Biophysical accounting in aquaculture: insights from current practice and the need for methodological development

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ABSTRACT

Several biophysical accounting techniques have been developed to assess the eco-efficiency of human activities and to inform decision-making. Most prominent are energy analysis, ecological footprint analysis and life cycle assessment. Their application is perhaps most pressing for food production, whose expansion and intensification has resulted in local to global scale impacts. Comparative analyses that can establish the biophysical performance and relative eco-efficiency of various food production systems are particularly important in the aquaculture industry.

Of the major biophysical accounting techniques now available, energy analysis has been applied most frequently to aquaculture systems. Where direct comparisons have been made between competing fishing and farming systems, the energy intensity of the farmed product can be substantially higher than that of the capture fishery. While applied less widely to aquaculture, ecological footprint analysis and life cycle assessment confirm the important roles that feed provision and the maintenance of water quality play in overall environmental impact.

Issues that remain unaddressed by all these methods include the proximate biological/ecological interactions associated with many aquaculture systems and, more generally, the cumulative impact of these activities on biodiversity.

INTRODUCTION

The intersection of increasing human population, rising consumption levels, and limited biophysical resources underscores the importance of improving the environmental performance of human activities in order to ensure their long-term sustainability. This is particularly pressing within the context of food production, where rapid industrialization has precipitated numerous unintended consequences. Not only do the industrial energy inputs to modern food production systems often exceed the

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caloric returns in food energy by orders of magnitude (Pimentel, 2004; Troell *et al.,* 2004; Tyedmers, Watson and Pauly, 2005), the widespread introduction of intensive production technologies has led to the fragmentation and outright conversion of habitats (Kerr and Desguise, 2004, Hartemink, 2005), species extirpation or extinction (Kruess and Tscharntke, 1994, Kerr and Desguise, 2004), widespread losses of topsoil (Heffernan and Green, 1986, Lal, 2000), depletion and contamination of fresh surface and groundwater (Zebarth *et al.,* 1998, Liess, Schulz and Leiss, 1999), nutrient enrichment of soils and receiving waters (Zebarth *et al.,* 1998), proliferation of pests (Mack *et al.,* 2000), and the general degradation of the productive capacity of both terrestrial and aquatic environments (El-Hage Sciallaba and Hattam, 2000). Transport of goods over long distances creates additional environmental burdens and allows economically advantaged regions to run ecological deficits at the expense of less developed regions (Hansson and Wackernagel, 1999).

The common root of these problems is a fundamental lack of regard for biophysical constraints. Their resolution requires restructuring human activities to maximize efficiency while respecting the limits of natural systems in supplying material and energy and absorbing wastes. Achieving this will therefore require analyses of competing food production systems in order to establish their comparative biophysical performance and facilitate informed decision-making regarding environmentally preferable development pathways. This is particularly important in the aquaculture industry, where rising demand for seafood products and concurrent declines in capture fisheries have resulted in rapid proliferation of industrial aquaculture production (FAO, 2004).

Aquaculture production systems are highly diverse, ranging from low-intensity subsistence operations to highly intensive industrial production models. Currently, more than 220 species of finfish and shellfish and dozens of aquatic plant species are cultured in a variety of freshwater, brackish and marine environments.

Depending on the form, setting, scale and intensity of the culture system, its biophysical impacts can vary widely. They can include localized nutrient enrichment or depletion (Folke, Kautsky and Troell, 1992; Merceron *et al.,* 2002; Holmer *et al.,* 2001), the effects of therapeutants and other chemicals on receiving waters and associated organisms (Hastein, 1995; Black *et al.,* 1997; Collier and Pinn, 1998; Davies *et al.,* 1998; Ernst *et al.*, 2001; Haya,Burridge and Chang, 2001), the disturbance or replacement of local ecosystems (Finlay, Watling and Mayer, 1995; Pohle, Frost and Findlay, 2001; Janowicz and Ross, 2001; Alongi, 2002), the introduction of exotic species (Canonico *et al.,* 2005; De Silva, Nguyen and Abery, 2006), gene flow from farmed to wild populations (Einum and Fleming, 1997; Youngson and Verspoor, 1998; Fleming *et al.,* 2000), the amplification and transmissions of disease/parasite loads (Kautsky *et al.,* 2000; Heusch and Mo, 2001; Bjorn, Finstad and Kristoffersen, 2001; Bjorn and Finstad, 2002; Morton, Routledge and Williams, 2005; Krkosek *et al.,* 2006), high levels of energy dependence and associated greenhouse gas emissions (Tyedmers, 2000; Troell *et al.,* 2004), and dependence on capture fisheries for feedstuff (Naylor *et al.,* 2000; Naylor and Burke, 2005).

