

Responsible use of resources for sustainable aquaculture

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ABSTRACT

Comparisons of production, water and energy efficiencies of aquaculture versus an array of fisheries and terrestrial agriculture systems shows that non-fed aquaculture (shellfish, seaweeds) is among the world's most efficient mass producer of plant and animal proteins. Various fed aquaculture systems also match the most efficient forms of terrestrial animal husbandry, and trends suggest that carnivores in the wild have been transformed in aquaculture to omnivores with impacts on resource use comparable to conventional, terrestrial agriculture systems, but are more efficient. Production efficiencies of edible mass for a variety of aquaculture systems are 2.5-4.5 kg dry feed/kg edible mass, compared with 3.0-17.4 for a range of conventional terrestrial animal production systems. Beef cattle require over 10 kg of feed to add 1 kg of edible weight, whereas tilapia and catfish use less than 3 kg to add a kg of edible weight. Energy use in unfed and low trophic level aquaculture systems (seaweeds, mussels, carps, tilapias) is comparable to energy usages in vegetable, sheep, and rangeland beef agriculture. Highest energy use is in fish cage and shrimp aquaculture, comparable to intensive animal agriculture feedlots, and extreme energy use has been reported for some of these aquaculture systems in Thailand. Capture fisheries are energy intensive in comparison with pond aquaculture of low trophic level species. For example, to produce 1 kcal of catfish protein about 34 kcal of fossil fuel energy is required; lobster and shrimp capture fisheries use more than 5 times this amount of energy. Energy use in intensive salmon cage aquaculture is less than lobster and shrimp fishing, but is comparable to intensive beef production in feedlots. Ayer and Tyedmers (2008) completed a life cycle assessment of alternative grow-out technologies for salmon aquaculture in Canada. They found that, for salmon cage aquaculture, feeds comprised 87% of total energy use, and fuel/electricity, 13%. Energy use in land-based recirculating systems was completely opposite: 10% of the total energy use was in feed, and 90% in fossil fuel/electricity (Ayer and Tyedmers, 2008). Freshwater use remains a critical issue in aquaculture. Freshwater reuse systems have low consumptive use comparable to vegetable crops. Freshwater pond aquaculture systems have consumptive water use comparable to pig/chicken farming and the terrestrial farming of oil seed crops. Extreme water use has been documented in shrimp, trout, and Pangasius catfish operations. Water use in Pangasius catfish is of concern to Mekong policy-makers as it is projected that these catfish aquaculture systems will expand and even surpass their present growth rate to reach an industry of approx. 1.5 million metric tons by 2020 (Phan et al., 2009; Lam, 2010). Water, energy and land usage in aquaculture are all interactive. Reuse and cage aquaculture systems use less land and freshwater, but have higher energy and feed requirements with the exception of "no feed" cage and seawater (shellfish, seaweeds) systems. Currently, reuse and cage aquaculture systems perform poorly in overall life cycle or other sustainability assessments in comparison to pond systems. Use of alternative renewable energy systems and the mobilization of alternative (non-marine) feed sources could improve the sustainability of reuse and cage systems considerably in the next decade to 2050. Resource use constraints regarding the expansion of global aquaculture are different for fed and non-fed aquaculture. Over the past decade for non-fed, shellfish aquaculture there has been a remarkable global convergence around the notion

that user (space) conflicts in shellfish aquaculture can be solved due to not only technological advances, but also due to a growing global science/NGO consensus that shellfish aquaculture can “fit in” not only environmentally but also in a socially responsible manner, and into many coastal environments worldwide, the vast majority of which are already overcrowded with existing uses. For fed aquaculture, new indicators of resource use have been developed and promulgated, the most comprehensive and useful of these by Boyd et al. (2007). Before this resource use in fed aquaculture was being measured in terms of Food Conversion Ratios (FCRs) followed by FIFO (Fish In Fish Out) ratios. First publications a decade ago measured values of FIFO in marine fish and shrimp aquaculture. More comprehensive indicator assessments of fish feed equivalencies, protein efficiency ratios, and fish feed equivalences will allow more informed decision-making on resource use and efficiencies. Over the past decade since the Bangkok Declaration major aquafeed companies have accelerated research to reduce the use of marine proteins and oils in feed formulations, and have recently adopted indicators for the production efficiencies in terms of “marine protein and oil dependency ratios” for fed aquaculture species. Current projections are that over the next decade to 2020, fed aquaculture will use less marine fishmeals/oils while overall aquaculture production will continue its rapid growth. Over the past decade, new, environmentally sound technologies and resource efficient farming systems have been developed, and new examples of the integration of aquaculture into coastal area and inland watershed management plans have been achieved, but most are still at the pilot scale commercially or as part of regional governance systems, and are not widespread. These pilot scale models of commercial aquaculture ecosystems are highly productive, water and land efficient, and are net energy and protein producers which follow design principles similar to those used in the fields of agroecology and agroecosystems. Good examples exist for both temperate zone and tropical nations with severe land, water, and energy constraints. Increasing technological efficiencies in the use of land, water, food, seed and energy through sustainable intensification such as the widespread adoption of IMTA and integrated agriculture-aquaculture farming ecosystems approaches will not be enough since these will improve only the efficiency of resource use and increase yields per unit of inputs and do not address social constraints and user conflicts. In most developing countries, an exponentially growing population to 2050 will require aquaculture to expand rapidly into land and water areas that are currently held in common. Aquaculture expansion into open water freshwater and marine waters raises the complex issues of access to and management of common pool resources, and conflicts with exiting users that could cause acute social, political, and economic problems. The seminal works of 2009 Nobel Laureate Elinor Ostrom could provide important insights for the orderly expansion of aquaculture into a more crowded, resource-efficient world striving to be sustainable, and rife with user conflicts.

1.0 Introduction

Today, about 1.3 billion people live on less than a dollar a day, and half of the world's population lives on less than 2 dollars a day (World Bank, 2008). A billion people are undernourished and in poverty, with an estimated 97% of them residing in Africa and Asia. By 2050, the world's population will rise from its current level of 6.8 billion and plateau ~9 billion, with nearly all population growth occurring in economically developing countries (Godfray et al., 2010). The World Bank (2008) has estimated that the world will need 70-100% more food by 2050, and will need to feed 2.3 billion poor, requiring food production to increase by at approximately 70% from its current levels (FAO, 2009). Today, in 10 African countries where aquatic proteins are a vital dietary component, having an estimated 316 million persons, 216 million live on US\$2/day, 88 million are undernourished, and 16 million children under 5 are malnourished (Allison et al., 2009).

On top of this population poverty crisis are scientific predictions of alarming environmental problems for both Asia and Africa. The IPPC predicts that a 2°C temperature increase could lead to 20-40% decrease in cereal yields in Asia and Africa. Lele (2010) believes that unless the global architecture of agricultural investments, research and development is changed over the next several years that the Millennium Development Goal of reducing hunger by 2015 will not be met. Aquaculture can play a major role in delivering high quality, energy and protein rich foods to the world's poor, in economic development, and overall poverty alleviation. However, as pointed out by Edwards (2002) "There is a need for a paradigm shift in philosophy away from food for the poor, which addresses the symptoms of poverty, not causes, to creation of wealth." Massive decreases in poverty due to wealth creation by aquaculture have occurred in China, Bangladesh, India, and Vietnam in the past 10 years (Edwards 2002; Phan et al., 2009). In Chile, the employment that is generated by the salmon aquaculture industry has a positive and direct impact on the poverty indicators of communities where this industry is developed (Bórquez and Hernández, 2009). However, in order to provide additional high energy aquatic foods for people to 2050, important flows of natural resources will need to be understood, measured, used and allocated more efficiently globally, regionally and locally, which could result in the reallocation of resources more consciously into the most efficient animal and plant production systems for food production. Food production will also need to be conducted in a way that reduces poverty, takes into account natural resource limitations, moves towards full cost accounting, resolves conflicts, and generates wealth.

There have been concerns that aquaculture has been moving away from its global responsibility to be more "sustainable" and to realize its altruistic goals of providing net benefits (additional foods) for a protein-hungry planet. Wurts (2000) stated that "Whether the word sustainability has become overused or not, it has catalyzed a forum for oversight of the growth and development of aquaculture on a global scale." Fed aquaculture has been criticized for its resource subsidies which have fueled the expansion of aquaculture systems that can be net resource losers and, as a result, some workers have called for full accounting of resource flows and for better planning for aquaculture as part of the global effort to provide additional foods but to also maintain essential ecosystems good and services (Folke et al., 1994; Goldberg and Naylor, 2005; Alder et al., 2008; Naylor et al., 2009). Greater than 75% of global fisheries are traded while only 7% of meat, 17% of wheat, and 5% of rice is traded. In 2000, more than 60% of fishmeal was traded. Concerns about the trajectories of resource use and subsidies in aquaculture have intensified as international trade in fisheries and aquaculture products and the essential resources to sustain them have increased dramatically.

