options

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Executive Summary

Reviewing contributions to the Forth Assessment Report of the Intergovernmental Panel on Climate Change, Working Group I (IPCC, 2007a) noted that greenhouse gas concentrations in the atmosphere have ‘increased markedly as a result of human activities’ and that ‘most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to observed increases in anthropogenic greenhouse gas concentrations.’

Working Group I reported that long-term changes in climate have been observed at continental, regional and ocean basin scales, while Working Group II noted that anthropogenic warming has affected many physical and biological systems and that further impacts on natural and human systems are emerging (IPCC, 2007b). Furthermore, the Stern Review concluded that ‘Climate change threatens the basic elements of life for people around the world - access to water, food production, health, and use of land and the environment’ (Stern, 2007).

Against this backdrop, Working Group III noted that with respect to agriculture ‘There is no universally applicable list of mitigation practices’ and that ‘practices need to be evaluated for individual agricultural systems and settings’ (IPCC, 2007c). This paper aims to address the gaps between existing knowledge and decision-making needs with respect to aquaculture development and climate change.

Aquaculture has emerged as a major contributor to global food supplies, with annual finfish and shellfish production in 2000 reaching 23.2 and 12.4 million tonnes, respectively. Since 1970 total aquaculture output grew at an average of 8.9% per year until 2002, as compared with 2.8% for terrestrial livestock farming and 1.2% for capture fisheries over the same period (FAO, 2004). Moreover, despite rapid population growth, aquaculture production per capita increased from 0.7 kg in 1970 to 6.4 kg in 2002; the number of people economically active in the sector in 2002 was 9.8 million and production (including plants) was worth US$60 billion.

However, aquaculture, as with other agricultural activities, appropriates a wide range of ecological goods and services and where demand exceeds the environmental carrying capacity adverse impacts are observed. Furthermore, aquaculture development represents a potential threat to greenhouse gas sinks and reservoirs, whilst aquaculture practices constitute a largely undefined source of greenhouse gas emissions.

Studies concerning the characteristics and magnitude of direct energy consumption associated with aquaculture are reviewed and the significance of associated carbon emissions assessed; indirect emissions associated with embodied energy use in inputs are considered; emissions from land conversion and as a result of soil, water and waste management are discussed.

Farm centred strategies to reduce carbon and other greenhouse gas emissions associated with aquaculture development are reviewed, including: reduced energy use and fuel conservation; enhanced production efficiency; direct renewable energy use and electricity generation; biomass crops for onsite substitution; source renewable energy supplies; enhanced soil, water and waste management.

Opportunities to enhance aquaculture associated carbon sequestration in the landscape are considered. Strategies discussed include: exploiting organic matter accumulated in aquatic farming systems to build soil organic matter and carbon in marginal or agricultural land; enhancing *in situ* primary production and cultivation of green manure and fodder crops to enhance productivity and sequester carbon; increased tree cover and integration of biomass crops on farms; wetland restoration; horizontal integration; extractive aquaculture in freshwater and marine settings.

Reviewing past initiatives and assessing the current state of knowledge points to both farm level and strategic opportunities for the aquaculture sector to reduce carbon emissions and enhance carbon sequestration in aquatic ecosystems. Prospects for heightened awareness amongst policy-makers and consumers stimulating demand for carbon sensitive aquaculture and aquatic resources management strategies are discussed. The need to direct support payments, subsidies and grants to producers adopting carbon and climate sensitive aquaculture practices is highlighted, as is the need to remove the varied disincentives to adoption. A requirement for more information and demonstration initiatives to promote best practices is highlighted.

Policies, measures and instruments to encourage adaptive aquaculture development are reviewed. Financial incentives to encourage the adoption of mitigation and adaptation strategies in the aquaculture sector include the redistribution of support payments, subsidies and tax credits to responsible producers and the imposition of taxes and charges on carbon; regulation and standards introduced to curb carbon emissions and promote good practice can also be effective. Highlighting potential money-saving opportunities will help in promoting adaptation strategies with farmers, as will the prospect of capitalising on the growing demand for low-carbon products.

Carbon labelling to ensure consumers can identify low-carbon products is needed to ensure that responsible producers are able to benefit directly from potential price premiums associated with adopting mitigation and adaptation. However, such a strategy demands a standardised approach to auditing carbon budgets across the sector and between production types and individual farms, for the entire lifecycle of the product. Widespread adoption of carbon labelling across the aquaculture sector might impact badly on smaller and poorer producers that are unable to participate in certification schemes. To ensure that poorer people in developing countries are able to benefit through economic development, their right to ecological space and an equitable share of the right to emit carbon dioxide must be guaranteed.

1. Introduction

The contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007a) stated that 'Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years'[1] and that 'Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations.' Moreover, Working Group I reported that several long-term changes in climate have been observed at continental, regional and ocean basin scales, including 'changes in arctic temperatures and ice, widespread changes in precipitation amounts, ocean salinity, wind patterns and aspects of extreme weather including droughts, heavy precipitation, heat waves and the intensity of tropical cyclones.'

The report from Working Group II 'Climate Change 2007: Impacts, Adaptation and Vulnerability' (IPCC, 2007b) noted that 'A global assessment of data since 1970 has shown it is likely that anthropogenic warming has had a discernable influence on many physical and biological systems' and that 'Other effects of regional climate change on natural and human environments are emerging, although many are difficult to discern due to adaptation and non-climatic drivers.' Moreover, the Stern Review: The Economics of Climate Change (Stern, 2007) concluded that 'Climate change threatens the basic elements of life for people around the world - access to water, food production, health, and use of land and the environment.'

Working Group II also concluded that 'Future vulnerability depends not only on climate change but also on development pathway' and that 'Sustainable development can reduce vulnerability to climate change, and climate change could impede nations' abilities to achieve sustainable development pathways.' Discussing the mitigation of climate change, Working Group III (IPCC, 2007c) noted that 'Making development more sustainable by changing development paths can make a major contribution to climate change mitigation'. Furthermore, that 'Changes in development paths emerge from the interactions of public and private decision processes involving government, business and civil society…' and that 'This process is most effective when actors participate equitably and decentralized decision making processes are coordinated.' Working Group III also concluded that 'There are still relevant gaps in currently available knowledge regarding some aspects of mitigation of climate change, especially in developing countries' and that 'Additional research addressing those gaps would further reduce uncertainties and thus facilitate decision-making related to mitigation of climate change.' Working Group III noted that with respect to agriculture 'There is no universally applicable list of mitigation practices; practices need to be evaluated for individual agricultural

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[1] 'global increases in carbon dioxide concentration are due primarily to fossil fuel use and land use change, while those of methane and nitrous oxide are primarily due to agriculture.' (IPCC, 2007a)

systems and settings.' This paper aims to address the gaps between existing knowledge and decision-making needs with respect to aquaculture development and climate change.

The international policy agenda for reducing carbon emissions and increasing sinks was established under the 1997 Kyoto Protocol to the United Nations Framework Convention on Climate Change (UN, 1992). Furthermore, Article 4.1.d. of the Framework Convention notes that all parties shall 'Promote sustainable management, and promote and cooperate in the conservation and enhancement, as appropriate, of sinks and reservoirs of all greenhouse gases not controlled by the Montreal Protocol, including biomass, forest and oceans as well as other terrestrial, coastal and marine ecosystems'. Whilst Article 4.2.a. notes the commitment of 'developed country Parties and other Parties included in Annex I' to 'adopt national policies and take corresponding measures on the mitigation of climate change, by limiting its anthropogenic emissions of greenhouse gases and protecting and enhancing its greenhouse gas sinks and reservoirs.'

However, since the 1997 Kyoto Protocol a significant trend in world food supplies has emerged which demands consideration with respect to implementing the Framework Convention; the growing importance of aquaculture. Landings from marine capture fisheries are static, whilst finfish and shellfish farming expanded at rates of 9.1% and 5.8% per year between 1995 and 2000, reaching production levels globally of 23.2 and 12.4 million tonnes, respectively and farmed fish, crustaceans and molluscs represented 27% of global supplies in 2000 (FAO, 2002a; FAO, 2002b; Muir, 2005). Furthermore, FAO (2004) note that since 1970 total aquaculture output grew at an average of 8.9% per year until 2002, as compared with 2.8% for terrestrial livestock farming and 1.2% for capture fisheries over the same period. Furthermore, despite rapid population growth, aquaculture production per capita increased from 0.7 kg in 1970 to 6.4 kg in 2002; the number of people economically active in the sector in 2002 was 9.8 million and production (including plants) was worth US$60 billion (FAO, 2004).

Despite rapid growth, farming accounts for a small proportion of marine finfish, less than five percent in 2000, of that consumed by humans, and many consider continued expansion of aquaculture the only means to maintain or increase per caput protein supplies[2]. However, aquaculture, as with other agricultural activities, appropriates a wide range of environmental goods and services (Berg et al., 1996; Beveridge et al., 1997; Kautsky et al., 1997; Folke et al., 1998; Bunting, 2001a) and where demand exceeds the environmental carrying capacity adverse impacts are observed. Moreover further aquaculture development represents a potential threat to greenhouse gas sinks and reservoirs, whilst

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[2] It should be noted that aquatic foods do not necessarily readily substitute for meat and livestock products and that farming marine fish and shrimp can constitute a net protein consumer (see Naylor et al., 2000).

aquaculture practices constitute a largely undefined source[3] of greenhouse gas emissions. Carbon sources associated with aquaculture include: direct use of fossil fuels in production activities; indirect fossil fuel use, expressed as embodied energy; conversion of natural ecosystems or agricultural land; stock respiration and waste decomposition. Soil and water management as a result of aquaculture may also affect greenhouse gas emissions and sequestration.

2. Carbon sources and aquaculture systems

Studies concerning the characteristics and magnitude of direct energy consumption associated with aquaculture are reviewed and the significance of associated carbon emissions assessed; indirect emissions associated with embodied energy use in inputs are considered; emissions from land conversion and as a result of soil, water and waste management are discussed.

2.1. Direct energy consumption

Direct energy consumption constitutes the most obvious and widely assessed source of carbon emissions from aquatic farming. With greater intensity of production, dependence on external resources expands and financial performance is governed to a large extent by input availability and costs, including that of energy. Production in intensively managed systems in particular is vulnerable to fluctuating energy prices and interruptions in supply. However, in both developed and developing countries subsidised fuel costs for agricultural use and lower rates for commercial energy consumers mean farmers are to some extent protected, which has implications for reforms needed to address global climate change. Direct energy consumption in intensively managed aquatic farming systems, notably for shrimp and salmon, has been assessed most widely and is often contrasted with extensive seaweed and shellfish farming (Table 1), all classed as marine farming systems. However, the majority of global aquaculture production is of freshwater finfish from semi-intensively managed ponds in Asia, but audits of the associated direct and indirect energy use are not routine.