Given the diverse impacts associated with aquaculture and food production systems more generally, there is a need for systematic analyses that provide rigorous bases upon which the biophysical performance of existing systems can be compared and improved upon. The balance of this paper reviews three leading biophysical accounting techniques that have been used to evaluate various forms of aquaculture and other food production sectors (energy analysis, ecological footprint analysis and life cycle assessment), summarizes the results of research that has employed these techniques and, where possible, makes comparisons between aquaculture systems and other competing animal protein production systems. Finally, we discuss some of the major limitations of existing techniques and suggest ways in which their application to food production systems can be improved.

ASSESSING THE BIOPHYSICAL PERFORMANCE OF AQUACULTURE

Three related analytical techniques – energy analysis, ecological footprint analysis and life cycle assessment – have been used to quantitatively assess the biophysical performance of aquaculture systems and other human activities. The three techniques use different methodology and speak to specific aspects of biophysical sustainability. The information they provide is complementary; where possible they should be used in concert for the broadest possible understanding of the biophysical sustainability of alternative production systems.

Method 1: Energy analysis

Energy analysis entails quantifying the direct and indirect industrial energy inputs required to provide a product or service (Peet, 1992; Brown and Herendeen, 1996). Its primary rationale is "to quantify the connection between human activities and the demand for this important (energy) resource" (Brown and Herendeen, 1996). However, as industrial energy use - and in particular fossil energy use – is directly related to a number of major environmental effects including global climate change, acid precipitation, eutrophication and biodiversity loss, energy analysis also has value as an indicator of biophysical sustainability (Kåberger, 1991; Brown and Herendeen, 1996).

Like other food production systems, aquaculture involves the redirection, concentration and dissipation of various forms of energy from the environment (Troell *et al.,* 2004). Different kinds of aquaculture dissipate different forms and amounts of energy. In some cases, such as the extensive culture of seaweeds or bivalves, all metabolic energy is derived from the immediate environment. Currently, however, over one third of global aquaculture output depends on auxiliary feeds from off-farm sources (Tacon, 2005). In general, these systems require a range of direct and indirect industrial energy inputs associated with the materials, labour, capital, and technology necessary to provide both feed and an appropriate culture environment.

Direct energy inputs

The direct industrial energy dependence of any culture system will vary with the means of production, the intensity of the operation, the degree of mechanization, and the quality and quantity of feed used (Troell *et al.,* 2004). For intensive systems, this includes the energetic costs of harvesting, processing, and transporting feed components from often remote ecosystems. Additional direct energy inputs are typically required for the hatchery production or wild harvest of juveniles, and for maintaining water quality in closed containment production systems.

Indirect energy inputs

The major indirect energy inputs to aquaculture production are the energy required to sustain human labour and to build and maintain fixed capital assets such as farm infrastructure, processing facilities, harvesting machinery, and transportation equipment. Depending on the nature of the culture system, the scale and form of these inputs will vary widely.