Scientists and policy-makers agree that ecologically sound farming systems that include aquaculture as part of more resource efficient, integrated farming systems are part of the answer to the world's impending protein food crisis for both inland and coastal areas (FAO, 2001; Federoff et al., 2010). In 2006 the Fisheries and Aquaculture Department of Food and Agriculture Organization (FAO) recognized this need and developed guidelines for an ecosystem based management approach to aquaculture similar to the Code of Conduct for Responsible Fisheries (Soto et al., 2008). This ecological approach to aquaculture (EAA) has the objectives of ecological well-being and human well-being and would achieve these ideals via the more effective governance of aquaculture within a hierarchical framework that is scalable from the farm, to regional and global levels. Ecological aquaculture is a holistic view of aquaculture development that brings not only the technical aspects of ecosystems design, ecological principles and systems ecology (an integrated framework for planning & design, monitoring, modeling & evaluation) to aquaculture, but also incorporates planning for community development, and concerns for the wider social, economic, and environmental contexts of aquaculture (Costa-Pierce, 2002, 2008; Yusoff, 2003; Culver and Castle, 2008). Ecological aquaculture farms are "aquaculture ecosystems" (**Figure 2**).

By using an EAA more sophisticated, environmentally sound designed and integrated aquaculture systems could become more widespread because they better fit the social-ecological context of both rich and poor countries. Ecological aquaculture provides the basis for developing a new social contract for aquaculture because it is inclusive of all producer stakeholders and decision-makers in a modern, market economy—fisheries, agriculture, ecosystems conservation, and restoration (**Figure 3**).

Aquaculture depends upon resource inputs connected to various food, processing, transportation, and other sectors of society. Outputs from aquaculture ecosystems can be valuable, uncontaminated waste waters and fish wastes, which can be important inputs to ecologically designed aquatic and terrestrial ecological farming systems and habitats. In this review, we attempt to summarize data on resource use in aquaculture systems and make comparisons to other terrestrial food production systems, plus examine trends over the past decade since the FAO Bangkok Declaration and project the trajectories of these to 2050.

2.0 Systems ecology of comparable food systems

All modern, large scale food systems have discernible environmental and social impacts. Even the sustainability of modern, large scale, organic agriculture has been questioned (Allen et al., 1991; Shreck et al., 2006). Fish products are the most widely traded products globally. As such, some important global resources and resource flows have since the Bangkok Declaration been diverted to support its increased growth. A decade ago, Naylor et al. (2000) raised the issue of some fed aquaculture systems being a net loss of protein to humanity. Concerns were also raised as to the relative benefits of aquaculture in terms of resource use in comparison to capture fisheries; however, few comprehensive reviews have been conducted to analyze and compare resource use, trends in use, production and energy efficiencies of aquaculture versus other large scale capture fisheries and terrestrial animal protein production alternatives. Only by comparing efficiencies of terrestrial and aquatic protein production systems can scientists, policy-makers, and the public address in a more rigorous manner the available choices for resource use and production systems given the plethora of human needs and user conflicts, and the growing scarcities in water, land, energy, and feeds.

No other food animal converts feed to body tissue as efficiently as fish (Smil, 2000). Farmed (fed) fish are inherently more efficient than any other farmed animals since they are cold-blooded (poikilotherms), and thus divert less of their ingested food energy to maintain body temperatures. In addition, fish are neutrally buoyant in their environment (water), and thus do not devote as much of ingested food energy to maintain bones/posture against gravity as do land animals. Principally for these reasons fish devote more of their digested food energy to flesh, and thus have a much higher meat to bone ratios (and meat “dress out” percentages) in comparison to terrestrial (land) animals. There are also inherent differences in the manner in which stored energy is processed through terrestrial and aquatic ecosystems. Land plants (primary producers) convert more of captured sunlight into plant structures in comparison to aquatic plants, and thus have lower edible percentages. Land plants store most of their energy as starches. Aquatic plants (algae) store oils (lipids) as their primary energy sources. Fish convert lipids much more efficiently than land animals convert starches and other carbohydrates (Cowey et al., 1985). As a result, fish are the most valuable foods for human nutrition, disease prevention, and brain development of any foods since they have the highest nutrient density (highest protein and oil contents in their flesh) of all food animals (Smil, 2002).

2.1 Mass balances

Comparisons of production efficiencies of aquaculture *versus* an array of fisheries and terrestrial agriculture systems shows that fed aquaculture is an efficient, mass producer of animal protein (**Table 2**). Production efficiencies of edible mass for a variety of aquaculture systems are 2.5-4.5 kg dry feed/kg edible mass, compared with 3.0-17.4 for conventional terrestrial animal production systems. Beef cattle require over 10 kg of feed to add 1 kg of edible weight, whereas catfish use less than 3 kg to add a kg of edible weight. In the worldwide effort to increase food production, aquaculture merits more attention than raising grain-fed cattle (Goodland and Pimental, 2000). Since food conversions to edible mass in aquaculture are lower, aquatic animals inherently produce relatively less pollution than do terrestrial animals as they use nitrogen much more efficiently. Nitrogen use efficiency for beef is 5% and pork (15%), while shrimp retain 20% and fish 30% of ingested nitrogen (Smil, 2002). As a result, aquatic animals release 2-3 times less nitrogen to the environment in comparison to terrestrial animal food production systems.

2.2 Trophic efficiencies

Coastal and oceanic ecosystems have energy transfer efficiencies of 10-15%, and mean trophic levels of 3.0 to 5.0 (Ryther, 1969). Marine capture fisheries have a mean trophic level of 3.2 (Pauly et al., 1998). Mean trophic levels in aquaculture systems range from 2.3 to 3.3, with highest trophic levels in North America and Europe (Pullin et al., 2007). Kaushik and Troell (2010) noted an even wider range of fish trophic levels for the species listed in FishBase. Pullin et al. (2007) found most ocean fish consumed by humans have trophic levels ranging from 3.0 to 4.5, which Pauly et al. (1998) state are “0 to 1.5 levels above that of lions”. In the wild, however, salmon are not top level carnivores, as they are consumed by whales, sea lions, and other marine predators, thus cannot be compared to lions. In cage aquaculture systems, salmon eat agricultural and fish meals and oils so cannot be classified at same trophic level as wild “carnivores”; rather, such animals in culture are feeding as “farmed omnivores”. Overall, Duarte et al. (2009) estimated a mean trophic level of 1.9 for mariculture and 1.0 for agriculture and livestock.

Most recent debates over the efficiencies of fed aquaculture have focused on “fish in/fish out” (FIFO) ratios, but use of single ratios to measure resource efficiencies have been superseded by the more sophisticated development and use of multiple indicators to compare resource use in aquaculture (Boyd et al., 2007). Since measurement of resource use in aquaculture systems is such an important determinant it is important to review the evolutionary development of these metrics. Naylor et al. (2000) began the FIFO discussion when they reported that for the 10 aquaculture species they examined, approximately 1.9 kg of wild fish were required for each 1 kg of farmed production. For flounder, sole, cod, seabass, and tuna Naylor et al. (2000) reported greater than 5 kg of wild fish were required; and that “many salmon and shrimp operations use approximately 3 kg of fish for each one produced”. Farmed catfish, milkfish, and carp were all found to “net producers” since they used less wild fish than was produced by aquaculture. At the time, these data were widely criticized for not accounting for the latest advances in aquaculture feeds, feed management technologies and nutrition science as the authors chose to calculate FIFO ratios using FCRs for farmed marine fish and farmed salmon of 5:1 and 3:1 (Naylor, et al., 2000) while rapid advances had decreased FCRs to approximately 1.5:1 for farmed marine fish and approximately 1.2:1 for farmed salmon.

Jackson (2009) presented FIFO data for the world’s most commonly farmed species. Jackson (2009) calculated a FIFO ratio for global aquaculture at 0.52, demonstrating that for each ton of wild fish caught, aquaculture produced 1.92 tons of aquaculture products, showing global aquaculture, as currently

practiced, is a net benefit to humanity. However, Jackson (2009) calculated a FIFO for salmon of 1.68, the highest for all farmed species, meaning that, for every ton of wild fish used in salmon aquaculture, just 600 kg of farmed salmon were produced, confirming the Naylor et al. (2000) concern that such aquaculture systems remain a net loss of protein to society from a simplistic, since ratio, “FIFO perspective”. Trends in FIFO since 1995, however, all indicate a massive increase in efficiencies of feed use and incorporation of alternative protein meals and oils in fed aquaculture (**Table 3**). Kaushik and Troell (2010) criticized the calculations of Jackson (2009) recalculating a global FIFO of 0.7 for feed-based aquaculture but more importantly they emphasized the need to consider the environmental performances of aquaculture systems more comprehensively and recommended that life cycle and equity approaches (Ayer et al., 2007) were more appropriate measures of resource use and stewardship in aquaculture. As a complement to life cycle approaches, Boyd et al. (2007) gave a more comprehensive set of numerical indicators of resource use in aquaculture.