According to Folke and Kautsky (1989) direct energy consumption on cage-based salmon farms (fuel and power) amounted to 6 GJ per tonne of fish produced annually, accounting for 5.7% of energy consumption overall (Table 1); efficiency gains in salmon farming over the intervening period suggest more recent estimates of direct energy consumption would be lower. Larsson et al (1994) calculated energy requirements for semi-intensively managed shrimp farming in Columbia and estimated that direct energy consumption amounted to 55 GJ per tonne of production, accounting for 32.5% of total energy consumption. Higher direct energy consumption in shrimp farming as compared with cage-based salmon farming relates to the circulation and exchange of water in pond-based systems through mechanical pumping. Efficiency gains since the initial study might be expected, however, more recent

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[3] Article 1.9 of the Framework Convention on Climate Change states that a source ‘means any process or activity which releases a greenhouse gas, or aerosol or a precursor of a greenhouse gas into the atmosphere’ (UN, 1992).

assessments of industrial energy use in semi-intensive and intensive shrimp farming were not available.

2.2. Indirect or embodied energy consumption

Indirect or embodied[4] energy consumption is associated with: site development and construction; production, acquisition and supply of inputs; waste handling and disposal; product processing, marketing and distribution. Extensive aquaculture operations require little in the way of site development and construction; semi-intensive aquaculture systems including earthen ponds, wood and bamboo pens and cages and cove culture account for modest energy consumption in preparing the site and construction. Although depending on topography and vegetation cover, site development, in for example forested inter-tidal areas, necessitates greater energy consumption in site clearance and earthworks.

Most attention has focused on indirect or embodied energy consumption in intensively managed production systems, notably shrimp and salmon farming. Embodied energy is consumed in producing construction materials commonly used for intensive systems, for example, concrete, steel, plastic and nylon, however, estimates of the magnitude of this are largely absent from the literature; Folke and Kautsky (1989) estimated industrial energy consumption associated with capital investments for salmon farming based on the rate of depreciation, which equated to 3 GJ t^{-1} y^{-1}. Overall these authors estimated that direct and indirect industrial energy consumption in salmon farming equated to 105 GJ per tonne of production annually. Embodied energy associated with feed inputs (80 GJ t^{-1} y^{-1}) accounted for the largest proportion of industrial energy use in salmon farming, followed by energy use in rearing the juvenile salmon smolts stocked in the cages (12 GJ t^{-1} y^{-1}). More recent estimates suggest lower overall energy consumption, indicating improved efficiency; Muir (2005) noted industrial energy consumption for intensive, cage-based salmon culture was 56 GJ t^{-1} of production.

Within semi-intensively freshwater pond-based systems, from which a large proportion of aquaculture production is derived, inorganic fertiliser inputs account for increasing embodied energy use, especially as producers switch from local organic food processing residues and domestic and agricultural waste products, to concentrated inorganic fertiliser inputs; other inputs such as seed, chemical treatments, miscellaneous equipment and labour account for a relatively small proportion of embodied energy inputs.

Where fish meal is used in feed formulation, the embodied energy calculation often includes energy used in harvesting and processing fish from capture fisheries; applying the same principles with

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[4] Embodied energy here refers to industrial energy or energy derived from fossil fuels, as opposed to both renewable ecological and industrial energy assessed in some studies.

respect to products and waste originating from aquaculture results in higher estimates for associated energy consumption. Waste material and mortalities from the farm must be disposed of, and in some of the most elaborate market chains, products must be collected from the farm, processed and packaged (resulting in further waste streams demanding attention), distributed to retail outlets, sold and carried away and prepared by the consumer. Some products such as shrimp originating, for example, in India or Vietnam might be processed locally, but ultimately sold in European or North American markets, in the process accounting for energy consumption during air travel.

Table 1. Energy use in aquatic farming systems

Farming system	Industrial energy consumption (GJ t^{-1})		
	Direct energy	Indirect and embodied energy	Total[3]
semi-intensive shrimp farming[1]	55	114	169
salmon cages[2]	6	99	105
grouper/sea bass cages			95
carp, intensive recycle			56
salmon cages, intensive			56
trout ponds, feeding			28
catfish ponds, feeding			25
carp ponds, feeding and fertilizer			11

Notes: GJ equivalent to 277.8 kWh; 1 kWh from gas / diesel oil equivalent to 0.25 kg CO_2 or 0.068 kg C
[1] average converted from GJ ha^{-1} assuming production of 3.96 t ha^{-1} based on Larsson et al (1994)
[2] Folke and Kautsky (1989)
[3] Muir (2005) unless otherwise stated

2.3. Land conversion

Land-based aquaculture development often occurs in low-lying, wetland areas and from the perspective of greenhouse gas emissions such areas often constitute important reservoirs and sinks. According to Thom et al. (2001) benthic aquatic vegetation (algal beds, mangroves, marshes, reefs, seagrasses and swamps) accounts for 5.6% of global net primary production, whilst coastal systems, including up-wellings, account for 7% of carbon fixation globally.

Considering tropical coastal aquaculture development, perhaps the most controversial issues is the often associated loss of mangrove forests. Based on changes in mangrove forest cover over two decades, Valiela et al. (2001) estimated, in countries where historical data permitted, that of the 35% of mangroves lost, aquaculture development accounted for just over half (18.2%) of the forest area lost (13.3% for shrimp culture and 4.9% for fish culture). Trees were routinely felled and burned and the rich, organic soils which characterise mangrove areas excavated for pond construction; machines and labour for conversion make a further contribution to emissions.

Considering the productivity of mangroves, Clough (1992) noted average dry weight aboveground wood accumulation and litter-fall rates of 20 and 8 t ha^{-1} y^{-1}, respectively, for *Rhizophora* dominated forests. Alongi (1998) reported aboveground net primary production rates for mixed *Rhizophora* spp. forests in New Guinea and Indonesia ranging from 9.9-37.9 t dry weight ha^{-1} y^{-1}. Furthermore, Robertson and Phillips (1995) suggested that below-ground production of fine root material could be equivalent to total aboveground net primary production equating to 28 t ha^{-1} y^{-1}. However, estimates of below-ground production in mangroves are difficult owing to problems with obtaining representative samples and difficulty in distinguishing between living and dead root material; many mangrove species also exude organic matter from their roots, rates of which have not been widely estimated. Robertson et al. (1992) reviewed the literature on mangrove productivity and reported that average above-ground net primary production for a mangrove forest in Missionary Bay, northeast Australia equated to 14.8 t C ha^{-1} y^{-1} and that the standing stock of carbon in above-ground living biomass was 190 t C ha^{-1}.

Caution is required when extrapolating from average production values, as mangrove forests vary hugely in their composition and the physiology of their constituent trees, even within mangrove stands there is often a complex mosaic of vegetation associated with zonation and patch-dynamics. Assimilation of nutrients within mangroves buffers marine ecosystems against excessive or highly variable nutrient levels, whilst subsequent export of organic matter contributes to sustaining complex food-webs, and therefore biodiversity, in near-shore ecosystems. However, the extent of this buffering-capacity and indeed the overall role of mangroves in coastal ecosystem nutrient and carbon budgets are influenced strongly by the prevailing hydrological regime (Woodroffe, 1992).

Despite discernable environmental and social impacts, a recent report by the United Nations Environment Programme (UNEP, 2006) suggested that converting mangrove forests to aquaculture ponds resulted in limited net changes in terms of carbon sequestration; assessing the conversion of mangroves to shrimp ponds in Thailand the report stated that ‘The global benefits of carbon sequestration were considered to be similar in intact and degraded systems’. This seems difficult to reconcile against the apparent high rates of net primary production and standing stocks for mangroves, as compared with likely net primary production and standing stocks in degraded mangrove systems and shrimp ponds.

Described sometimes as ecologically equivalent to mangroves, salt marshes in temperate regions have been subject to pressure from aquaculture development, however, the extent of conversion has been far less than for mangroves. Gabriel and de la Cruz (1974) reported that the maximum dry-weight standing stock (alive, dead and partially decayed plants) of a salt marsh community in the St. Louis Bay Estuary, Mississippi was 15.9 t ha^{-1} and that net community production was 10.5 t ha^{-1} y^{-1};

literature reviewed by the authors revealed primary production rates for salt marshes in North America ranging from 4.5 to 28.8 t ha^{-1} y^{-1}. Pomeroy et al. (1981) reported total primary production for a salt marsh on the Duplin River, Georgia, equivalent to 1.45 t C ha^{-1} y^{-1}. It is likely that the standing stock and assimilation rate in most temperate coastal aquaculture systems are much lower. Therefore, conversion of large areas could make a contribution to net greenhouse gas emissions, although this is unlikely as development in salt marsh areas is increasingly subject to control. However, a more comprehensive review of carbon dynamics in temperate and tropical coastal aquaculture systems would help establish more clearly the likely magnitude of change in carbon dioxide standing stock or assimilation associated with either salt marshes or mangrove conversion.

Most other aquaculture development has occurred in agricultural areas where the net change in carbon sequestration depends largely on the type of farming being replaced. Soil carbon levels under intensive and continuous cereal cultivation in Australia and the USA declined on average by between 0.21 and 0.42 t ha^{-1} y^{-1} over several decades (Rasmussen et al., 1998); erosion and biological oxidation remove carbon from soils. Conversely, intensive arable production employing zero-tillage can result in the accumulation of 0.3 to 0.6 t C ha^{-1} y^{-1}, and combined with mixed rotations and cover crops this can increase to between 0.66 and 1.3 t C ha^{-1} y^{-1} (Pretty and Ball, 2001).

Carbon sequestration with different land-uses and with land-use change was reviewed by the IPCC (2000). Improved management of rice paddies was predicted to achieve a net change in the carbon stock of 0.1 t ha^{-1} y^{-1} whilst wetland restoration was estimated to contribute to a net change of 0.4 t ha^{-1} y^{-1}. Assuming rice paddies subject to improved management covered 150 million hectares and restored wetlands covered 230 million hectares it was estimated that the total net change in carbon stocks in 2010 would be 7 and 4 million t C y^{-1}, respectively. For comparison it was estimate that the net change in carbon stocks from land-use change to agroforestry would be 3.1 t ha^{-1} y^{-1} and that with a potential area for conversion of 630 million hectares this would equate to 390 million t C y^{-1} in 2010. Furthermore, improved grazing land, forest and cropland management were estimated to result in net changes in carbon stocks of 240, 170 and 125 million t C y^{-1} in 2010, respectively.