Extensive aquaculture production systems

Extensive aquaculture supplies a relatively low yield of edible protein per unit area of production and typically requires relatively small direct and indirect energy inputs. Generally, this can be attributed both to farming practices and to the feeding requirements of the cultured organisms. Many species farmed in extensive systems subsist on locally available primary productivity (e.g. mussels) or supplemental inputs of low-grade agricultural by-products (e.g. carp and tilapia), and require little or no manufactured feed. Although production may be enhanced using organic and inorganic fertilizers, these are typically of relatively low energetic cost. Depending on the expense and availability of labour, extensive systems in industrialized countries often have higher energy consumption than comparable systems in less developed regions because fossil fuels or electricity are substituted for human power. The energetic costs of material inputs, processing and transport will similarly vary depending on the location and specific conditions of production (Troell *et al.,* 2004).

Intensive aquaculture production systems

Intensive aquaculture production systems have high throughput of material and energy resources and generate a significantly higher edible protein yield per unit area than do extensive systems. The considerable energy requirements of intensive aquaculture production result from a combination of factors including the level of mechanization and environmental intervention required, the intensity of the production system, the feeding requirements of the species being grown, and the degree of dependence on manufactured feeds.

Intensive land-based systems generally require substantially higher energy inputs than open water systems. This is largely due to water quality requirements. Recirculation, for example, requires aeration and waste removal and is particularly energy-intensive. In open water systems, these services are provided by the natural environment.

The feeding requirements of intensively cultured organisms often play a major role in the total energy demands. For example, approximately 90percent of the total industrial energy inputs to farmed salmon production are associated with feed (Folke, 1988; Tyedmers, 2000; Troell *et al.,* 2004) (Figure 1, Table 1). For species that feed in the wild at mid to higher trophic levels, formulated feeds often include relatively high levels of animal-derived feedstuffs such as fish meal, fish oil and, less frequently, livestock processing wastes (Tacon, 2005). It is important to note, however, that the animal-derived fraction of a formulated diet is not inherently fixed. As long as the basic nutritional requirements of the cultured species are met, relatively high levels of substitution of plant- and animal-derived inputs are possible (Watanabe, 2002). Plant-derived inputs are in general less energy intensive than many animal-derived alternatives (Tyedmers, 2000), while transport-related energy costs can sometimes be reduced by using locally sourced inputs (Troell *et al.,* 2004).

Comparing energy inputs of various production systems can, however, take us only so far. Inputs produce outputs, and if we are to attempt meaningful comparisons of the environmental costs of aquaculture and other food-production systems, we need to look at both sides of the energy equation. For example, proponents of aquaculture often cite the feed-to-flesh conversion efficiency of aquaculture species relative to those obtained in terrestrial livestock production systems (Hardy, 2001), and there is no doubt that fish are generally very efficient converters of the food energy they ingest. Cold-blooded aquatic organisms require much less energy to fuel metabolic processes and consequently are able to utilize a higher proportion of ingested food energy for biomass gain. In contrast, warm-blooded animals metabolize as much as 90 percent of food energy to maintain body temperature alone.

However, unless such comparisons include the full range of energetic costs associated with feed provision, this argument is somewhat misleading. Comparisons of the energy intensity of alternative animal protein production systems indicate that, despite the conversion efficiency achieved in many cultured aquatic species, the energy inputs to feed provision result in a poorer edible protein energy return on industrial energy investment relative to many terrestrial production systems. For example, the ratio of industrial energy requirements to edible protein energy output of intensive net-cage culture of salmon is actually greater than that associated with milk, egg and even broiler chicken production and similar to that of feedlot beef production (Table 2), largely due to the substantial energy inputs associated with the nutritionally dense concentrated

TABLE 1

Direct and indirect energy inputs to a range of marine and freshwater aquaculture systems (modified from Troell *et al.*, 2004)