2.3 Efficiencies of resource use in aquaculture

A literature review of resource uses in aquaculture for land, water, energy, and seed was conducted, with materials summarized in subsequent Tables. A compilation of trends in each resource that has occurred over the last decade since the Bangkok Declaration with a projection of trends for each to 2050 was accomplished, taken both from literature sources and with inputs from Expert Panel members.

2.31 Land use

In the major aquaculture production centers of Asia, serious land constraints for the expansion of aquaculture have occurred over the past decade, especially in China, Indonesia, Bangladesh, Thailand, and India (Liao and Chao, 2009). In a few of these areas where capital is available (esp. China), intensive aquaculture systems that use less land (and water) have developed using imported feedstuffs for the formulation of pellet feeds for aquaculture. Land use efficiencies for semi-intensive and intensive aquaculture systems are the highest for land based aquaculture production systems which produce a metric ton (MT) of products for as little as 100 m² of land (**Table 4**). However, these simple calculations do not recognize the concept of the “ecological footprint” of aquaculture, or the appropriation of ecosystems goods and services acquired by aquaculture systems in their production (Kautsky et al., 1997; Folke et al., 1998). For example, Tyedmers (2000) measured the area of ecosystem support services for a range of farmed and commercially fished salmon species, finding that farmed species needed ecosystem support services equivalent to 12.7-16.0 ha/MT of farmed product, higher than salmon fisheries which appropriated 5.0-11.0 (**Table 5**).

Trends in land use are:

<u>Last Decade</u>	<u>Trends to 2050</u>
<p>Ponds have high land use in comparison to terrestrial agricultural protein production systems; Rice fields are increasingly being converted into fish ponds in many countries (Hambrey et al., 2008); Application of the use of “footprints” to quantify areas of ecosystem support services required per MT of aquaculture production as important metric being used.</p>	<p>Ponds taken over by urbanization; Cage systems proliferating with user conflicts driving the development and use of submerged systems; More widespread use of cages in small water bodies, reservoirs and coastal open water uses but submerged systems more common in marine areas; Intensive, recirculating systems are more efficient uses of land (ha/MT aquaculture production) than terrestrial animal production systems but remain uneconomic in most areas of Asia in comparison to other production systems; More widespread use of integrated aquaculture into landscape-scale systems of mixed aquaculture/land uses; Greater use of land/water use planning to address growing land/water user conflicts.</p>

2.32 Water use

A compilation of various studies on water use in aquaculture and animal production systems is shown in **Table 6**. Intensive, recirculating aquaculture systems are the most efficient water use systems. Extensive aquaculture pond systems and intensive, terrestrial animal production systems are the least efficient. Water use in aquaculture can be extreme—as high as 45 m³/kg of fish production. The potential for increased water use efficiencies in aquaculture is higher than terrestrial systems. Globally about 1.2 m³ (or 1200 liters) of water is needed to produce 1 kg of grain used in animal feed (Verdegem et al., 2006). A kg of tilapia can be produced with no consumptive freshwater use (cages, seawater farming systems), or using as little as 50 L of freshwater (Rothbard and Peretz, 2002). Seawater aquaculture systems (mariculture) can use brackishwaters unsuitable for agriculture; plus, integrated, land-based saltwater farming is possible (Fedoroff et al., 2010).

Water use is connected to changing land use, and conflicts between these have reached a crisis point in some of the major aquaculture farming regions of the world, such as Bangladesh. Fish and fisheries are very important in Bangladesh where millions of people are directly and indirectly involved. Aquaculture, which developed only recently (1980's) in Bangladesh now contributes around 40% of total fish production of the country (FAO, 2009). Bangladesh is a nation of rivers that originate in the Himalayas. It is home to a huge hydrological system that connects the world's highest mountains to the Bay of Bengal. Upstream dams in India across South Asia's major rivers (e.g. the Ganga, Tista, etc.) have caused serious water problems in southern Bangladesh which is a major aquaculture production zone. As a result, important tributaries are drying, reducing both capture fisheries and aquaculture production. Fish breeding, nursery and feeding areas have been degraded due to heavy siltation and less water in the rivers.

Coastal Bangladesh has rapidly become saline due to the decreased flows of freshwaters and intrusions of saline waters from the Bay of Bengal which has disrupted both rice and shrimp farming in the region.

Trends in water use are:

<u>Last Decade</u>	<u>Trends to 2050</u>
<p>High water use in ponds in comparison to terrestrial agricultural protein production systems; Severe water competition growing with alternative users; Massive damming and urbanization in Asia diverting water to coastal cities and agriculture;</p>	<p>Upstream dams cut off downstream users; Freshwater use conflicts and droughts increase in aquaculture production zones closing many pond areas; More rapid development of cage systems in open waters; Rapid decrease in the costs and increased efficiencies of intensive, recirculating systems that use water more efficiently than ponds and terrestrial animal production systems; Multiple uses of water in landscape scale systems of mixed reservoir production with downstream aquaculture/agriculture; Changes to traditional rice/fish systems in Asia, with large scale land modification, addition and replacement of rice with high value species (prawns) in Bangladesh, Vietnam and China; Development of seawater farming systems in arid areas; Development of low energy membranes with wind turbines breaking the 2kW/hr/m³ barrier which accelerates use of seawater for freshwater aquaculture.</p>

2.33 Energy use

A compilation of various studies on energy use in aquaculture and animal production systems is shown in **Table 7**. Seaweed and extensive pond aquaculture of omnivores are comparable to vegetable farming, while mussel aquaculture is comparable to sheep and rangeland beef farming. Catfish farming is similar to poultry and swine production. Cage aquaculture of salmonids and marine fish is comparable to intensive capture fisheries.

Energy comparisons between systems have become part of more detailed analyses of life cycles (Papatryphon et al., 2004; Ayer and Tyedmers, 2008). Comparisons of these with terrestrial farming show clearly the huge production benefits of intensive aquaculture albeit at a much higher energy cost, contained mostly in feed (Ayer and Tyedmers, 2008, **Table 8**). Over the coming decades, increasing global energy, processing, shipping/transportation costs of both products and feeds are predicted (FAO, 2008; Tacon and Metian, 2008).

Trends in energy use are:

<u>Last Decade</u>	<u>Trends to 2050</u>
Globalization and intensification of food production increases energy density and use in fed aquaculture in comparison to fishing and terrestrial agricultural protein production systems.	Recirculating systems are energy intensive compared to other systems and have large carbon footprint; Life Cycle Assessments show advantages/disadvantages of aquaculture; Large scale development and use of cost-effective renewable energy systems make intensive recirculating systems more widespread and accessible.

2.34 Feed Use

Aquaculture uses most of the world's fishmeal (68%) and fish oil (88%) with the balance used by intensive livestock agriculture and for pet foods (Tacon, 2005; Tacon et al., 2006; Tacon and Metian, 2008). Salmon, trout and shrimp aquaculture which account for less than 10% of world aquaculture production, use an estimated 26% of the world's fish meal, but 74% of the fish oil (Tacon and Metian, 2008). However, Tacon and Metian (2008) predict that fishmeal and oil use in aquaculture will decrease while aquaculture production grows significantly (**Figure 1**), and that fish meal/oil will increasingly be diverted from uses as bulk products to high priced, specialty, feed ingredients.

The major development in feed use in aquaculture over the past decade has been the rapid increase in the global trade of feedstuffs and feeds for fed aquaculture systems in Asia which has allowed the widespread use of formulated feeds. Tacon and Metian (2008) estimated that in 2005 about 45% of world aquaculture production (about 63 million tonnes including aquatic plants) was estimated to be dependent on the direct use of feed either as a single feed ingredient, farm-made aquafeed, or industrially-manufactured compound aquafeeds. A striking increase in the use of formulated feeds for the intensification of herbivorous and omnivorous fish culture in Asia, especially for carps in China, India and Bangladesh, and for catfish in Vietnam has occurred since the Bangkok Declaration. An estimated 23 million tonnes of aquafeed was produced in 2005, and about 42% was consumed by carps (**Figure 4**). However, it has to be noted that use of fishmeal for carp feed is only about 13-14% of total fishmeal use for aquaculture while the amount of fishmeal for salmon, trout, marine fish and marine shrimp are 18, 18 and 22% respectively.

Research on the use of agricultural meals and oils to replace use of ocean resources especially the functional components of fishmeals/oils needed for fish nutrition are a major subject of aquaculture research and development (Watanabe, 2002; Opstvedt et al., 2003). Turchini et al. (2009) reported that for all of the major aquaculture fish species 60–75% of dietary fish oil can be substituted with alternative lipid sources without significantly affecting growth performance, feed efficiency, and feed intake. Naing et al. (2007) found that palm oil could replace fish oil in rainbow trout diets, and reduce the dioxin contents in fish.