2.4. Soil, water and waste management

Sediment management in pond-based aquaculture systems can have a significant affect on the accumulation of carbon and release of greenhouse gases. Without management sediments tend to accumulate in the deeper parts of ponds, reducing the water volume available for cultivation and through various processes negatively impacting on water quality. Accumulation of organic carbon in pond sediments promotes anaerobic conditions at the sediment-water interface leading to the evolution of toxic microbial metabolites and disruption to benthic communities. Commonly, to avoid such problems, ponds are periodically drained with accumulated sediments left exposed to the atmosphere to promote organic matter mineralization, tilling is also sometimes employed to promote more rapid oxidation, and lime is routinely applied to increase pH and disinfect the pond; liming also neutralises acidity and increases total alkalinity and hardness (Xinglong and Boyd, 2006). Exposure of pond sediments can result in a loss of soil carbon through microbial processes as carbon dioxide, however, failure to manage sediments can result in the evolution of more damaging greenhouse gases, notably methane.

Where excessive accumulation occurs sediments are often excavated and removed. Application of excavated sediments to degraded or agricultural land could contribute significantly to building soil organic matter and carbon stocks and raising nutrient levels and concomitantly productivity. Traditional farming practices including *chinampas* in Mexico, dike-ponds in China and dike-canals in Vietnam, relied on the excavation and land-application of accumulated sediments to boost fertility and sustain production.

Over the past decade rice-fish culture has become more widespread and is increasingly perceived and promoted as a means to achieving: enhanced resource use efficiency; improved rice yields using fewer pesticides; increased animal protein production; better livelihoods for producers; greater food security within communities; ecological restoration (Halwart and Gupta, 2004). However, from the perspective of global warming, Frei and Becker (2005) noted that introducing fish to experimental rice plots resulted in reduced photosynthesis in the water column, explained by phytoplankton grazing and increased turbidity; resulting in lower dissolved oxygen levels, decreased pH and increased methane emissions. Methane production was promoted by the development of anaerobic sediments and emissions increased by the release of soil-entrapped methane owing to the activity of fish. However, prior to extrapolating these findings and drawing broad conclusions, more research is required to verify these results in field-based trials and to assess the dynamics of other emissions from paddy fields stocked with fish.

Considering flow-through and open-water culture systems options for sustainable sediment management are less well defined. Flow-through systems result in the loss of organic matter and carbon to the environment unless treatment is employed; various filters and settlement chambers have been successfully employed which retain a significant proportion of solids entrained in aquaculture wastewater. However, sludge disposal often constitutes a financial burden and poor management of the process can result, ultimately, in a significant proportion of the retained nutrients being released as diffuse pollution to the environment. Sludge can be spread on agricultural land, Bergheim et al. (1998) applied de-watered sludge from land-based Atlantic salmon (*Salmo salar*) smolt farms in Norway to agricultural land, however, the cost of sludge management including sieving, settlement and stabilization amounted to 5% production costs, whilst the concentration of zinc and cadmium were a cause for concern with respect to regulatory limits for unrestricted agricultural use. Moreover, sludge from marine aquaculture systems is only suitable for application on marginal land or at very low application rates on more productive land to avoid problems with salinisation. Costa-Pierce (1996) proposed applying solids collected from under cage-based farms to regenerate and enhance coastal areas, however, such applications would need to be balance against natural processes to avoid undesirable habitat change.

Stock respiration and waste decomposition also contribute to carbon emissions to the surrounding environment and potentially the release of greenhouse gases to the atmosphere. Forsberg (1997) reported that carbon dioxide excretion from fasting 2 kg Atlantic salmon was 0.9 mg CO_2 kg^{-1} min^{-1}, rising to 2.1 mg CO_2 kg^{-1} min^{-1} after maximal feeding; equating to a post-prandial excretion rate of 17 g CO_2 MJ^{-1} of feed. Decomposition of waste feed, faeces and mortalities will contribute further to the release of greenhouse gasses from the system, however, appropriate management could help reduce such emissions, whist controlled digestion could actually contribute to on-site energy production (see Section 3.7).

2.5. Discussion

The limited number of studies, and varied scope and methodology of those that have been conducted, make it difficult to present a fully comprehensive and contemporary review of aquaculture development and associated carbon budgets. Pretty and Ball (2001) noted a similar difficulty having reviewed audits for soil carbon in agriculture, variations in the audit methodology, farming systems and approaches to reporting made comparisons and therefore conclusions problematic. With greater emphasis on the comparative energy efficiency and greenhouse gas emissions of different economic sectors, heightened awareness amongst consumers, and prospects of higher non-renewable energy prices and charges for greenhouse gas emissions, standardised approaches to auditing aquaculture carbon budgets and reporting are required.

The ecological footprint approach has been applied to aquaculture in various settings (Larsson et al., 1994; Berg et al., 1996; Folke et al., 1998; Bunting, 2001a). Comparisons between intensive and semi-intensive systems based on the area occupied by the physical infrastructure have implied that semi-intensive systems have smaller ecological footprints (Robertson and Phillips 1995; Berg et al. 1996) however reassessment based on per unit production indicated that natural resource use efficiency may be highest in more intensive systems, although not for all goods and services (Bunting, 2001a).

Berg et al. (1996) estimate that 1 m^2 of semi-intensively managed pond aquaculture producing tilapia requires a pond area of 0.9 m^2 for phosphorus assimilation and 0.5 m^2 for oxygen production. However, when considering tilapia production in 1 m^2 of intensively managed lacustrine cages it was estimated that an ecosystem area of 115 m^2 and 160 m^2 was required for phosphorus assimilation and oxygen production, respectively. Robertson and Phillips (1995) quantified the area of mangrove required to assimilate the excess nitrogen and phosphorus present in the wastewater and sediments produced by semi-intensively managed shrimp ponds in Tra Vinh Province, Vietnam and intensively managed ponds in Chantaburi Province, Thailand. It was estimated that the nitrogen and phosphorus discharged from 1 ha of semi-intensive shrimp ponds could be assimilated in 2.5 ha and 3.4 ha of mangrove forest, respectively. The nitrogen and phosphorus discharged from 1 ha of intensive shrimp ponds was estimated to be assimilated in 7.2 ha and 21.7 ha of mangrove forest, respectively.

Assessments regarding the ecological footprint for carbon assimilation from aquaculture were not routinely included in the studies mentioned above. Larsson et al. (1994) estimated that production of shrimp in semi-intensively managed ponds in coastal mangroves, required an area of forest 0.8-2.5 times larger than the culture system to assimilate carbon dioxide released during the semi-intensive production of shrimp on the Colombian coast. The larger estimate took into account indirect energy consumption associated with investment, labour, pelleted feed and post-larvae inputs. Considering efficiency gains in many aspects of shrimp farming over the past decade it is likely that the ecological footprint of the system would now be smaller. However, such assessments are not straightforward as data on many aspects of production must be extrapolated from secondary sources and production efficiency is likely to vary considerably between different farming systems.

Inconsistencies in the way energy consumption and resource use studies are conducted and reported constitute major impediments to assessing the relative performance of different aquaculture systems and farming sectors. Adopting a Life Cycle Analysis approach and reporting energy consumption, greenhouse gas emissions, resource use and ecological footprints per unit area, production, protein yield and monetary value might help in drawing out more useful comparisons. However, even so this fails to account for broader socio-economic, including health and wellbeing, attributes and impacts of differing farming systems. Agreement on a standardised protocol would help avoid this problem, potentially certification schemes, producer associations and governments could set standards for such studies, but more general agreement may be unrealistic.

3. Farm centred approaches to reducing emissions

Strategies to reduce carbon and other greenhouse gas emissions from agriculture and enhance carbon sinks on farms have been identified (Lal et al., 1998; Robertson et al., 2000; USDA, 2000; Pretty and Ball, 2001), but options for aquatic farming systems have not been widely assessed. Cognisant of differences between terrestrial and aquatic farming, options open to individual aquaculture producers are summarised in Table 2 and discussed further below.

3.1. Reduced energy use and conserving fuel

Reducing direct and indirect fossil fuel use through substitution and improved energy efficiency offers a potential strategy for farms to reduce carbon emissions. Employing low carbon emitting building materials, wood, plastic and fibreglass as opposed to cement, and using recycled materials, for example, motorway crash-barriers, to construct tanks would contribute to reduced emissions. Sourcing inputs (feed, seed and fertiliser) locally, employing inputs with lower embodied energy, for example, organic as opposed to inorganic fertiliser, onsite processing and selling to local markets would further reduce indirect energy consumption. Vertical integration, reducing overheads and making the most efficient use of infrastructure, equipment and labour, can help reduce carbon emissions, whilst on-site seed and feed production, processing and direct marketing and sales, could contribute further to lowering carbon emissions, in particular those associated with transport. Further enhancements in energy efficiency can be achieved using practical approaches: staff training; improved command and control processes; energy efficient lighting and equipment use; correctly rated pumps and motors; judicious machinery use and good engineering.

3.2. Enhanced production efficiency

Good farm management, and critically the efficient conversion of resource and energy demanding formulated feeds to animal biomass, would minimise unnecessary carbon emissions. Food conversion efficiency, often expressed as the Food Conversion Ratio can be enhanced through good site selection, adopting optimal feeding strategies, ensuring good husbandry (proactive disease and pest management, high animal welfare standards, regular grading and careful handling) and selective breeding programmes. Care should be paid, however, to ensuring steps to optimise production efficiency do not have adverse consequences; excessive use of disease or pest control chemicals can impact on public, animal and environmental health, whilst elimination of competitors or predators could lead to biodiversity loss (Beveridge et al., 1996; Howgate et al., 2002) and adverse social impacts, as many poor communities, particularly in south and southeast Asia depend of small indigenous fish species for food security and livelihood opportunities.

3.3. Direct renewable energy use and electricity generation

Fossil fuel consumption and consequently carbon emissions could be reduced significantly by investing in onsite micro-generation of power, electricity or heat from renewable sources. Installing photo-voltaic, wind or water powered electricity generation equipment could reduce fuel use and surplus electricity could potentially be sold. Increasingly, pico- and micro-hydroelectric generation is being promoted as a viable renewable energy source, especially in rural settings where connection to mains electricity or gas is problematic, however, loss of hydraulic head associated with generation may impact on the nature and extent of the associated aquaculture activity. Traditional farming practices, notably fishponds flushed by tidal exchange or water from reservoirs filled during high tides, such as those on the Atlantic coast of France, avoid fossil fuel and energy use, but have a limited carrying capacity and require more space than energy intensive systems; tidal barrages and reservoirs are increasingly advocated for power and electricity generation in their own right, but suitable sites may be limited and development contested. Structures associated with proposed offshore electricity generation exploiting wave and wind power have also been suggested as suitable sites for aquaculture production, however, the logistics of this have yet to be fully assessed. Moreover, the energy requirements of offshore aquaculture units could potentially be supplied through appropriately sized wave, wind or solar powered systems.