SYSTEM CHARACTERISTICS	MARINE						FRESHWATER							
	Shrimp		Salmon		Mussel		Carp (Recirculating polyculture)		Carp (semi-intensive polyculture)		Catfish		Tilapia	
Site area (ha)	10		0.5		2		1		1		1		0.005	
Production/yr (tonnes)	40		200		100		4		4.3		3.4		0.058	
Production/yr/ h(tonnes)	4		400		50		4		4.3		3.4		12	
ENERGY INPUTS (kJ/kg)	**EI**	%	**EI**	%	**EI**	%	**EI**	%	**EI**	%	**EI**	%	**EI**	%
FIXED CAPITAL														
Structures/equipment	2 500	2	5 940	6	2 700	58	3 556	7	2 114	8	11 691	10	0	0
OPERATING INPUTS														
Fertilizer, chemicals	22 750	15	0	0	0	0	9 316	18	633	2	369	0	1 000	3
Seed	18 750	12	2 970	3	0	0	15	0	0	0	11.076	10	0	0
Feed	58 250	37	78 210	79	0	0	15.451	31	287	1	86.389	75	23.280	97
Electricity, fuel	54 250	35	11 880	12	1 900	42	21.928	44	26.176	97	5 415	5	0	0
TOTAL	156 750		99 000		4 600		50 265		27 096		114 940		24 000	
ENERGY INTENSITY														
Edible product (MJ/kg)	275		142		12		84		45		192		40	
Edible protein (MJ/kg)	784		688		116		272		135		575		199	
LABOUR INPUTS														
Person-days/t	n.a.		10		5		6.5		66.7		3.5		172.4	

TABLE 2

Ranking of foods (aquaculture products highlighted) by ratio of edible protein energy output to industrial energy inputs (compiled from Troell *et al*., 2004; Tyedmers, 2004; Pimentel, 2004; and Tyedmers, Watson and Pauly, 2005)

Food Type (technology, environment, locale)	Protein Energy Output/ Industrial Energy Input (percent)
Carp (extensive freshwater pond culture, various)	**100 - 11**
Herring (purse seining, North Atlantic)	50-33
Vegetable Crops (various)	50-33
Seaweed (marine culture, West Indies)	**50-25**
Chicken (intensive, U.S.A.)	25
Salmon (purse seine, gillnet, troll, NE Pacific)	15 - 7
Tilapia (extensive freshwater pond culture, Indonesia)	**13**
Cod (trawl and longline, North Atlantic)	10 - 8
Mussel (marine longline culture, Scandinavia)	**10 - 5**
Turkey (intensive, U.S.A.)	10
Carp (unspecified culture system, Israel)	**8.4**
Wild caught seafood (all gears, marine waters, global average)	8.0
Milk (U.S.A.)	7.1
Swine (U.S.A.)	7.1
Tilapia (freshwater unspecific culture system, Israel)	**6.6**
Tilapia (freshwater pond culture, Zimbabwe)	**6.0**
Shrimp (trawl, North Atlantic and Pacific)	6.0 – 1.9
Beef (pasture-based, U.S.A.)	5.0
Catfish (intensive freshwater pond culture, U.S.A.)	**3.0**
Eggs (U.S.A.)	2.5
Beef (feedlot, U.S.A.)	2.5
Tilapia (intensive freshwater cage culture, Zimbabwe)	**2.5**
Atlantic salmon (intensive marine net-pen culture, Canada)	**2.5**
Shrimp (semi-intensive culture, Colombia)	**2.0**
Chinook salmon (intensive marine net-pen culture, Canada)	**2.0**
Lamb (U.S.A.)	1.8
Seabass (intensive marine cage culture, Thailand)	**1.5**
Shrimp (intensive culture, Thailand)	**1.4**

feeds used. By comparison, extensive culture of carp and tilapia requires 5-15 times less industrial energy per unit of edible protein energy produced, while semi-intensive tilapia culture requires less than half as much (Table 2).

Method 2: Ecological footprint analysis

The ecological concept of carrying capacity, or the maximum population that can be sustained by a given quantity of habitat without impairing its long-term productivity, has been used for decades to help grapple with the problem of human over-consumption of natural resources. This concepts forms the basis of a biophysical evaluation technique known as ecological footprint analysis (Rees and Wackernagel, 1994; Rees, 1996; Wackernagel and Rees 1996) in which the material and energy flows required to sustain a human population or activity are re-expressed in terms of the area of productive ecosystem required to support them (i.e. supply resources and assimilate wastes). The method thus provides a measure of relative ecological efficiency that cannot be gained from energy input analysis alone.