Current projections forecast an expansion of agricultural and other terrestrial sources of feed proteins and oils in aquaculture and these alternatives are developing rapidly. Terrestrial proteins and oils from

soybeans, sunflowers, lupins and rendered livestock are available at volumes larger than the quantity of global fishmeal. Soybeans have high protein content of ~28%, peas have ~22%, and these have good amino acid profiles. Other abundant cereals have protein contents of only 12-15%. However, soybean meal processing can create protein concentrates with protein levels of >50% (Bell and Waagbo, 2008). Vegetable oils have very low EPA and DHA levels. However, substitution of plant oils upwards of 50% of added dietary oil has not resulted in growth reductions or increased mortalities in fish such as salmon and trout. Terrestrial animal by-products from the rendering industry are the largest supply of high quality feed-grade animal protein and lipid for animal feeds (Tacon and Nates, 2007).

The massive use of plant resources in feeds for meat production in developed countries has been recently questioned considering food deficits of some countries and regions and the global food availability balance (Agrimonde, 2009). According to this study, attending for predicted population increments in food deficit countries in next decades would include the access to some near food-grade raw materials currently used for animal feeds. Thus, future aqua feeds could largely depend upon lower grade raw materials (including those possibly recovered from crop wastages) that may be further improved by processing and biotechnological transformation to fit as consistent nutrient sources for farmed species. This variety of available raw materials with different qualities and costs would further require strategic diversification in feed formulation and processing strategies to allow manufacture flexibility according to availability and cost-benefit relationship.

If agricultural sources of meals and oils are the future of fed aquaculture there will be a need for a new global dialog on the impacts of fed aquaculture as a driver of agriculture production, especially so for soybeans. Increased aquaculture consumption of the world's grains and oils raises the concern over the spread of unsustainable agriculture practices. Brazil has been targeted as one of the world's major soybean suppliers. Costa et al. (2007) has demonstrated that soybean farms are causing reduced rainfall in the Amazonian rainforest. About one-seventh of the Brazilian rainforest has been cut for agriculture, about 15% of which is soybeans. Soybeans, which are light in color, reflect more solar radiation, heating the surface of the land less and reducing the amount of warm air convected from the ground. Fewer clouds form as a result, and less precipitation falls. In soybean areas there was 16% less rainfall compared to a 4% decrease in rainfall in land areas cleared for pasture.

Trends in feed use are:

<u>Last Decade</u>	<u>Trends to 2050</u>
<p>Overuse of marine meals/oils threatening sustainability of pelagic fish stocks; High feed costs; Fish feed ingredients imported and there is a crisis in feed qualities; meat-bone meal also imported but quality is not assured; Social equity/poverty concerns with use of pelagics as feeds rather than as direct human foods; PCB and mercury contamination of fish meals/oils.</p>	<p>Increased use of imported fishmeals/oils in formulated feeds for traditional carp and imported tilapia species in Asia, esp. China, decreasing FCR; Increased use of wet feeds (cakes, wastes from poultry processing plants) and chicken manures in South Asia fish culture with high FCR (>3.0) resulting in deterioration of water quality; Decreased use of marine meals/oils in intensive cage/tank systems and improvement in FCRs; Replacement of marine meals/oils by agricultural sources and by algal/bacterial/fungal bioreactors but new issues arising about aquaculture leading to deforestation; Use of biotechnology to elongate/upgrade essential fatty acids; Cleansing of oils by high technology.</p>

2.35 Seed

A major FAO review of freshwater seed sources for aquaculture which included 21 country case studies was completed recently by Bondad-Reantaso (2007). Studies indicated that seed resources were an essential and profitable phase of aquaculture production, and that efficient use of seed resources is necessary to guarantee optimum production. Studies identified challenges concerning water allocation and land use conflicts for seed culture production in all countries. The study recommended a shift from high water use, land based hatchery systems to water saving and water productivity enhancing technologies such as integrating seed production with agriculture and optimizing the use of irrigated agricultural land, and the use of cages and *hapas* for fry- to fingerling rearing, especially where large numbers of perennial water bodies exit. Such integrations enhance the productivity of reservoirs and irrigation dams and enable landless households to participate in aquaculture.

Seed quality is related to the quality of the broodstock used, genetic quality and good hatchery/nursery management. Broodstock management and seed quality will be a key issue in meeting projected fingerling requirements to 2020 (Bondad-Reantaso, 2007). Approaches to genetic improvement using selective breeding, use of genetic markers, sex control techniques, chromosome set manipulation, crossbreeding and transgenesis need to be integrated during the domestication and translocation of aquaculture stocks. Seed certification and accreditation of hatchery practices are needed worldwide. Certification is a quality assurance system with certain minimum pre-determined quality standards and criteria, e.g. genetic purity, appropriate husbandry, high grow-out performance, pathogen-free, etc. Seed certification is part of a wider program on genetics and breeding, biodiversity conservation and international trade. In many Asian countries, seed is produced in hundreds of small hatcheries where genetic erosion is a serious concern. For example, around 99% of freshwater seed available in Bangladesh is produced in about 900 public and private hatcheries where the quality of seed has seriously deteriorated due to genetic erosion of broodstock.

Trends in seed use are:

<u>Last Decade</u>	<u>Trends to 2050</u>
Inadequate and unreliable supply of quality seed; Poor genetic quality of seed; Basic production from regional hatcheries—the human infrastructure, financial & business/marketing support and policy and legal frameworks are not in place in many nations; Impacts of uncontrolled releases of cultured seed stocks	Rapid expansion of export-oriented international seed trade esp. of high-value species; Increasing need to introduce quality assurance measures beyond simple official zoosanitary certificates; Regional hatchery infrastructure taking shape in many nations

3.0 Non-fed aquaculture

Concerns and constraints regarding the expansion of global aquaculture are much different for fed and non-fed aquaculture. Non-fed, herbivorous fish capture-based aquaculture in Asian reservoirs remains a major source of production, but has not expanded (FAO, 2008). Aquaculture of herbivorous fish in African reservoirs remains a priority but is still poorly developed, largely due to inadequate hatchery capacity and training, while having among the highest reservoir density in the world (Sri Lanka highest at 230 ha/100 km² while Zimbabwe has 139) (Petr, 2005). Seaweed aquaculture is one of the world's largest marine production systems, with plant production in 2004 reaching an estimated 13.9 million tons, of which 99.8% originated in the Asia-Pacific region, 10.7 million tons from China. Japanese kelp (*Laminaria japonica* – 4.5 million tons) was the most commonly produced species followed by wakame (*Undaria pinnatifida* – 2.5 million tons) and nori (*Porphyra tenera* – 1.3 million tons) (FAO, 2008). Production of aquatic plants has increased rapidly from the 2002 total of 11.6 million ton, largely due to large production increases in China. The greatest threats to aquatic plant production in Asia are water pollution, biofouling, and the “urbanization” of coastal oceans.

For non-fed, shellfish aquaculture there has been a convergence over the past 10 years or so around the notion that user conflicts in shellfish aquaculture can be solved due to not only technological advances, but also due to a growing global science/NGO consensus that shellfish aquaculture can “fit in” in an environmentally and socially responsible manner, and into many coastal environments, many of which are already crowded with existing users (Costa-Pierce, 2008). Included in this “evolution” of shellfish aquaculture are:

- (1) development of submerged technologies for shellfish aquaculture such as longlines (Langan and Horton, 2003), modified rack and bag shellfish gear (Rheault and Rice, 1995), and upwellers for nursery stages of shellfish, some of which are placed unobtrusively under floating docks at marinas (Flimlin, 2002),
- (2) scientific findings and reviews demonstrating the environmental benefits of shellfish aquaculture providing vital ecosystem and social services (National Research Council, 2010) such as nutrient removal (Haamer, 1996; Lindahl et al., 2005) and habitat enhancement (DeAlteris et al., 2004; National Research Council, 2010),

- (3) research on natural and social carrying capacities for shellfish aquaculture, and sophisticated, collaborative work group processes (McKinsey et al., 2006; Byron et al., 2008),
- (4) development and wide use by industry of best (and better) management practices (National Research Council, 2010),
- (5) diversification of traditional wild harvest fishing/shellfishing families into shellfish aquaculture as part-time enterprises, breaking down barriers between fishing/aquaculture user communities,
- (6) publication of global comparisons with fed aquaculture indicating a strong movement in shellfish aquaculture global towards an adoption of ecological approaches to aquaculture at all scales of society (Costa-Pierce, 2008).

Major constraints to shellfish culture are the growing occurrences of red tides causing paralytic shellfish poisoning, and the proliferation of human bacterial and viral diseases.

4.0 Major trends potentially affecting resource allocation and uses

“As population growth, urbanization, and climate change have affected all industrial inputs and outputs, humanity entered, for all food producing industries, the sustainability transition at the turn of the 21st century.” (Brown, 2009)

The three major trends occurring in the last decade that will affect decision-making as to resource use and allocation in aquaculture are: energy use in transportation affecting the globalization/localization of aquaculture feeds and products and capital investments in alternative energy; and a global strategy for aquaculture to deliver massive amounts of aquatic proteins to the world’s poor.