Where accessible, geothermal energy for heating culture water, helps increase growth rates, especially throughout cold winter months, and contributes towards lower non-renewable energy consumption; although energy is often still required to extract and circulate the heated water. Geothermal aquaculture is practiced throughout the western United States, farmers in California, Idaho, Oregon and Utah culture tilapia, catfish, alligators and ornamental fish, coral and plants; abalone, trout and juvenile salmon are raised using geothermal energy in Iceland; geothermal energy use for aquaculture in China is reportedly expanding rapidly.

However, competition for renewable energy resources is likely to intensify, especially in response to meeting rising demand from domestic, manufacturing and service sector consumers, who may be willing to pay more for ‘clean energy’. Geothermal aquaculture could proliferate in remote locations where other energy users are absent or the cost of electricity generation and transfer is prohibitive, but relative energetic and cost benefits would demand assessment with respect to sourcing other inputs and marketing. Aquaculture exploiting residual heat in wastewater from geothermal electricity generation or other geothermal energy users such as horticulture has been developed. However, possible negative impacts associated with such arrangements must be considered, for example, chemical use upstream or variations in the quality and temperature of discharge water, and appropriate management strategies developed accordingly.

Recent advances in the design and efficiency of ground source heat pump technology should also be assessed as this might constitute a dependable source of heat energy to enhance aquaculture production, especially in temperate areas where low ambient air temperatures might currently limit production or necessitate the consumption of non-renewable energy. Fuller (2007) reviewed passive and active solar technologies to reduce energy consumption in aquaculture, employing a greenhouse reduced conventional energy requirements in hot dry climates and cooler temperate climates by 87% and 66%, respectively. Biomass production and use in energy generation also holds promise for aquaculture producers and is discussed further below.

3.4. Biomass crops for onsite substitution

Biomass crops cultivated onsite and used to substitute for direct fossil fuel and electricity use offer a potential cost saving and strategy to reduce net carbon emissions. Furthermore, using unexploited waste resources, nutrient rich water or sediments, to enhance production could contribute further to environmental protection. Several approaches to treating aquaculture wastewater with constructed wetlands planted with various macrophytes (reeds, mangrove fern, mangrove trees, halophytes) have been proposed.

Schwartz and Boyd (1995) assessed using reedbeds to treat water from a channel catfish pond. Two cells, measuring 84 m long and 14 m wide, were constructed in series; the first was planted with California bulrush (*Scripus californicus*) and giant cutgrass (*Zizaniopsis miliacea*); the second with Halifax maidencane (*Panicum hemitomon*). Treatment performance was best with vegetated cells with a hydraulic retention time of 4 days; suspended solids, total nitrogen and total phosphorus mass loadings of 34.6, 4.8 and 0.16 kg ha^{-1} were reduced by 31.4, 3.1 and 0.14 kg ha^{-1}, respectively. However, good pollutant removal rates were also recorded with shorter retention times and when the vegetation was dormant. The authors recognised that the large area of land required to treat wastewater discharged from aquaculture can be a limitation.

Large wetland areas used to treat aquaculture wastewater could be justified through the integrated production of additional crops, for example, fish, plants or crustacea. Valliculture practices in the northern Adriatic, described by Melotti et al. (1991) utilised wastewater from the intensive culture of seabass (*Dicentrarchus labrex*) and seabream (*Sparus aurata*) to fertilise areas for the extensive culture of seabass, seabream, mullet (*Mugil* spp.) and eel (*Anguilla anguilla*). The authors noted that the mean harvest weight for mullet increased significantly following wastewater reuse from 302g in 1987, to 375g in 1990; however, at the same farm, mean harvest weights for seabass declined significantly, from 525g to 422g. It was also proposed that wastewater reuse in extensive culture systems could reduce coastal zone pollution, although no change was recorded in nutrient levels in neighbouring coastal waters.

Although several studies have assessed the possibility of using macrophytes for aquaculture wastewater treatment, the potential of using the resulting biomass for onsite power or electricity generation has only been considered to a limited extent. Bunting (2001b) estimated the energetic and financial value of reed biomass cultivated in a constructed wetland receiving smolt unit wastewater but not the potential of onsite use in offsetting carbon emissions. The author concluded that a 11.38 ha wetland would be required to treat the wastewater from a unit producing 100,000 smolts annually, and that with aboveground biomass production of 29 t ha^{-1} y^{-1} (Li et al., 1995) the wetland would yield 330 t of biomass annually. Björk and Granéli (1978) estimated that reed biomass had an energy content of

5 MWh t^{-1}, consequently, the overall reed biomass has an energy content of 1,650 MWh, energetically equivalent to 130.2 t of diesel oil (12,668 kWh t^{-1}), use of which would emit 412.3 t CO_2 or 112.2 t C (Carbon Trust, 2006).

3.5. Source renewable energy supplies

Vehicles, boats, machinery and generators converted to run fully or partially on renewable biofuels such as biomass, bioethanol, biobutanol, biogas, straight or waste vegetable oil and biodiesel could contribute to a marked reduction in direct fossil fuel use. Biodiesel is increasingly being manufactured on a commercial scale and can often be used with only minimal adjustments to conventional diesel engines. Biomass crops can simply be burnt to generate heat or converted through gasification or anaerobic digestion to produce combustible gases. With increasing liberalisation in energy supply markets globally it is sometimes possible to elect to buy electricity generated from renewable sources, thus reducing carbon emissions and stimulating investment in off-site renewable energy generation.

3.6. Reduce inorganic fertiliser and pesticide inputs

Increasingly, traditional aquaculture production systems based on livestock manure inputs or by-products from agricultural production and processing are undergoing intensification, with farmers opting to use inorganic fertilisers (Wong Chor Yee, 1999; Bunting et al. 2002). The reasons for this are probably multifaceted. Farmers may perceive inorganic fertilisers as more manageable and uniform in terms of nutrient content and quality, others may no longer have access to manure or by-products owing to changes in prevailing farming systems and processing arrangements, and efficiency gains resulting in less wastage. There may also be environmental and public health concerns associated with the reuse of waste resources that force producers to switch to sanitised inorganic fertiliser inputs. Farmers will also be cognisant of the immediate financial costs involved with switching to inorganic fertilisers, although this decision may be influenced, in some cases, by the subsidised nature of inorganic fertiliser inputs, a mechanism often employed by governments to stimulate and sustain more intensively managed agriculture. Where inorganic fertilisers are employed there is a danger that aquaculture systems might become limited by trace elements, although no systematic review has been undertaken; continued use of organic fertiliser inputs would help avoid this.

Bhat et al. (1994) noted that nitrogen fertilizer manufacture required, depending on the type of fertilizer and production efficiency, between 51-68 MJ of energy per kilogram. With recommended fertiliser application rates for semi-intensive tilapia production in ponds ranging from 2-4 kg N ha^{-1} d^{-1} (Lin et al., 1997) conversion to organic production could save 37.2-99.2 GJ ha^{-1} y^{-1} of industrial energy and avoid associated greenhouse gas emissions. Adopting organic production or integrated pest management approaches would also avoid industrial energy use in pesticide manufacture.

Table 2. Farm centred strategies to reduce carbon emissions and enhance sinks

Strategy	Options	Practical actions
Reduced emissions	- reduce energy use and conserve fuel	- reduce machinery use; utilise energy efficient lighting, pumps, and machinery; avoid waste through raised awareness amongst workforce and staff training; better command and control; fit insulation
	- adopt less energy demanding, more resource efficient culture practices	- ensure good site selection; reduce stocking densities; improve stock fitness; optimise feeding; minimise disease, pest and predator problems
	- invest in onsite power generation from renewable sources	- solar, wind, geothermal, water, tide, wave, biomass
	- switch to renewable energy supplies	- convert machinery, boats, vehicles to run on renewable energy sources e.g. bio-diesel; switch to renewable energy supplier
	- cultivate biomass crops using waste resources for on-site substitution	- constructed wetlands to treat and reuse wastewater to cultivate biomass crops; cultivate additional crops as biofuels
	- reduce inorganic fertiliser inputs	- use waste resources and green manures; optimise fertiliser use efficiency
	- enhanced waste management to avoid greenhouse gas emissions	- digest waste, using methane production for energy production
	- manage water and soil to reduce carbon and greenhouse gas emissions	- treat wastewater to retain carbon, manage soils to reduce mineralization, capture carbon in integrated farming systems
Enhanced sinks	- enhance soil organic matter conservation	- reduce organic matter mineralization; utilise accumulated sediments to improve degraded or poor soils
	- cultivate green manures, leguminous and oilseed crops on site for fertiliser and feed substitutes	- cultivate *Azolla* spp., duckweed or fodder plants to enhance carbon and nitrogen fixation, and use as fertilise and feed inputs
	- promote *in situ* primary production to stimulate production, waste processing and carbon sequestration	- optimise management regimes to stimulate and sustain phytoplankton and periphyton production
	- increase tree cover and cultivate biomass crops	- plant tress or cultivate short-rotation coppice on embankments and bare land; cultivate biomass crops (reed, willow, mangrove, halophytes) in constructed wetlands
	- restore and protect wetlands	- avoid unnecessary development in natural wetlands; mitigate unavoidable wetland loss; restore degraded wetlands
	- adopt horizontally integrated production systems	- enhance carbon assimilation through adopting horizontally integrated production practices
	- convert aquatic farming areas to wetlands and woodlands	- convert unproductive aquatic farming areas back to wetlands (mangroves, salt-marshes, floodplains, riparian wetlands) or woodlands, supporting conservation, mitigation and sustainable livelihoods and production

3.7. Enhanced soil, water and waste management

Carbon stocks and flows in semi-intensive and intensive aquaculture systems, where primary production is enhanced with organic and inorganic fertiliser or supplementary feed are provided can be significant. Therefore, management strategies are required that aim to optimise the assimilation or long-term storage of carbon in such systems. The organic carbon content of sediments in pond-based aquaculture systems seldom exceeds 5% (Boyd, 1995). In Thailand, the highest soil organic carbon concentration recorded in tilapia ponds ranging from 3-35 years old was 3.39% (Thunjai et al., 2004). Assessing channel catfish (*Ictalurus punctatus*) ponds in Mississippi, Steeby et al. (2004) reported an average soil organic carbon concentration of 1.77%, with an associated range from 0.71-2.89%. Xinglong and Boyd (2006) noted a significant relationship between soil organic carbon in channel catfish ponds and potential aerobic soil respiration (mg CO_2 g soil^{-1}) in samples taken from the upper 5 cm of the soil layer.

Wudtisin and Boyd (2006) found that the mean soil organic concentration in 42 catfish, 40 prawn and 18 carp ponds in Thailand was 1.46%, 1.38% and 3.02%, respectively, and noted that pond management practices used to maintain ‘relatively good pond bottom quality’ included drying between crops, liming, tilling and periodic sediment removal. Enhanced pond bottom management strategies should focus on protecting against excessive accumulation and mineralization of soil organic carbon and either promote *in situ* assimilation of excess soil organic carbon, or where sediment removal is practiced, ensure this material is properly managed and applied elsewhere to improve soil quality and enhance soil carbon concentrations (see Section 4.1).