Several studies have used ecological footprint analysis to evaluate the ecosystem capacity required to sustain different forms of aquaculture (Folke *et al.,* 1998). Folke (1988) evaluated the amount of primary production appropriated by the culture of Atlantic salmon in the Baltic Sea, and found that the production of the fish component of salmon feed required a supporting marine production area 40–50 000 times larger than the surface area of the culture facility. Berg and colleagues (1996) compared the ecological support requirements for semi-intensive pond farming and intensive cage farming of tilapia and found that the intensive system appropriated a much greater area of ecosystem support than did the pond culture system (Figure 2). Larsson and colleagues (1994) estimated the spatial ecosystem support required to operate semi-intensive shrimp aquaculture on the Caribbean coast of Colombia. The ecological footprint for this type of culture system was calculated to be 35-190 times larger than the area of the farm itself.

In the only known analysis to directly compare competing wild capture fisheries and culture systems, Tyedmers (2000) calculated the ecological footprint of salmon fisheries and aquaculture in British Columbia as of the mid1990s, and found that salmon farming was less eco-efficient than commercial salmon fisheries for chinook, coho, sockeye, chum and pink salmon (Figure 3).

The results of the above analyses underscore the need to consider a broad range of material and energetic processes when evaluating the relative sustainability of production systems. The analyses also show that, while the physical area of an aquaculture facility may be quite small, the ecosystem support area required to sustain feed and other inputs and assimilate resulting wastes can be dramatically larger. This is particularly true in intensive production, where the material and energy throughputs are largely independent of the farm's location and dimensions. In contrast, less intensive systems may require little, if any, inputs beyond that which can be supplied by the ecosystem goods and services within the farm's boundaries.

Method 3: Life cycle assessment

Life cycle assessment (LCA) evaluates the potential environmental impacts of human activities from a systems perspective and can thus be used to quantify the range of environmental impacts associated with each stage in the provision and use of a product or service (Consoli *et al.,* 1993), and to pinpoint opportunities for improving environmental performance.

Modeled initially on energy analysis, formal development of LCA methodology began in the late 1980s and has been refined and improved by the International Organization for Standardization (ISO), the U.S. Environmental Protection Agency and the Society for Environmental Toxicology and Chemistry (SETAC), as well as by other national and international organizations. Now widely accepted by the scientific community, industry and policy makers, LCA methodology is formally standardized under ISO 14 040-14 043 (ISO 1997).

LCA provides high resolution with respect to the relative magnitude of environmental impacts of specific aspects of different production scenarios. In contrast to other techniques such as ecological footprint analysis, which allows an estimation of the ecosystem support required to sustain various forms of aquaculture production, the LCA framework is used to evaluate the environmental "costs" of individual energetic and material inputs and outputs associated with each stage of a production system. These costs are expressed in terms of their relative potential contributions to a range of global environmental problems (e.g. global warming, eutrophication, biotic and abiotic resource use, ozone depletion, ecotoxicity, and acidification) (Table 3). Such analyses help identify environmental "hot spots" in production systems, providing a clear basis upon which environmental performance improvements can be made.

While originally developed for evaluating manufactured products, LCA is increasingly applied to food production systems (Mattsson and Sonesson, 2003), where it has been used not only to compare environmental performance but also to identify activities or subsystems that contribute disproportionately to the environmental impacts of specific food production technologies (Andersson, Ohlsson and Olsson, 1998; Andersson and Ohlsson, 1999; Haas, Wetterich and Köpke, 2001; Hospido, Moreira and Feijoo, 2003). A considerable body of published research has reported the life cycle impacts of various agricultural systems. More recently, LCA has also been used to evaluate seafood production, including several forms of aquaculture (Christensen and Ritter,