Increasing seafood imports remains a viable option for the rich countries such as Japan, the USA and the EU, but it is questionable if this level of globalization is sustainable and will continue, especially as the era of “peak oil” arrives and fuel prices continue to rise. The UK Energy Research Centre (UKERC, 2009) reports that peak oil may be reached by 2030 and that humanity may have already consumed 1228 of the estimated 2000 billion barrels of the “ultimate recoverable resource”. Local seafood production will spread rapidly as the cost and availability of transportation fuels from oil increase. Rapid developments of alternative energy and water treatment systems (desalinization) offer new opportunities for large scale integrated food production in the coastal zone (**Figure 5**).

Siting of intensive industrial aquaculture facilities, especially siting of cages in enclosed seas such as the Mediterranean Sea, is a very controversial topic, especially so when it is now estimated that cage aquaculture facilities contribute ~7% of total nitrogen and ~10% of total phosphorous discharges (Pitta et al., 1999). Inappropriate siting of cages has been blamed for the destruction of nearshore and benthic aquatic ecosystems (Gowen and Bradbury, 1987). However, Mitro et al. (2009) found that if seabass/bream cages were sited above seagrass (*Posidonia oceanica*) meadows that seagrasses responded positively to aquaculture discharges and that there were no impacts on benthic biodiversity. These findings raise the possibility that seagrass meadows can be created and enhanced by ecological engineering a systems approach and evolving a non-toxic, cage ecological aquaculture model for fish production and environmental improvement in this region. There are well-developed examples of aquaculture ecosystems, both land and water-based, mostly in Asia (Costa-Pierce, 2008; Hambrey et al., 2008; Edwards, 2009). In the West, however, there are few commercial aquaculture ecosystems, with most being small scale, research and development operations; however, there are advanced freshwater

aquaculture ecosystems that combine aquaculture units (ponds/tanks), aquaponics for food and fodder with wetlands, and aquaculture ecosystems that incorporate advances in waste treatment and solar energy, and others that are landscape ecological models that have a tight integration between aquaculture and agriculture (Rakocy, 2002; Costa-Pierce and Desbonnet, 2005; Costa-Pierce, 2008). A wide array of technologies and organisms can be used to not only remediate nutrient discharges (esp. nitrogenous compounds) from aquaculture, but only produce additional, highly valuable aquatic crops for both human consumption or for environmental and agricultural improvement (**Table 10**). In Israel, highly efficient, landscape-sized integrations of reservoirs with aquaculture and agriculture have been developed (Hepher, 1985; Mires, 2009), as well as highly productive, land-based aquaculture ecosystems for marine species (Neori et al., 2000). Intensive, integrated coastal farming systems are common in many areas of China where the two main forms of marine integrated systems are seaweed aquaculture integrated with fish cages and suspended shellfish aquaculture (Troell et al., 2009). In China the polyculture of shrimp with mussels, and clams plus crabs is also a popular, with shrimp yields approximately 300-600 kg/ha/yr (Nunes et al., 2003), which, if properly managed, could be a model for ecological intensification worldwide (Nunes et al., 2011).

A global strategy for aquaculture to assist in delivering more benefits to the world's poor could include: (1) allocation of more feed fish for poverty alleviation and human needs worldwide, thus allocating less for fed aquaculture so as to: (a) increase the ecosystem resilience of the Humboldt ecosystem, and (b) relieve the increasing overdependence of aquaculture countries such as Thailand (shrimp) and Norway (salmon) on this southeastern Pacific Ocean marine ecosystem. Alder et al. (2006) estimated that about 36% of the world's fisheries catch (30 million tons) are processed into fishmeal and oil, mostly to feed farmed fish, chickens, and pigs. Jacquet et al. (2009) report that Peru exports about half of the world's fishmeal from its catch of 5–10 MMT/y of anchovies while half of its population of 15 million live in poverty and 25% of its infants are malnourished. A campaign launched in 2006 combining scientists, chefs, and politicians to demonstrate that anchovies are more valuable to the Peruvian people and its economy as direct foods has resulted in a 46% increase in demand fresh and 85% increase in canned anchovies. One ton of fillets has sold for five times the price of 1 ton of meal and requires half the fish (3 tons for 1 ton fillets vs. 6 tons for 1 ton meal). Peru has decided to dedicate 30% of its annual food security budget (approx. US\$ 80 million) for programs to supply anchovies to its people. Higher prices for fish used as direct human foods for food security will limit processing of fish to meals for terrestrial animal and aquaculture feeds, thereby decreasing the supply of fishmeal and oils for global aquaculture trade and development, but meeting the Millennium Development Goals of eliminating everywhere extreme hunger and starvation. (2) Accelerating research into the elucidating functional feed ingredients in fish diets that are showing the potential to eliminate the needs for fishmeal and oils in aquaculture. Skretting Aquaculture Research Centre (2009) reported on research on “functional ingredients” that are contained in fishmeals and oils which contribute to efficient feed conversions and high growth rates, fish health, and welfare. Initial research focused on beta-glucans that stimulate the immune system of fish and protect against the effects of bacterial furunculosis but also allow reductions in fishmeal contents in diets to 25%. Additional research with phospholipids in meals, triglycerides in fish oil, and antioxidants in 2008 have resulted in excellent fish performances from feeds with almost no marine fishmeal and oil. Current research is exploring the extraction of functional ingredients from other non-marine by-products. (3) Developing alternative ecological aquaculture models that accelerate the movement towards use of agricultural, algal, bacterial, yeasts meals and oils.

The globalization of seafood trade has meant less dependence on local natural and social ecosystems, and has resulted in some virulent opposition to aquaculture development, especially as industrial aquaculture has removed the local sources of production and markets, and jobs have been externalized. One major

consequence of this globalization has been the increased dependence of industrial, “fed” aquaculture on the southeastern Pacific Ocean marine ecosystem for fishmeals and oils. The global implications for the Humboldt ecosystem, for local poverty, and the scoping of this unsustainable situation to the entire global protein food infrastructure are profound, and are still largely unrealized.

The Bangkok Declaration expressed the need to develop resource-efficient farming systems which make efficient use of water, land, seed and feed inputs by exploring the potential for commercial use of species feeding low in the food chain. Although significant resource competition exists, significant technological advancements in aquaculture over the past decade have occurred to make production systems less consumptive of land, water and energy, to the point where aquaculture resource use, overall, is comparable to poultry production. However, there are serious questions about feed resources over the next decade. The potential is limited for direct or on-farm integration to satisfy national food security due to the limited on-farm resource bases, especially in Africa. To make a more significant contribution by increasing production there is a need to use off-farm inputs, as has occurred most dramatically in Asia. Currently, about 40% of aquaculture depends on formulated feeds: 100% of salmon, 83% of shrimp, 38% of carp (Tacon and Metian, 2008). An estimated 72% of all use of global aquafeeds is by low trophic level herbivorous and omnivorous aquatic organisms (carps, tilapias, milkfish and shrimp) (Figure 4). Trophic level positioning for aquaculture species that is contained in the “Fishbase” database for wild species is thereby less useful as an indicator of “sustainability”.

The major species being fed in Asia are “herbivores/omnivores” such as tilapia, rohu, grass carp, common carp, and *Pangasius*, each of which dominates in various countries. Where aquaculture is growing rapidly—China, Vietnam, Bangladesh and India, for example—many finfish aquaculture systems are increasingly being fed on lower quality “cakes”, which are mixtures of local brans, oil cakes, and manure from intensive terrestrial animal feedlots. Discharges from these systems are causing water quality problems. Movement of these aquaculture production centers towards the use of high quality complete feeds could exert major pressure on global (and regional) marine and agricultural meals/oil resources. *Pangasius* catfish development in ponds in the Mekong Delta of Vietnam by 2007 was estimated at 683,000 MT, 97% fed by commercial feeds from 37 feed companies (Phan et al., 2009). Plans are to expand this production to 1.5 million MT over the next few years, causing concerns not only over feed but on water use as well.

The next 20 years will see an increase in the efficient use of land, water, food, seed and energy through intensification and widespread adoption of integrated agriculture-aquaculture farming ecosystems approaches. However, this will not be enough to increase aquaculture production as these will improve only the efficiency of use, and increase aquaculture yields per unit of inputs. An exponentially growing population will require aquaculture to expand rapidly into land and water areas that are currently held as common pool resources (“commons”). This raises issues of access to and management of common pool resources, which could result in conflicts with exiting users and potentially acute social, political, and economic problems. Nobel Laureate Elinor Ostrom provides important insights for the future expansion of aquaculture in a more crowded world striving to be resource-efficient and sustainable. Ostrom has studied how humans interact with ecosystems in common pool resource systems, emphasizing the value of self-organization, stakeholder engagement due to the complexity of issues, the diversity of actors involved, and the growing scarcity of resources that have to be shared. Her proposal is that of a local, “polycentric approach”, where key management decisions should be made as close to the scene of events and the actors involved (Ostrom, 1990; Ostrom et al., 1994). Examples of the merits of such approaches to smallholder aquafarmers now exist, especially in Asia (De Silva and Davy, 2010).