In flow-trough systems significant amounts of carbon can be released to receiving waters in the form of faeces and uneaten food. Wastewater treatment strategies ranging from settlement ponds to mechanical filters are routinely used to remove solids and nutrients prior to discharge, however, such treatment process result in accumulated sediments and sludge requiring disposal. Conversion of waste products to harvestable biomass in horizontally integrated aquaculture systems, including constructed wetlands has been proposed as an alternative more sustainable strategy. Moreover, use of biomass produced this way could be used to substitute for fossil fuels (see Section 3.4).

Where constructed wetlands for primary aquaculture wastewater treatment are prohibited by physical or hydrological constraints, development of smaller constructed wetlands could assist in managing sludge produced following treatment using conventional approaches. Nielson (1990) incorporated common reed (*Phragmites australis*) in a conventional unplanted drying bed for concentrated domestic sludge and concluded that this increased the rate of de-watering and mineralisation. The potential of using vertical and horizontal flow wetlands planted with vetiver grass (*Vetiveria zizanioides*) to treat backwash water from filters in an aquaculture system stocked with trout and employing water reuse has been described (Summerfelt et al., 1999). Sludge was applied to wetlands at a rate of 13.5 l m^{-2} d^{-1} or 30 kg dry solids m^{-2} y^{-1}. Vertical and horizontal flow wetlands removed 98% and 96% of suspended solids and 91% and 72% of chemical oxygen demand, respectively.

Concentrations of total nitrogen, total phosphorus and dissolved phosphate were reduced by 82-93% in both wetland types. Mineralisation in the wetlands was also significant, with total volatile solids in the sludge reduced by 50%. Biomass produced in the wetland could be used for energy generation, although the feasibility of on-site use would require further assessment.

Considering sludge management in a pilot-scale, recirculating rainbow trout production systems, Lanari and Franci (1998) assessed whether an onsite digester could be used to produce biogas. They concluded that the gas produced could either be used to produce thermal energy or used as a fuel in a cogeneration process to obtain both thermal and electrical of mechanical energy. For thermal energy production these authors recommended a digester with a minimum capacity of 50-70 m^3, and that the fish biomass needed to supply adequate waste to such a digester would range from 22 to 30 t, depending upon feed quality, feeding regime and efficiency of sludge collection. Despite demonstrating the technical viability of the system the authors noted various constraints that prevented them from estimating the cost of a full-scale system.

4. Enhancing aquaculture associated carbon sequestration in the landscape

Opportunities to harness productivity and other ecosystem services in aquatic systems to sequester carbon are reviewed here. Strategies considered include: exploiting organic matter accumulated in aquatic farming systems to build soil organic matter and carbon in marginal or agricultural land; enhancing *in situ* primary production and cultivation of green manure and fodder crops to enhance productivity and sequester carbon; increased tree cover and integration of biomass crops on farms; wetland restoration; horizontal integration; extractive aquaculture in freshwater and marine settings.

4.1. Organic matter conservation

Potential strategies to reduce the loss of organic matter and carbon from aquaculture systems have been reviewed (Section 3.7). However, broader integration of aquaculture within farming landscapes might present further opportunities to enhance carbon sequestration. Using sludge produced during the treatment of aquaculture wastewater to fertilise agricultural crops has been widely advocated and tested to a limited extent (Bergheim et al., 1998; Chen, 1998). Sludge and wastewater from aquaculture facilities have also been proposed as soil conditioners for degraded sites and production enhancing inputs to other aquatic systems.

Costa-Pierce (1996) described how waste collected under lake-based trout cages might be pumped onshore to facilitate environmental enhancement through the creation of wetlands and rehabilitation of eroded hillsides. This may be suitable for cages in lakes or sheltered coastal locations close to land, where topographic and nutrient load conditions are suitable, but is unlikely to work for cages in exposed or offshore settings or where the additional nutrients may overload terrestrial systems. In addition to regular maintenance, the pump-ashore facility would require a localised energy source, a possible constraint at isolated sites. Furthermore, capital costs of infrastructure for collecting and transferring waste matter and constructing the wetland may deter commercial development. As a complementary approach to this system Costa-Pierce (1996) suggested that a secondary enclosure stocked with unfed baitfish could be positioned around the grow-out cages, and that this ecosystem enclosure would capture fine particles and dissolved phosphorus released from the grow-out cage. Fish produced could then be either sold or released to enhance capture fisheries.

Little and Muir (1987) described using nutrient enriched fishpond water to irrigate rice fields that might be used to raise fish. Whilst, in northeast Thailand, productivity of rainfed lowland rice paddy fields, following the incorporation of 5 cm of fishpond sediment transferred from the lower toposequence of the mini-watershed, increased on average by 28% over three growing seasons, as compared with control plots (Mochizuki et al., 2006). Furthermore, soil organic carbon increased following incorporation of pond sediments from 4.6 g kg^{-1} to 5.7 g kg^{-1}; pond sediments contained 12.9 g kg^{-1} of soil organic carbon. Higher yields were attributed to increased cation exchange capacity which rose from 5 cmol kg^{-1} to 7.1 cmol kg^{-1} following pond sediment application. The authors conclude that incorporation of pond sediments accumulated in the lower toposequence in rainfed rice fields in the upper areas of mini-watersheds is an effective way to improve yields. However, the financial and energetic costs associated with excavating, transporting and incorporating pond sediments were not assessed.

4.2. Green manures and fodder crops

Azolla spp. commonly called the water fern, has been cultivated in paddy fields, alongside rice, to promote atmospheric nitrogen fixation and exclude weeds through competition for light and nutrients. Cultivation of *Azolla* spp. in the Philippines yielded 57 t ha^{-1} of fresh weight after 100 days, whilst associated nitrogen fixation can equate to 400 kg N ha^{-1} y^{-1} (Pretty, 1995). Although the nitrogen only becomes available to other crops following decomposition, 400 kg of nitrogen fixed in this way would, based on energy use in fertilizer manufacture of 51-68 MJ kg (Bhat et al., 1994), constitute a saving of 20.4-27.2 GJ of industrial energy consumption.

Duckweed cultivation has been proposed as a useful intermediate step in transforming unexploited inorganic nutrients in wastewater into fodder and as a component of integrated aquaculture systems, improving resource use efficiency and contributing to more stable culture conditions (Skillicorn et al., 1993; Bunting, 1995; Alaerts et al., 1996; Iqbal, 1999; Azim and Wahab, 2003). The resulting biomass can be fed directly to herbivorous fish species and livestock or dried and added to formulated feeds for fish, poultry, waterfowl and livestock.

Production rates of 9.4 and 39 t dry weight ha^{-1} y^{-1} have been reported for duckweed in temperate and tropical environments, respectively (Edwards, 1980). Duckweed cultured on managed sewage lagoons in Bangladesh produced extrapolated yields, based on average wet and dry season production, of 21 and 38 t dry weight ha^{-1} y^{-1}, respectively (Alaerts et al., 1996). Hunter (1976) reported a carbon content of 437.3 µg C mg^{-1}, based on the ash free dry weight, and that the ash content of *Lemna* spp. was 24.6%. Assuming the same composition and production rates reported from Bangladesh, net primary production in the wet and dry season can be calculated at 6.9 and 12.5 t C ha^{-1} y^{-1}, respectively. It should be noted however that the species of duckweed cultured at the site in Bangladesh was predominately *Spirodela* sp. whilst the composition of duckweed, both with respect to ash and organic carbon, is likely to vary based on site specific physical and environmental conditions. There is a further caveat to consider, duckweed covering the surface will suppress phytoplankton production in the water column and periphyton production on submerged substrates. Yusoff and McNabb (1989) reported net primary production in fertilized fishponds in Malaysia ranging from 1.04 to 2.41 g C m^{-2} d^{-1}, extrapolated to 3.8 to 8.8 t C ha^{-1} y^{-1}. Therefore, in certain cases where carbon sequestration is a priority it might be better to opt for a phytoplankton-based strategy, although the decision should also be influenced by the options available for the long-term storage of carbon sequestered in this way.

Converting to organic production, managers at Bahía de Caráquez shrimp farm, Ecuador found that it was possible to use plant protein as a substitute for the high proportion of fish meal used in commercial feeds, consequently, the Encarnacion Organic Farm was established to supply the required organically cultivated feed ingredients. Furthermore, seed pods from leguminous trees (*Prosopis* sp. and *Leucaena* sp.) planted on pond embankments provided an extra source of high protein feed ingredients; owing to the harsh local environment and saline growing conditions a combination of native and exotic tree species was planted. Other plant species cultivated around the ponds produced aloe vera, fruit, nuts and flowers; generating additional income, supporting organic honey production and providing wildlife habitat. Moreover, harvesting these products provides employment for local community members, an important development as disease outbreaks and the abandonment of many conventional shrimp farms resulted in widespread unemployment.

Brown et al. (1999) investigated using halophytic species with potential as forage crops (*Suaeda esteroa*) and oil seed production (*Salicornia bigelovii* and *Atriplex barclayana*) to remove nutrients from saline aquaculture wastewater. Brown and Glenn (1999) estimated that wastewater from 1 ha shrimp ponds (1 m deep) with exchange rates of 20% and 70% per week could be used to grow approximately 2.5 and 13 ha of *S. esteroa*, respectively, at irrigation rates of 250% E_{pan}. Furthermore, these authors reported that production of *S. esteroa* (6.9 g m^{-2} d^{-1}) irrigated at these rates was greater than that of Sudan grass (6.1 g m^{-2} d^{-1}) irrigated with more water and that where phosphorus is not a limiting factor in the receiving environment, using saline aquaculture wastewater to irrigate halophyte crops is an appropriate treatment strategy. However, the authors suggested that longer-term trials should be used to determine the ultimate fate of nutrients applied in wastewater, as the root-soil matrix may eventually become saturated, leading to nutrient leaching.

Trials with seawater irrigated halophytes recorded at Puerto Penasco resulted in annual production of *S. esteroa* at 17.2 t ha^{-1} and with an assumed carbon content of 36% of ash-free dry weight this was estimated to assimilate 4.3 t C ha y^{-1} (Glenn et al., 1993; Table 3). Based on this production rate and carbon content fields planted with *S. esteroa* and irrigated with wastewater from 1 ha shrimp ponds operated with exchange rates of 20% and 70% could assimilate a 10.8 and 55.9 t C y^{-1}, respectively. Furthermore, using the resulting forage and oil seed, possibly for non-renewable energy substitution at the farm level, would result in a further reduction in net carbon dioxide and other greenhouse gas emissions. Considering the sustainability of carbon sequestration using halophytes, Glenn et al. (1993) noted that this would depend upon how much primary production enters long-term storage or could be used to replace fossil fuels. The authors proposed incorporating biomass into dryland soils as one means of achieving long-term storage; it was estimated that 30-50% of assimilated carbon might enter long term storage. It was also noted that the residence time of carbon in dryland soils can be longer than forest soils.