TABLE 3
Impact categories commonly employed in LCA research

Impact Category	Description of Impacts
Global Warming	Contributes to atmospheric absorption of infrared radiation
Acidification	Contributes to acid deposition
Eutrophication	Provision of nutrients contributes to Biological Oxygen Demand
Photochemical Oxidant Formation	Contributes to photochemical smog
Aquatic/Terrestrial Ecotoxicity	Creates conditions toxic to aquatic or terrestrial flora and fauna
Human Toxicity	Creates conditions toxic to humans
Energy Use	Depletes non-renewable energy resources
Abiotic Resource Use	Depletes non-renewable resources
Biotic Resource Use	Depletes potential primary production
Ozone Depletion	Contributes to depletion of stratospheric ozone

2000; Seppälä *et al.,* 2001; Ziegler *et al.,* 2003; Eyjólfsdóttir *et al.,* 2003; Thrane, 2004; Hospido and Tyedmers, 2005; Mungkung, 2005; Thrane, 2006; Ellingsen and Aanondsen, 2006; Aubin *et al.*, 2006). The increasing number of life cycle assessments of industrial aquaculture indicates a growing interest in its use to better understand the environmental performance of alternative aquaculture production systems.

Published LCA results for aquaculture production systems include French farmed turbot in land-based facilities (Aubin, 2006), Norwegian salmon (Ellingsen and Aanondsen, 2006), Thai shrimp products (Mungkung, 2005), French farmed trout and salmonid feeds (Papatryphon *et al.,* 2003, 2004), and Finnish trout production (Seppälä *et al.,* 2001). While these studies have dealt with relatively diverse production scenarios (land-based, marine and fresh water) and culture organisms, a comparison of life-cycle impacts indicates some striking similarities. For example, in almost every system studied, the environmental cost of feed dominates most, if not all, impact categories. Papatryphon and colleagues (2003) found that feed production for intensive, freshwater-based rainbow trout culture in France accounted for 52 percent of the total energy use, 82 percent of the contributions to acidification, 83 percent to climate change, and 100 percent of biotic resource use. Similarly, Seppälä *et al.* (2001) reported that the production of raw feed materials together with the manufacturing of feed were responsible for most of the atmospheric emissions associated with rainbow trout aquaculture in Finland. More striking still, Ellingsen and Aanondsen, (2006) found that feed accounted for the majority of environmental burdens in all impact categories in their analysis of Atlantic salmon culture, while an LCA of Danish trout production showed that feed production and use accounted for the majority of impacts in six of the ten impact categories analyzed (LCA of Food, 2006).

Eutrophication from nitrogen and phosphorous emissions has also been found to be significant across production systems. Seppälä and colleagues (2001) reported that nutrient emissions to water on the farm were much more significant in terms of environmental impact than atmospheric emissions. These results are not surprising when one considers the fossil fuel and material consumption associated with reduction fisheries and plants, agricultural production systems, fish feed plants, and the associated transportation infrastructure. Efforts to mitigate the environmental impacts of intensive aquaculture must therefore pay considerable attention to improving the eco-efficiency of feed production and use.

As was the case with respect to energy inputs, the environmental costs of feed production will be relatively high, regardless of the ingredients chosen, if the feeds contain substantial fractions of animal by products (which is often the case in the culture of higher trophic level species). Decisions regarding the use of these limited resources should therefore be aimed at maximizing end-use efficiency – for example, by developing suitable plant-derived substitutes and choosing culture organisms that require less nutrients of animal origin.

In open-water production systems such as net-cage salmon aquaculture, the majority of life cycle costs are directly attributable to feed provision. However, LCA research of land-based aquaculture facilities indicates that the energy inputs required to maintain water quality and oxygen levels can also contribute substantially to the overall environmental costs. For example, Papatryphon and colleagues (2003) found that production intensity during the dry summer months, when more fuel and electricity were required for aeration and circulation, was an important indicator of overall environmental performance. Similarly, in an LCA of Thai shrimp aquaculture, Mungkung (2005) found that energy inputs for aeration contributed heavily to the environmental costs of production. An LCA study of French turbot production in a land-based recirculating system showed that energy use, global warming, and acidification impacts were particular environmental "hot spots", and were largely a function of both the quantity and origin of the energy used (Aubin, 2006). Danish LCA research of trout production similarly reported high global warming and toxicity impacts associated with on-farm energy inputs for aeration and recirculation because the electrical energy used was generated from natural gas (LCA of Food, 2006).