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Table 1. Summary of key resource use in aquaculture, issues associated with use, and trends in use 2000 to 2050

Resources	Key Resource Issues	Trends to 2050
Land	<p>Ponds have high land use in comparison to terrestrial agricultural protein production systems; Rice fields are increasingly being converted in to fish ponds in many countries (Hambrey et al., 2008); Application of the use of “footprints” to quantify areas of ecosystem support services required per MT of aquaculture production as important metric being used.</p>	<p>Ponds taken over by urbanization; Cage systems proliferating with user conflicts driving the development and use of submerged systems; More widespread use of cages in small water bodies, reservoirs and coastal open water uses but submerged systems more common in marine areas; Intensive, recirculating systems are more efficient uses of land (ha/MT aquaculture production) than terrestrial animal production systems but remain uneconomic in most areas of Asia in comparison to other production systems; More widespread use of integrated aquaculture into landscape-scale systems of mixed aquaculture/land uses; Greater use of land/water use planning to address growing land/water user conflicts.</p>
Water	<p>High water use in ponds in comparison to terrestrial agricultural protein production systems; Severe water competition growing with alternative users; Massive damming and urbanization in Asia diverting water to coastal cities and agriculture;</p>	<p>Upstream dams cut off downstream users; Freshwater use conflicts and droughts increase in aquaculture production zones closing many pond areas; More rapid development of cage systems in open waters; Rapid decrease in the costs and increased efficiencies of intensive, recirculating systems that use water more efficiently than ponds and terrestrial animal production systems; Multiple uses of water in landscape scale systems of mixed reservoir production with downstream aquaculture/agriculture; Changes to traditional rice/fish systems in Asia, with large scale land modification, addition and replacement of rice with high value species (prawns) in Bangladesh, Vietnam and China;</p>

		<p>Development of seawater farming systems in arid areas;</p> <p>Development of low energy membranes with wind turbines breaking the 2kW/hr/m³ barrier which accelerates use of seawater for freshwater aquaculture.</p>
Feed	<p>Overuse of marine meals/oils threatening sustainability of pelagic fish stocks; High feed costs; Fish feed ingredients imported, with a crisis in feed qualities; meat-bone meal also imported, quality is not assured; Social equity/poverty concerns with use of pelagics as feeds rather than as direct human foods; PCB and mercury contamination of fish meals/oils.</p>	<p>Increased use of imported fishmeals/oils in formulated feeds for traditional carps & exotic tilapia species in Asia, esp. China, decreasing FCR; Increased use of wet feeds (cakes, wastes from poultry processing plants; us of chicken manures in South Asia fish culture with high FCRs (>3.0) result in deterioration of water quality; Decreased use of marine meals/oils in intensive cage/tank systems and improvement in FCRs; Replacement of marine meals/oils by agricultural sources and by algal/bacterial/fungal bioreactors but new issues arising about aquaculture leading to deforestation; Use of biotechnology to elongate/upgrade essential fatty acids; Cleansing of oils by high technology.</p>
Seed	<p>Inadequate and unreliable supply of quality seed; Poor genetic quality of seed; Basic production from regional hatcheries—the human infrastructure, financial & business/marketing support and policy and legal frameworks are not in place in many nations; Impacts of uncontrolled releases of cultured seed stocks</p>	<p>Rapid expansion of export-oriented international seed trade esp. of high-value species; Increasing need to introduce quality assurance measures beyond simple official zoosanitary certificates; Regional hatchery infrastructure taking shape in many nations</p>

Table 2. Production Efficiencies of Edible Proteins from Some Aquaculture Systems Compared with Some Animal Agriculture Systems (modified from Costa-Pierce 2002 except where indicated)

Food Systems	Food Conversion Ratios (kg dry feed/kg wet weight gain +/- standard deviation)	% Edible	Production Efficiencies (kg dry feed/kg of edible wet mass)
Tilapia	1.5 (0.2)	60	2.5
Catfish	1.5 (0.2)	60	2.5
Marine Shrimp	1.5 (0.5)	56	2.7
Freshwater Prawns	2.0 (0.2)	45	4.4
Milk	3.0 (0.0)	100	3.0
Eggs	2.8 (0.2)	90	3.1
Broiler Chickens (Verdegem et al., 2006)	2.0 (0.2)	59	3.1
Swine	2.5 (0.5)	45	5.6
Rabbits	3.0 (0.5)	47	6.4
Beef	5.9 (0.5)	49	10.2
Lamb	4.0 (0.5)	23	17.4

Table 3. Trends in Fish In Fish Out Ratios from 1995 to 2008 (Tacon and Metian, 2008).

Subsidized aquaculture	FIFO (1995)	FIFO (2008)
Salmon	7.5	4.9
Trout	6.0	3.4
Eels	5.2	3.5
Misc. Marine Fish	3.0	2.2
Shrimp	1.9	1.4
Net production aquaculture		
Chinese and Indian major carps		0.2
Milkfish		0.2
Tilapia		0.4
American catfish		0.5
Freshwater prawns		0.6

Table 4. Efficiencies of Land Use for Aquaculture System. Production figures taken from Verdegem et al. (2006).

System types	Descriptions	Production (kg/ha/year)	Efficiency of Land Use (m²/MT)
Extensive	On-farm resources	100-500	20,000-100,000
Extensive	On-farm resources, fertilizers	100-1000	10,000-100,000
Semi-intensive	Supplemental feeds, static	2000-8000	1,250-5,000
Semi-intensive	Supplemental feeds, water exchanges	4000-20,000	500-2,500
Semi-intensive	Supplemental feeds, water exchanges, night aeration	15,000-35,000	300-700
Intensive	Complete feeds, water exchanges, night aeration	20,000-50,000	200-500
Intensive	Complete feeds, water exchanges, constant aeration	20,000-100,000	100-500

Table 5. Area of ecosystem support services needed to salmon fishing and farming systems (Tyedmers, 2000)

Salmon Species, Systems	Area Use (ha/MT)
Farmed Chinook	16.0
Farmed Atlantic	12.7
Fished Chinook	11.0
Fished Coho	10.2
Fished Sockeye	5.7
Fished Chum	5.2
Fished Pink	5.0

Table 6. Estimated consumptive water usages in aquaculture and terrestrial agriculture protein food

production systems¹

Systems	Estimated Freshwater Use (liters/kg product)	References	Comments
LOW USE	Ave. use less than 3000 liters/kg product		
Seawater farming (halophytes, marine fish, shellfish, seaweeds, euryhaline fish such as tilapia)	0-100	Hodges et al. (1993); www.seawaterfoundation.org ; Federoff et al. (2010)	Freshwater use is for makeup waters to replace evaporation in land-based farming systems
Small farm pig production	0-100	Zimmer and Renault (nd.)	In China about 80 % of pig meat production (est. 454 million heads) is of this type
Vegetables (cabbages, eggplants, onions)	100-200	Smil (2008)	
Lemons, limes, oranges, grapefruit, bananas, apples, pineapples, grapes	286-499	Barthelemy et al. (1993)	In California, USA
Recirculating aquaculture systems	500-1,400	Verdegem et al. (2006)	Intensive Africa catfish, eel and turbot fed complete feeds
Wheat, millet, rye	1,159	Barthelemy et al. (1993)	In California, USA
Wheat	1,300	Smil (2008)	
Sugar	1,929	Barthelemy et al. (1993)	In California, USA
Soybeans	2,000	USDA (1998)	
Legumes (peas, beans)	2,000-4,000	Smil (2008)	
Rice	2,300	Smil (2008)	
Egg production	2,700	Verdegem et al. (2006)	
Milk production	2,700	Verdegem et al. (2006)	Temperate dairy farm
Freshwater fish production	2,700	Verdegem et al. (2006)	Intensively mixed pond with production of 100 MT/ha/yr
Tilapia	2,800	Brummett (1997)	