Table 3. Production and carbon assimilation by halophytes irrigated with seawater

Halophyte species	Production (t ha^{-1} y^{-1})	Carbon assimilation (t ha^{-1} y^{-1})
Batis maritima	33.95	8.2
Atriplex linearis	24.27	6.7
Salicornia bigelovii	17.72-22.40	4.3-5.6
Suaeda esteroa	17.22	4.3
Sesuvium portulacastrum	16.70	4.2

(Source: Glenn et al., 1993)

4.3. Promoting *in situ* primary production

Freshwater pond-based aquaculture accounts for the largest proportion of finfish production globally, mostly focused on carp and tilapia culture in semi-intensively managed ponds; traditionally these were fertilised with manure and agricultural by-products, but increasingly farmers use inorganic fertilisers. Kautsky et al. (1997) noted that primary production (2.3 g C m^{-2} d^{-1}) within a semi-intensively managed fishponds in Zimbabwe, stocked with tilapia at rates of 0.1-0.5 kg m^{-3} and fed locally available plant and agriculture by-products, was sufficient to sustain fish production at 1.3 g m^{-2} d^{-1} or

4.75 t ha^{-1} y^{-1}. Furthermore, that the ecosystem support areas for oxygen production and phosphorus assimilation both equated to 0.9 m^2 per m^2 of fishpond and that this could probably be sustained within the pond.

However, in the context of this review it is appropriate to consider whether the capacity of semi-intensively managed fishponds to absorb atmospheric carbon and sequester this in harvestable biomass or sediments can be enhanced? And indeed whether it is reasonable to request the majority of producers culturing fish in ponds semi-intensively not to intensify production, with its attendant higher use and dependence on inorganic fertiliser, in pursuit of greater returns?

Considering the first point comparisons with other semi-intensively managed aquaculture systems are difficult as the methodologies employed in primary production studies vary considerably (Melack, 1976; Liang et al., 1981; Yusoff and McNabb, 1989; Knud-Hansen et al., 1993) resulting in production estimates which are not readily inter-converted. Yusoff and McNabb (1989) recorded rates of net primary production of 1.48 and 2.41 g C m^{-2} d^{-1} in fishponds fertilized monthly with either triple superphosphate (5.7 kg P ha^{-1}) or triple superphosphate (1.4 kg P ha^{-1}) and urea (16.6 kg N ha^{-1}), respectively. However, the ease with which such production rates could be replicated remains to be tested as does whether or not such pond management strategies are conducive to culturing other fish species.

Semi-intensively managed pond aquaculture constitutes one of the most productive sectors, therefore, enhanced carbon management and potentially capture in such systems could make a significant contribution the sequestration of carbon in freshwater systems. However, whether operators might be persuaded to adopt more carbon conscious management strategies, against a trend towards intensive production of more commercial species, sometimes destined for export markets remains questionable. Over recent years the extent of land under traditional dike-pond cultivation in the Zhujiang Delta, Guangdong Province, South China, often touted as a working example of sustainable integrated aquaculture, has declined; farmers have removed dikes to increase available pond area for stocking intensive market-orientated monocultures, producing high-value products such as eels, prawns and terrapins destined for export markets (Wong Chor Yee, 1999). Factors leading to these changes included the prospect of greater economic returns, and the decline in the value of silk, an important output of the traditional dike-pond system.

4.4. Increased tree cover and biomass crops

Planting trees on embankments and fallow land could contribute to enhanced carbon sequestration. On marginal and low-lying land associated with aquaculture sites, it might be possible to implement a short-rotation coppice that further to enhancing carbon sequestration: constituted an alternative income generating land-use; reduced chemical inputs compared to arable crops; enhanced environment through increased biodiversity. Furthermore, planted along riparian zones such coppices can buffer against diffuse pollution draining from adjacent agricultural land (Tubby and Armstrong, 2002). In Europe, varieties of willow and poplar have been employed in short-rotations, whilst in tropical countries fast growing species such as bamboo and eucalyptus might be suitable.

Considering the range of options available, land-use conversion from aquaculture to agro-forestry may constitute the most significant net benefit, avoiding emissions associated with aquaculture and enhancing carbon accumulation. Conversion of agricultural land to agro-forestry resulted in increased carbon accumulation of 3.1 t C ha^{-1} y^{-1}, accounted for by both increased soil organic matter and above ground biomass; where the wood is subsequently used for energy generation there is an added benefit if it substitutes for fossil fuel (Pretty and Ball, 2001). However, significant gains might also be made through integrating more carbon sensitive aquaculture operations with agro-forestry.

Integrated mangrove-shrimp, mangrove-fish and mangrove-crab systems have emerged, primarily, throughout Southeast Asia. Integrated shrimp-mangrove production systems have been developed in Indonesia, Thailand, Vietnam and the Philippines (SEAFDEC Asian Aquaculture, 2000) where two predominant models have emerged, mixed and separate farming systems. On mixed farms mangroves are planed on pond embankments and on raised areas within the pond, with the separate system mangroves areas are developed adjacent to the shrimp ponds. Considering Ca Mau, Vietnam, the recommended composition of the farming system specified in government policy was 70% mangrove forest, 20% pond and 10% housing and domestic, however, farmers have reportedly failed to comply with this, allocating 40% or more to ponds (Johnston et al., 1999). These authors noted that farms in Ca Mau generally range from 2-17 ha and production is largely extensive based on tidal recruitment and little or no supplementary feeding, aeration, pumping or soil treatment. Furthermore, according to the prevailing forest management policy, mangrove tress (*Rhizophora apiculata*) planted at 20,000 ha^{-1} should be thinned by 20-30% after 5, 10 and 15 years with the final harvest at 20 years. Under this regime thinnings reportedly produced wood for poles, firewood and charcoal at a rate of 44 m^3 ha^{-1}, whilst the final harvest produced 180 m^3 ha^{-1} of wood with a stem diameter of 11-12 cm.

Discussing integrated mangrove-crab (*Scylla serrata*) farming systems in the Philippines, Trino and Rodriguez (2002) noted that ‘integration of crab aquaculture within natural mangroves is … feasible in the Philippines, providing both immediate and long-term commercial and environmental benefits’. In Vietnam preliminary studies have investigated the potential of integrating rice cultivation with melaleuca (*Melaleuca cajuputi*) plantations, from which other products including fish and honey may be obtained (Ni et al., 2001).

An alternative strategy for integrating the production of biomass or fodder crops in static water ponds has developed in association with traditional *chinampas* farming systems from Xochimilco-Chalco, Mexico, where 6-9 m long floating rafts of reed and cattail were covered with mud and used as nurseries for vegetables (Armillas, 1971). More recently, rafts made from artificial materials e.g. polystyrene sheets were used to grow rice, flowers, vegetables, wheat and fibre producing plants; preliminary results demonstrated this was technically viable (Song et al., 2000). However, the cost of construction materials may constrain development, and the physical presence of the planted beds may interfere with pond management activities.

4.5. Wetland restoration and protection

Addressing the potential of wetland restoration in agricultural systems, the IPCC (2000) noted that such land use change would result in the accumulation of 0.4 t ha^{-1} y^{-1} of carbon. As with terrestrial farming, there may be opportunities for aquaculture operators to restore wetland areas and make a commitment not to convert existing wetlands for further aquaculture development. Shrimp farmers striving for organic certification in Ecuador, under the auspices of Naturland, are obliged to replant at least 50% of any mangrove forest cleared to establish the farm. Where more than 50% of the farm property was formerly mangrove forest, organic conversion is only permissible with respect to specific geographical or historical conditions where extensive and integrated mangrove-aquaculture systems are planned. Considering proposed aquaculture development the Naturland standards state that ‘it is not permitted to remove or damage mangrove forest for purposes of construction or expansion of shrimp farms’ and that ‘Any measure carried out by the farm or on the farm’s demand likely to influence adjacent mangrove forest (e.g. construction of pathways and channels to the farm area) shall be announced to and approved by Naturland.’

4.6. Horizontal integration

Horizontally integrated production has been defined as ‘the use of unexploited resources derived from primary aquaculture activities to facilitate the integration of secondary aquaculture practices’ (Bunting, 2001b). Examples include: culturing green mussels (*Perna viridis*) on bamboo sticks in wastewater draining from a commercial shrimp farm in the Upper Gulf of Thailand (Lin et al., 1993); culturing cockle and seaweed in shrimp farm wastewater in Malaysia (Enander and Hasselstrom, 1994); integrating the culture of macroalgae in shrimp farm effluent under the DFID AFGRP programme (Briggs and Funge-Smith, 1994); cultivating seaweed in association with salmon cages (Troell et al., 1997).

Horizontal integration has the potential to perform several important functions, notably the assimilation of wastes, reducing discharges to the receiving environment, whilst at the same time producing aquatic species that can be marketed. Reducing waste discharges through horizontal integration will contribute to environmental protection and reduce the risk of negative feedback mechanisms, limiting the possibility of self-pollution. Considering the scope of this review, most of the studies on horizontally integrated systems have included an assessment of nutrient dynamics and production rates for the various species being cultured.

Neori et al. (1998) monitored a pilot-scale modular culture unit where seaweed (*Ulva lactuca* or *Gracilaria conferta*) was cultivated in wastewater from fed abalone (*Haliotis tuberculata*) culture units; seaweed biomass produced was used in the formulation of abalone feed. Nitrogen input to the abalone tanks averaged 494 mg per month, of which 62 mg (14%) was assimilated in biomass, equating to a rate of 105 mg m^{-2} d^{-1}, 284 mg (59%) was discharged in the wastewater, the remainder was unaccounted for. Seaweed harvested from the system removed a further 1,621 mg N m^{-2} d^{-1}, accounting for 34% of that entering the system. Although practical management constraints were identified, the authors note that where integration is not practiced, double the water volume would be required to supply separate culture units, nitrogen derived from abalone culture would be discharged to the sea, whilst seaweed cultivation would require nitrogen fertiliser. Bunting (2001b) provides a comprehensive review concerning the constraints and opportunities associated with horizontal integration.