These results consistently indicate the appreciable energy demands of closed-containment aquaculture. While opponents of open-water aquaculture have often championed land-based technologies as a panacea, such a perspective fails to account for the broader range of environmental impacts related to energy consumption in these systems, and the implications for overall environmental performance.

The degree of representation of actual environmental costs that can be achieved by life cycle assessment will be determined by the range of impact categories considered. At present, the categories used in most LCA research tend to focus attention on broad-scale environmental issues that are often overlooked in public discourse regarding specific production technologies (Table 3). However, there are numerous other environmental burdens associated with aquaculture production systems, such as the transmission of diseases and parasites between farmed and wild organisms, impacts to the benthos from wastes emitted from open-water culture facilities, and the potential alteration of trophic dynamics resulting from large-scale reduction fisheries, and these are currently not quantifiable within the LCA framework. For this reason, the results derived from life cycle assessment do not alone provide sufficient grounds for decision making. LCA should therefore be treated as just one tool among many in decision-making processes.

CONCLUSIONS

Aquaculture represents an important and growing global source of animal protein. However, as recognized by FAO in the convening of this workshop, efforts must be made to maximize the eco-efficiency of the sector as a whole and of its various components, beginning with the identification of research tools that can be used to make meaningful comparisons with other food producing sectors.

Experience in the use of the three methods described in this paper allows us to make two preliminary generalizations:

- Although extensive culture systems typically deliver lower yields per unit area of farm site, they are generally much less material and energy intensive, and consequently result in smaller environmental burdens per unit of protein produced than do intensive systems.
- While all forms of industrialized food production are highly dependent on substantial energy inputs, extensive aquaculture systems are amongst the most energy efficient producers of animal protein currently in operation. In contrast, published data suggests that many forms of intensive aquaculture are amongst the least energy efficient protein producing systems (Table 2).

Such conclusions are just a start, but they do afford some much-needed direction for future research into the environmental cost of aquaculture. Perhaps more importantly for the purposes of the present workshop, they have been arrived at through the use of all three of the cost-accounting methods described in this paper, a process that has not only helped bring to light areas for methodological improvement but has, most importantly, demonstrated that the creation of national policies regarding food production need not be done in the dark: they *can* be developed on the basis of rigorous, quantitative study.

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FAO FISHERIES PROCEEDINGS **10**

Comparative assessment of the environmental costs of aquaculture and other food production sectors

Methods for meaningful comparisons

FAO/WFT Expert Workshop
24–28 April 2006
Vancouver, Canada

The global food production sector is growing and in many areas farming systems are intensifying. Although food production from all sectors has environmental impacts and environmental costs, public opinion and regulatory oversight amongst the sectors in this area is uneven. In order to understand better the place of aquaculture amidst the other food production sectors in regards to environmental costs, the first session of the FAO Committee on Fisheries' Sub-Committee on Aquaculture recommended "undertaking comparative analyses on the environmental cost of aquatic food production in relation to other terrestrial food production sectors". Comparisons can be useful for addressing local development and zoning concerns, global issues of sustainability and trade and consumer preferences for inexpensive food produced in an environmentally sustainable manner.

Methods to assess environmental costs should be scientifically based, comparable across different sectors, expandable to different scales, inclusive of externalities, practical to implement and easily understood by managers and policy-makers. These proceedings include review papers describing methods for such comparisons as well as the deliberations of their authors, a group of international experts on environmental economics, energy accounting, material and environmental flows analysis, aquaculture, agriculture and international development.

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