HIGH USE	Ave. use 3000-10,000 liters/kg product		
Some legumes	>3,000	Smil (2008)	
Sunflowers	3,283	Barthelemy et al. (1993)	In Egypt
Catfish	3,350 (with reuse for irrigation)	Brummett (1997)	
Catfish	4,000-16,000 (lowest for undrained embankment ponds, highest for drained watershed ponds)	Boyd (2005)	Eliminating well water as consumptive use would decrease water use in embankment ponds to 2,600-3,200 ¹
Broiler Chickens	3,500	Pimentel and Pimentel (2003)	
Rapeseed and Mustard Seed Oils	3,500	Barthelemy et al. (1993)	In California, USA
Chicken	4,000	Smil (2008)	
Pigs (farrow-finish operation)	4,700	Verdegem et al. (2006)	
Fish in freshwater ponds	5,200	Verdegem and Bosma (2009)	If infiltration, drainage and recharge are considered green water
Soybean oil	5,405	Barthelemy et al. (1993)	In Egypt
Coconut Oil, Cottonseed Oil, Palm Oil, Palm Kernel Oil, Sesame Seed Oil	5,500	Zimmer and Renault (nd.)	Malaysia, Indonesia
Pork	6,000	Pimentel and Pimentel (2003)	
Channel Catfish	6,300 industry wide	Brummett (1997)	
Pangasius catfish Vietnam	6,400 ave. industry wide	Phan et al. (2009)	
Fish in freshwater ponds	4,700-7,800	Verdegem et al. (2006)	Production of 10-20 MT/ha/yr with nighttime aeration
Sunflower Seed Oil	7,550	Barthelemy et al. (1993)	In California, USA
Groundnut Oil	8,713	Barthelemy et al. (1993)	In California, USA
Pork	10,000	Smil (2008)	

EXTREME USE (ave. use >10,000 liters/kg product)			
Shrimp farming in ponds	11,000-43,000	Beveridge et al. (1991)	
Olive Oil	11,350	Barthelemy et al. (1993)	In Tunisia
Fish culture	11,500	Verdegem et al. (2006)	Fed freshwater species
Beef	15,000-43,000	Smil (2008); Pimentel and Pimentel (2003)	
Butter	18,000	Barthelemy et al. (1993)	In California, USA
Trout (90% recycling)	25,000 (252,000 withdrawal)	Brummett (1997)	
Boneless Beef	30,000	Smil (2008)	
Fish in freshwater ponds	30,100	Verdegem et al. (2006)	Production of 30 MT/ha/yr with 20% water exchange
Extensive fish culture	45,000	Verdegem et al. (2006)	No feed
Sheep	51,000	Pimentel and Pimentel (2003)	
Pangasius catfish Vietnam	up to 59,700	Phan et al. (2009)	Wide range from 700 to 59,700
Trout (75% recycling)	63,000 (252,000 withdrawal)	Brummett (1997)	

¹Consumptive water use in aquaculture remains a controversial measure. Hargreaves (pers. communication) noted that Boyd (2005) defined, then measured water use in aquaculture, but that his definition included groundwater use as consumptive use which contradicts the definitions used by hydrologists and agricultural scientists (Gleick, 2003; Falkenmark and Lannerstad, 2005; Lamm, 2008).

Table 7. Ranking of Fossil Fuel Protein Production Efficiencies for Various Aquatic and Terrestrial Food Production Systems (summarized from Costa-Pierce 2002; Troell et al., 2004; where multiple studies exist they are both listed)

Food Production Systems	Fossil Fuel Energy Input/Protein Output (kcal/kcal)
LOW ENERGY USE (ave. use less than 20 kcal)	
North Atlantic Herring Fisheries	2-3
Seaweed aquaculture, West Indies and elsewhere	1 (range 5-7)
Carp Aquaculture, Asian ponds	1-9
Vegetable Row Crops	2-4
North Pacific Salmon Fisheries	7-14
Atlantic Salmon Ranching	7-33
Tilapia Aquaculture, Indonesian ponds	8
Trout Cage Aquaculture, Finland & Ireland	8-24
Rangeland Beef	10
Sheep Agriculture	10
North Atlantic Cod Fisheries	10-12
Mussel Aquaculture, European Longlines	10-12
USA Dairy	14
Tilapia Aquaculture, Africa Semi-Intensive	18
HIGH ENERGY USE (ave. use 20-50 kcal)	
Cod Capture Fisheries	20
Rainbow Trout Raised in Cages	24
USA Eggs	26
Atlantic Salmon Capture Fisheries	29
Pacific Salmon Fisheries	up to 30 (range 18-30)
Broiler Chickens	up to 34 (range 22-34)

American Catfish Raised in Ponds	up to 34 (range 25-34)
Swine	35
Shrimp Aquaculture, Ecuador Ponds	40
Atlantic Salmon Cage Aquaculture, Canada & Sweden	up to 50 (range 40-50)
EXTREME USE (ave. use greater than 50 kcal)	
North Atlantic Flatfish Fisheries	53
Seabass Cage Aquaculture, Thailand	67
Shrimp Aquaculture, Thailand Ponds	70
Feedlot Beef	up to 78 (range 20-78)
Oyster Aquaculture, Intensive Tanks, USA	136
North Atlantic Lobster Capture Fisheries	up to 192 (range 38-59)
Shrimp Capture Fisheries	up to 198 (range 17-53)

Table 8. Total Energy Use Efficiencies of Agriculture versus Salmon Farming Systems. To obtain salmon production, data in Table 2 in Ayer and Tyedmers (2008) was used and a cage depth of 5 m.

Food Systems	Production (MT/ha)	MJ/MT	References
Sugar Beets	57.9	550	Elferink et al. (2008)
Potatoes	47.0	940	Elferink et al. (2008)
Soybeans	2.5	2,950	Elferink et al. (2008)
Wheat	8.2	3,100	Elferink et al. (2008)
Canada Salmon Net Pen Water-Based	1,000	26,900	Ayer and Tyedmers (2008)
Canada Salmon Bag System Water-Based	1,733	37,300	Ayer and Tyedmers (2008)
Canada Salmon Flow- through Land Based	2,138	132,000	Ayer and Tyedmers (2008)
Canada Salmon Recirculating Land- Based	2,406	233,000	Ayer and Tyedmers (2008)

Table 9. Technological Progress in Desalination of Seawater by Reverse Osmosis (RO) (Smil, 2008)

Developments	kW-hr/m³
Min theoretical electricity need	0.86
1990's RO plants	5-7
Ashkelon, Israel (250,000 m ³ /day)	3.85
R&D (Affordable Desalination Collaboration)	1.5

Table 10. Different organisms/technologies used in biological management of nitrogenous compounds to improve water quality in aquaculture systems (Yusoff et al., 2010). References to the many individual studies that are summarized here can be found in the paper.

Organisms/ technologies	% reduction/uptake
Bacteria – <i>Nitrosomonas</i> and <i>Bacillus</i>	96% TAN
Fungus – <i>Aspergillus niger</i>	25 mg TAN/L
Fungus – <i>Penicillium</i>	0.72 mg TAN/L
Macrophyte – <i>Elodea densa</i>	0.2 mg NH ₄ -N/L; 0.4 mg NO ₂ -N/L
Biofilter	3.46 g TAN/m ³ /day; 0.77 g NO ₂ /m ³ /day
Trickling filter	0.24-0.55 g TAN/m ² /day 0.64 g TAN/m ² /day
Microbead filter	0.45-0.60 g TAN/m ² /day 0.30 g TAN/m ² /day
Fluidized bed reactor	0.24 g N/m ² /day
Seaweed – <i>Ulva lactuca</i>	49-56% mean NH ₃ -N
Seaweed – <i>Ulva pertusa</i>	0.45 g N/m ² /day
Periphyton – cyanobacteria	91% TAN/L; 91% NO ₂ -N/L
Periphyton- diatoms	62% TAN/L; 82% NO ₂ -N/L
Periphyton	0.56 mg TAN/L
AquaMats®	0.22 g ammonia/m ² /day
Biofilms	0.42 µg ammonia/L
Immobilized nitrifying bacteria	4.2–6.7 mg TAN/L/day

Figure 1. Pelagic fish harvested and fed to aquaculture systems is predicted to decline while aquaculture production grows rapidly from 2006 to 2020 (Tacon and Metian 2008)