Nutrient budget data from previous studies dealing with horizontal integration could, in combination with representative proximate analysis data and carbon to nitrogen or carbon to phosphorus ratios, be used to extrapolate carbon budgets for the same systems. However, there are limitations to such an approach, representative data for the particular species of seaweed may not be readily available, whilst carbon to nutrient ratios will be influenced by the location, timing and means of cultivation. Troell et al. (1997) estimated that *Gracilaria chilensis* cultivation in association with salmon cages would yield 34 t dry weight ha^{-1} y^{-1}, assuming a carbon content of 25-29 mmol C g^{-1} reported by the authors this would equate to 10.2-11.8 t C ha^{-1} y^{-1}. On the Atlantic coast of France, Lefebvre et al. (2004) conducted trials with a land-based marine system, but instead of seaweed, batches of phytoplankton were cultured in ponds receiving fishpond wastewater, and subsequently fed into culture ponds stocked with shellfish. Phytoplankton production was reported at 8 g C m^{-2} d^{-1}, equivalent to 29.2 t C ha^{-1} y^{-1}, however, the authors noted problems in maintaining phytoplankton blooms.

4.7. Extractive aquaculture

Enhanced carbon retention and capture in coastal ecosystems could in theory be achieved by conducting extractive aquaculture operations in such areas, and would not necessarily be linked to any other aquaculture activities.

Seaweed

Cultivating seaweed can enhance primary production in coastal waters and contribute to increased carbon sequestration. Most seaweed cultivation occurs in Asia, with production being used for food or industrial processes. There is growing interest, however, in whether seaweed cultivation can be used as a means to sequester anthropogenic nutrients and carbon from the oceans. Mann (1973) estimated that seaweed production in St Margaret's Bay, Nova Scotia, Canada, was 1750 g C m^{-2} y^{-1}, equivalent to 17.5 t C ha^{-1} y^{-1}, and that seaweed production was over three times greater than that of phytoplankton in the bay. Gevaert et al. (2001) noted that kelp species, notably *Laminaria saccharina*, are the largest and most abundant seaweed populations on the French coast of the Dover Straits, and that the nitrogen and carbon concentration of kelp specimens collected from this area ranged from 2.23-3.42% and 23.9-31.4% of total dry weight, respectively. These authors also noted that the carbon concentration and ratio of carbon to nitrogen showed a distinct seasonal pattern; the highest carbon concentrations in sporophytes were recorded in September following the summer period of high photosynthesis where carbon assimilation exceeded carbon utilization.

Open-water cultivation to sequester carbon might focus on faster growing species as opposed to pigment quality, taste or market demand. Moreover, whereas seaweed cultivated for food or industrial purposes might be restricted to good quality sites, less favourable areas might be utilised to cultivate seaweed for carbon retention. Thus avoiding competition for sites and potentially opening up new opportunities for poor and vulnerable coastal communities. Whether seaweed cultivation to sequester carbon is compatible with cultivating seaweed for other purposes remains to be tested. Where seaweed culture is proposed the planning approach should be participatory in nature and engage with all stakeholder groups, failure to achieve this might result in inappropriate development and risk social conflict and further marginalising vulnerable groups.

Shellfish

Generally, farmed shellfish remove nutrients contained in seston filtered from the water column; carbon being incorporated into both the flesh and shell of the organism. Where elevated seston levels are undesirable, the action of farmed shellfish may contribute to environmental improvements. Elsewhere, however, the impact of shellfish production on ambient phytoplankton communities, both in terms of structure and function, could be considered negative. According to Beveridge et al. (1997) where shellfish farms are densely aggregated they can result in modifications to the food web; localised deposition of pseudofaeces can damage macrobenthic communities. As with seaweed, shellfish aquaculture could potentially contribute to the net removal of carbon from coastal systems. Based on production data relating to the culture of mussels (*Mytilus edulis*) on rafts in Killary Harbour, Ireland, Rodhouse and Roden (1987) estimated that 10.8 t C y^{-1} would be assimilated in mussel production and that the removal rate of carbon during harvest was 0.008 t C m^{-2} y^{-1}, equating to 80 t C ha^{-1} y^{-1}.

Ranching

Salmon ranching has been defined as ‘an aquaculture system in which juvenile fish are released to grow, unprotected, on natural foods in marine waters from which they are harvested at marketable size’ (Thorpe, 1980). A simple mass balance approach might be employed to assess the relative contribution of ranching to removing nutrients, including carbon, from an ecosystem. However, the efficiency of the approach might be increased if the ranching operation were to target nutrient rich areas and take sufficient steps to optimise recapture.

As well as feeding on natural biota, fish stocked as part of a ranching programme could feed directly on waste feed and faeces discharged from aquaculture facilities. Johansson et al. (1998) studied the fate of indicator particles contained in feed given to rainbow trout farmed in cages in Lake Southern Bullaren, Sweden. Results indicated that wild fish consume a significant proportion of faeces expelled by cultured fish. Therefore, fish stocked as part of a ranching programme may be expected to exploit this source of nutrition, assimilating nutrients and reducing the impact on underlying sediments. The foraging behaviour of grey mullet (*Mugil cephalus*), stocked into open-bottom cages on the seabed, significantly improved the quality of sediments below a commercial cage farm in the northern Gulf of Aqaba, Eilat (Porter et al., 1996). After a period of seven weeks, the proportion of organic matter and redox potentials in sediments below the farm returned to levels comparable to an undisturbed reference site. Furthermore, the invertebrate assemblage in sediments below the cage shifted from a mono-specific population of small nematodes to a mixed community of nematodes and polychaetes; a diverse macrofauna assemblage consisting of nematodes and polychaetes was observed at the reference site.

Several factors constrain the adoption of ranching; unrestricted movement may lead to the species stocked avoiding heavily impacted sites, and therefore potential benefits, such as those reported by Porter et al. (1996) may not be realised. Species being ranched may range widely, however, optimal foraging theory suggests that this freedom-of-movement may assist in optimising the assimilation of nutrients from the receiving environment. Containment strategies, such as bubble curtains and behavioural conditioning, could be employed to prevent animals being ranched from straying too far. However, such approaches are likely to be expensive and difficult to manage; problems with restricting the movements of stocked species suggest that organisms which do not range widely, e.g. lobsters, scallops, sea-cucumbers, might be best suited to nutrient removal and carbon capture.

Respecting the definition of aquaculture (FAO, 1995) operators engaging in ranching must retain ownership of organisms being cultured. Ownership may be difficult to establish unless the stocked species can be identified e.g. tagging to identify populations of scallops, lobsters and fish. Previous studies concerning ranching can be used to identify high potential management strategies and suitable species for ranching. However, concerns regarding the impact of introducing non-indigenous species should restrict ranching operations to using native species or organisms originating from local populations. Harvesting may also require operators to invest in suitable equipment and develop new skills. Furthermore, operators may face problems in obtaining exclusive rights to harvest the ranched species. Exclusion of other actors from the fishery may be difficult, especially where commercial fishing operations are established. Although ranching has the potential to enhance commercial fisheries, there may be little incentive to invest unless mechanisms are developed that allow operators to benefit from increased catches. A potential strategy might be to transfer revenue generated through the sale of rights to enhanced fisheries to aquaculture operators engaged in ranching. However, this would cause conflicts where access to the fishery changed. An alternative strategy would be for the operator to trade-off enhanced nutrient assimilation through ranching against a permit to discharge nutrients, with any surplus being traded with other operators.

Artificial reefs

Employing artificial reefs to remove nutrients from aquatic ecosystems is closely related to ranching as a strategy facilitating horizontal integration in association with open culture facilities. Laihonen et al. (1997) outlined the theory of removing nutrients from aquatic ecosystems using artificial reefs: they represent an increased area capable of supporting colonial organisms, grazers and predators; growth of these assimilates nutrients in biomass that may be harvested, resulting in net nutrient removal and products of value.

Laihonen et al. (1997) reported on the effectiveness of using a variety of artificial reefs to remove nutrients from the Baltic Sea, proposing that sessile filter-feeding organisms and aquatic plants that are capable of efficient and rapid assimilation of dissolved nutrients appear most promising. These authors used concrete pipes (0.6 m diameter, 1 m long) to construct star, tube and pyramid shaped artificial reefs at depths of 9-12 m in both inshore and offshore locations in Pomerian Bay, Poland. Offshore, colonisation of the star shaped reef was highest; mussels (*M. edulis*) and barnacles (*Balanus improvisus*) dominated both reefs; the filtration rate of the organisms colonising the reef was estimated at 5,500 $m^3\ m^{-2}\ y^{-1}$. The authors linked colonisation of the artificial reefs in Pomerian Bay with increased visibility, rising from 2-5 m in June 1991, to 5.5-7 m in October 1993, and decreased nitrate concentrations, falling from 0.5-2 mg l^{-1} to <0.5 mg l^{-1} during the same period.

Several factors demand consideration when proposing artificial reefs. The physical, chemical and biological conditions at the site must be assessed, temperatures should be high enough to allow a reasonable level of biological activity, light penetration into the water column should be sufficient to allow photosynthesis and nutrients circulating around the reef should be readily bio-available. The reef should also be positioned as close as possible to the nutrient source as the dilution of nutrients will reduce the removal efficiency of the reef system.

Assessing the dispersal of waste discharged from open culture systems e.g. cages and pens, this is a dynamic process, dependent upon a range of factors. The physical properties of the waste, topography and composition of substrate underlying the site, tides and currents governing hydrology, and interaction of natural biota all influence the ultimate dispersion pattern. Detailed information is therefore required to produce a reliable model of expected dispersion, thereby allowing the horizontally integrated culture unit or artificial reef to be positioned correctly.

Biomanipulation

Deliberately altering the species assemblage in aquatic ecosystems to induce changes in ecological processes, ameliorating negative environmental impacts, is a key element to biomanipulation. Approaches to biomanipulation include: introducing predatory fish, or suppressing zooplanktivores to increase phytoplankton grazing by zooplankton; encouraging filter-feeders, reducing the seston concentration; introducing herbivores to increase the conversion efficiency of primary production and promoting populations of organisms which are readily consumed by fish (Klapper, 1991). Despite several examples where the biomanipulation of fish populations has produced significant improvements in water quality, several constraints to this approach have been identified. Suppressing populations of fish, particularly small species and juveniles, is labour intensive and difficult to maintain (Moss, 1992) and grazing pressure from the increased population of zooplankton may lead to the selection of undesirable phytoplankton species. Furthermore, unless nutrient levels in the water-body are permanently reduced, any improvement in water quality will be unsustainable and the ecosystem will tend to revert to its prior trophic state.

Biomanipulation of aquatic ecosystems with the objective of promoting carbon assimilation and sequestration could be envisaged, however, the impact on other ecosystem functions and services would demand consideration and evaluation. Nutrient removal by harvesting species stocked in freshwater aquatic ecosystems has been considered to a limited extent. Fichtner (1983; cited in Klapper, 1991) described how harvesting grass carp stocked in a weed-infested lake removed 5-10% of the phosphorus from the water-body. Beveridge (1984) reported that operators of a Scottish cage farm producing 200 t y^{-1} of rainbow trout recovered 10 t of escaped fish using nets, whilst anglers caught a further 2.5 t; this generated income for the farm through increased sales and angling revenue and reduced the annual phosphorus load to the lake by 1.3%. Culture-based fisheries are increasingly being considered as a strategy to supplement declining wild stocks and enhance poor livelihoods, and potentially their management could become more focused on carbon assimilation and sequestration.