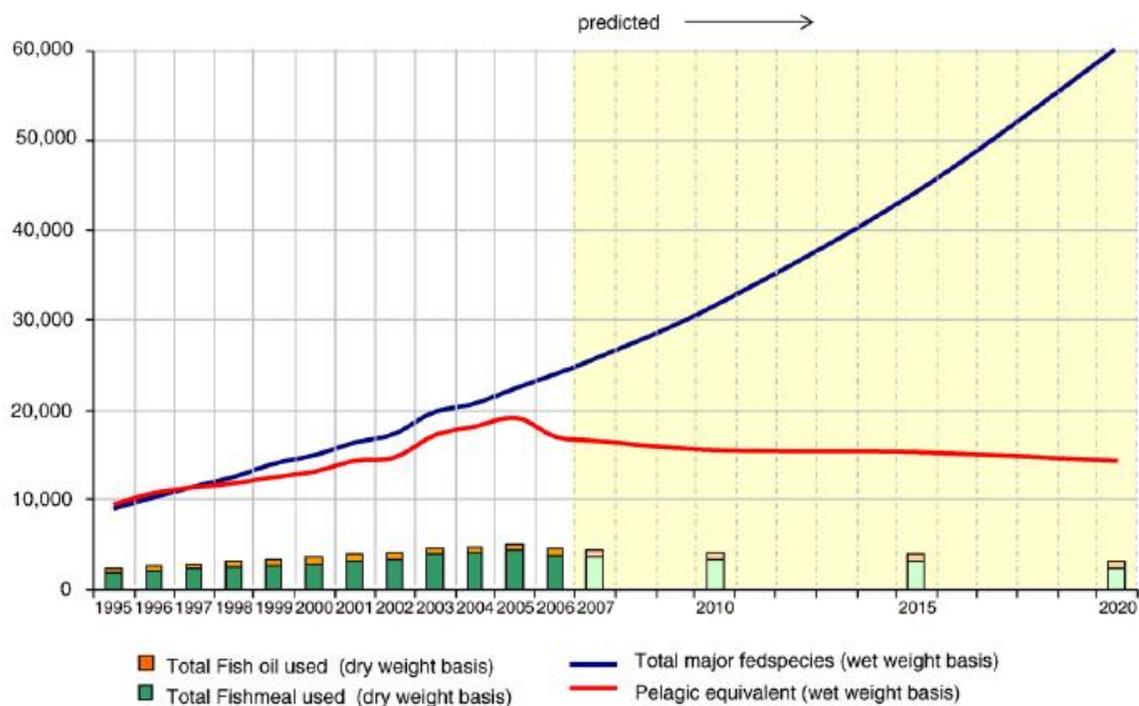


Figure 2. Aquaculture ecosystems mimic the form and functions of natural ecosystems. They are knowledge-based designed farming ecosystems planned as combinations of land and water-based plant, agronomic, algal and animal subunits which are embedded into the larger context of human social systems (Costa-Pierce, 2010).

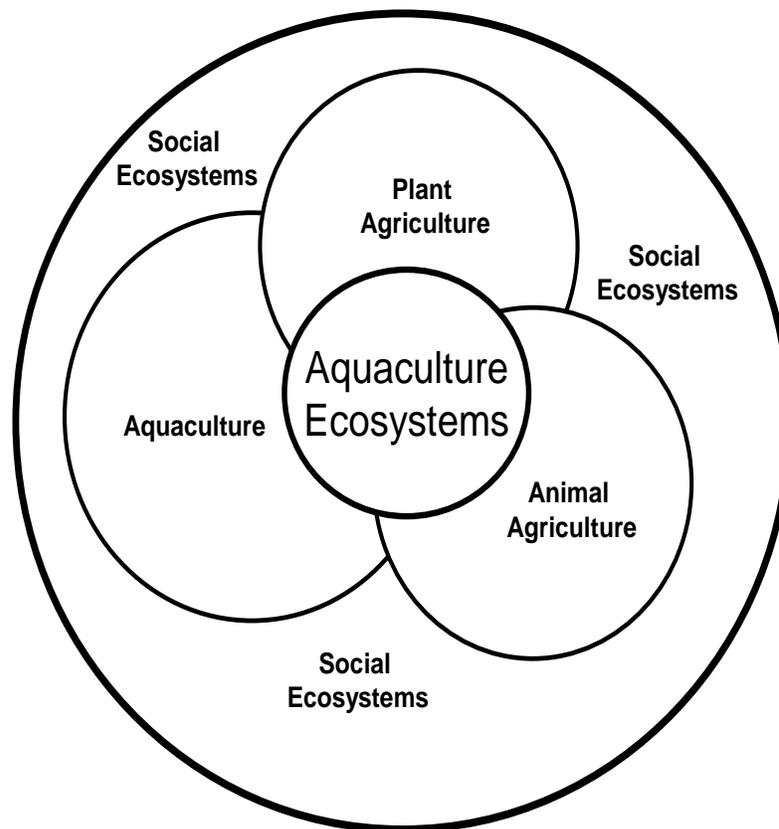


Figure 3. Success of aquaculture developments is not only the alignment of the “seed, feed and the need”. Each of these vital aquaculture resources has important interactions with natural ecosystems and the larger society in which they are located and therefore must be planned for in a comprehensive manner, not downgraded, misplaced or as an afterthought in the planning for more sustainable food systems. Comprehensive planning for aquaculture’s economic, employment, ecological and social interactions with opportunity costs in fisheries and agriculture, and goods and services provided by natural ecosystems can ensure not only aquaculture’s success, but also society’s success (Costa-Pierce, 2010).

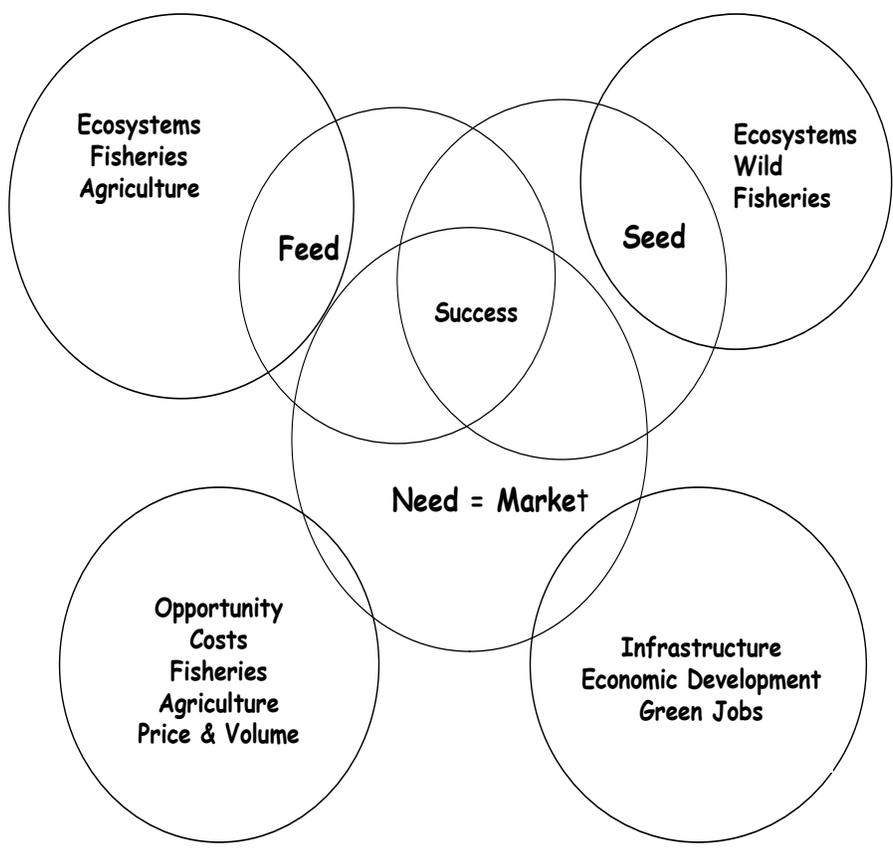


Figure 4. The major global consumers of aquafeeds are herbivorous and omnivorous fish and shrimp (Tacon et al., 2007)

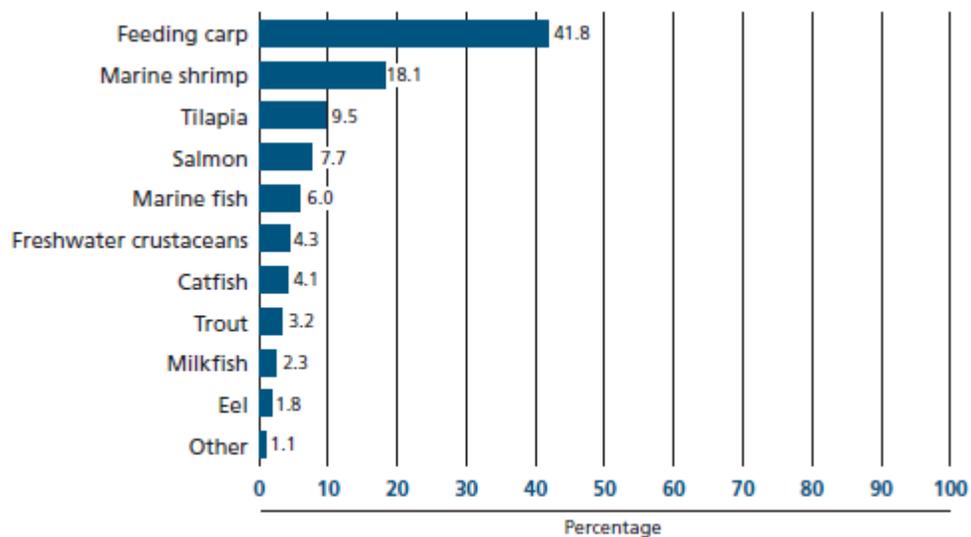


Figure 5. Coastal ecological aquaculture systems of the future will merge energy, desalination, wastewater treatment with integrated aquaculture-agriculture systems to deliver renewable sources of energy, food and water. This pictorial diagram is an ecological design which connects three coastal 3 MW electric generating windmills to a coastal desalination plant using low energy, reverse osmosis membranes (the Ashkon plant in Israel is pictured) to produce freshwater that can be used for: a) for human direct consumption (120,000 persons), and/or b) food production in integrated reservoir/aquaculture-agriculture farming systems.