5. Achieving lower emissions and enhanced sinks

Reviewing past initiatives and the current state of knowledge points to both farm level and strategic opportunities for the aquaculture sector to reduce carbon emissions and enhance carbon sequestration in aquatic ecosystems. Below we discuss the need to raise awareness amongst policy-makers and consumers to help stimulate demand for carbon sensitive aquaculture and aquatic resources management strategies, call for the removal of varied disincentives to such strategies, highlight the requirement for more information and demonstration initiatives to promote best practices and outline the potential of sector oriented schemes that ensure the benefits of ameliorating climate change accrue to those tackling the issue of carbon and aquaculture development.

5.1. Raise awareness amongst policy-makers and consumers

Heightened awareness amongst policy-makers and consumers regarding the negative climate change impacts associated primarily with semi-intensively and intensively managed aquaculture could stimulate more widespread promotion and adoption of carbon sensitive aquaculture. Working Group III of the IPCC (2007c) noted that '*Information instruments* (e.g. awareness campaigns) may positively affect environmental quality by promoting informed choices and possibly contributing to behavioural change' but that 'their impact on emissions has not been measured yet.' Environmental campaigners generally try to inform consumers and influence buying behaviour, but the objective will more likely be to persuade consumers to purchase goods with a range of environmental credentials, of which greenhouse gas emissions will be one consideration. Ethical products are increasingly identified through organic, fair-trade or animal welfare labelling schemes, each with different objectives and standards.

Certification bodies overseeing organic and fair-trade production are likely to develop more explicit standards relating to greenhouse gas emissions. Carbon labelling, to inform consumers about the emission of carbon and carbon equivalents during a products life-cycle has been proposed by the Carbon Trust, however, their methodology is still in development (Carbon Trust, 2007). Organic certification schemes are also likely to place more emphasis on greenhouse gas emissions, issuing guidance and standards. However, the challenge for producer associations and proactive farmers not able to participate in carbon labelling schemes and not members of organic schemes will be to communicate to buyers and consumers about their strategy for reducing carbon emissions and enhancing sequestration and to justify the claims made.

Producer associations and bodies representing the aquaculture sector have a duty to coordinate sector wide strategies to implement responsible farming with respect to greenhouse gas emission and climate change. Policy-makers and government departments responsible for aquaculture nationally and supporting aquaculture development internationally should also promote and support carbon and climate sensitive initiatives. Guidelines such as those governing organic aquaculture production in Europe should be developed with respect to aquaculture and carbon emissions and sequestration, whilst research in this area should be prioritized. National development plans for aquaculture should be amended to include concerns over greenhouse gas emissions and climate change associated with aquaculture and strategies set out to: reduce emissions; enhance production efficiency with respect to energy consumption; capitalise on the potential role of aquaculture in sequestering carbon and mitigating climate change. Where national development plans are absent they should be developed based on a strategy for sustainable aquaculture that addresses climate change concerns.

However, considering the vital role aquaculture has assumed in sustaining aquatic product supplies, it is important that alternative carbon sensitive production strategies are available. In particular to producers in developing countries, otherwise poor and vulnerable households and communities dependent on aquaculture may be severely disadvantaged. There may also be a transition phase in moving to enhanced carbon sensitive management practices, where producers would benefit from transitionary payments or conversion grants, perhaps to subsidise the conversion of machinery to biofuel or purchase onsite power or electricity generation equipment. Support payments, direct subsidies and grants should also be directed to producers adopting carbon and climate sensitive aquaculture. Mechanisms are also required to ensure buyers and consumers are able to differentiate between products based on the carbon footprint or climate change impact associated with its lifecycle.

5.2. Remove disincentives

Having proposed that financial support should be directed to carbon and climate sensitive aquaculture production, the implication is that support for producers and sectors operating on a business-as-usually basis should diminish, with subsidies that encourage resource degradation or depletion being withdrawn. Moreover, Stern (2007) stated that ‘Climate-change policy can help root out existing inefficiencies.’ And that ‘At the economy-wide level, climate-change policy may be a lever for reforming inefficient energy systems and removing distorting energy subsidies, on which governments around the world currently spend around $250bn a year.’ Considering aquaculture development, support is often provided by governments in the form of subsidised fertiliser, fuel or electricity; such subsidies should be reconsidered in the face of climate change, with support being directed to low impact aquaculture development and more sustainable production strategies (Bunting, 2006; Bunting, 2007).

Assessing prospects for the commercial adoption of microgeneration technologies in the UK, a review by the Energy Saving Trust, Econnect and Element Energy (2005) predicted that photovoltaic energy generation would not be cost effective until 2050 owing to low commercial electricity prices and that these low prices would delay the cost-effectiveness of commercial small (10 kW) wind generation by around 5 years, as compared with domestic small wind generation, predicted to be cost effective by 2010-2015. Low commercial energy prices in the future, predicted by this study, could well constitute a major disincentive to smaller aquaculture operators adopting the farm level adaptation strategies discussed in Section 3.

Not having to pay for the externalities of climate change impacts constitutes a major disincentive to adaptation in the aquaculture sector. Moreover, according to Working Group III of the IPCC (2007c) ‘Policies that provide a real or implicit price of carbon could create incentives for producers and consumers to significantly invest in low-GHG [greenhouse gas] products, technologies and processes.’ Relevant policies mentioned included economic instruments, regulation and government funding. At a practical level, Working Group III noted that ‘In industry, management tools that include staff training, reward systems, regular feedback, documentation of existing practices can help overcome industrial organization barriers, reduce energy use, and GHG emissions’.

5.3. Promote best practice

Government agencies, aquaculture federations and societies and producer associations should promote best practices with respect to aquaculture, greenhouse gas emissions and climate change mitigation. Greater awareness concerning possible cost savings e.g. lower energy consumption, greater regulatory compliance or reduction in carbon tax, and potential market premiums for products with smaller carbon footprints could help promote good practice. Practical farm level initiatives, such as those outlined in Table 2, could be developed further to provide more specific guidance for selected aquaculture sectors or producer groups. Where institutions such as producer associations or national or regional federations and societies exist, then new bodies i.e. committees or working groups should be convened to address climate change issues and established communication media and pathways used subsequently to inform members. Codes of Conduct established by several national and international organizations and federations should be amended to include consideration of the climate change impacts of aquaculture practices and guidance on how to minimize such impacts. Support from government extension services and non-government organizations active in aquaculture development and allied fields should also be directed to the adoption of recognised Codes of Conduct and the promotion of good practice.

In the absence of established communication channels between policy-makers, practitioners and producers it may be necessary to undertake an assessment of communication stakeholders that would benefit from new knowledge on how to mitigate the climate change impacts of aquaculture development and the best media and pathways to reach the various groups identified. Better practice guides have been developed to inform stakeholders in south and southeast Asia concerning a number of issues relating to enhanced aquaculture development and aquatic resources management (STREAM, 2007). Similar guides in local languages addressing aquaculture, carbon emissions, sequestration and climate change could help raise awareness amongst policy-makers, civil society and producers; guidance could be included on how to reduce energy consumption and maximise input use efficiency, thus reducing costs which would be of interest to many producers, whilst at the same time helping minimise greenhouse gas emissions. Advice could also be provided on how to benefit form potential opportunities such as product certification and labelling, but a note of caution should be included about the associated costs and risks associated with different schemes; this type of information will become more useful as more schemes become established and market demand increases.

To promote best practices there needs first to be an assessment of the options available and agreement on the most promising approaches, however, as Working Groups III of the IPCC (2007c) noted, with respect to agriculture ‘There is no universally applicable list of mitigation practices; practices need to be evaluated for individual agricultural systems and settings.’ The review presented here constitutes a first step in addressing the gap between existing knowledge and decision-making needs with respect to aquaculture development and climate change.

5.4. Policies, measures and instruments to encourage adaptive aquaculture development

Working Group III of the IPCC (2007c) stated that ‘A wide variety of national policies and instruments are available to governments to create the incentives for mitigation action.’ However, it was noted that their ‘applicability depends on national circumstances and an understanding of their interactions’ and that there are constraints and opportunities associated with any instrument, they ‘can be designed well or poorly, and be stringent or lax.’ It was suggested that specific policies and measures can be evaluated based on four criteria: environmental effectiveness, cost effectiveness, distributional effects (including equity) and institutional feasibility. Reviewing sectoral policies, measures and instruments relevant to agriculture that have been environmentally effective, Working Group III identified ‘Financial incentives and regulations for improved land management, maintaining soil carbon content, efficient use of fertilizers and irrigation’.

Financial incentives to encourage the adoption of mitigation and adaptation strategies in the aquaculture sector include the redistribution of support payments, subsidies and tax credits to responsible producers and the imposition of taxes and charges on carbon. Tradable permits also enable a price for carbon to be established, however, the environmental effectiveness of such an approach depends upon the volume of permitted emissions (IPCC, 2007c). Regulation and standards introduced to curb carbon emissions and promote good practice can also be effective, however, such measures may not encourage innovation and technological development. Regulation and standards may be better suited to situations where decision-making by producers and consumers is not particularly influenced by climate change considerations or associated price differentials.

Within companies, Stern (2007) suggested that ‘implementing climate policies may draw attention to money-saving opportunities.’ There will also be opportunities for producers to capitalise on the growing demand for low-carbon products. Focus groups with seafood consumers revealed that they would potentially be willing to pay a 20-30% premium for products from horizontally integrated aquaculture systems such as those described in Section 4.6 (Ferguson et al., 2005) however, what proportion of this premium might be attributed to issues surrounding carbon is unknown. Carbon labelling to ensure consumers can identify low-carbon products would help ensure that responsible producers are able to benefit directly from potential price premiums associated with adopting mitigation and adaptation. However, such a strategy demands a standardised approach to auditing carbon budgets across the sector and between production types and individual farms, for the entire lifecycle of the product.

The labelling scheme proposed by the Carbon Trust in the UK provides an example of what might be possible, but the methodology is still under development and the costs associated with auditing and labelling are likely to be prohibitive for all but the largest aquaculture firms. Widespread adoption of carbon labelling cross the aquaculture sector might also impact badly on smaller and poorer producers that are unable to participate in certification schemes. Poorer producers in developing countries supplying export oriented markets may suffer disproportionately as carbon emissions associated with transport, including air-travel, make their products less desirable; in this context greater emphasis on ‘fair miles’, as opposed to ‘food miles’ would be appropriate. Food miles do not take into account the social and economic benefits of trade to poorer countries and communities (MacGregor and Vorley, 2006). To ensure that poorer people in developing countries are able to benefit through economic development, their right to ecological space and an equitable share of the right to emit carbon dioxide must be guaranteed.

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