PAPER

Sustainable Ecological Aquaculture Systems: The Need for a New Social Contract for Aquaculture Development

AUTHOR

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ABSTRACT

Ecohistories of aquaculture suggest that aquaculture is a natural part of human development throughout history and that modern, industrial aquaculture could strengthen its social and ecological roots by articulating its evolution along a sustainability trajectory and by adopting fully the Food and Agriculture Organization (FAO) ecosystems approach to aquaculture (EAA; Soto et al., 2008). The EAA creates a new code for global aquaculture development, combining into one common framework the two most important social–ecological trajectories for global aquaculture—aquaculture for the world's rich and aquaculture for the world's poor. Knowledge of the rich archeology and anthropology of aquaculture connects this FAO code to antiquity, creating a single development pathway for aquaculture throughout human history. Without widespread adoption of an EAA, FAO (2009) projections of aquaculture development over the next 30 years may provide a far too optimistic scenario for its global growth. In this regard, aquaculture over the last 20 years has been criticized as lacking adequate attention and investment in developing grassroots, democratic, extension processes to engage a broader group of stakeholders to evolve the "blue revolution." As an example, there has been a failure of fisheries and aquaculture to plan together to ensure sustainable supplies of seafood—the world's most valuable proteins for human health—for seafood-eating peoples. Nonfed aquaculture (seaweeds, shellfish) has received worldwide attention for its rapid movement toward greater sustainability, which has led to more widespread social acceptance. For fed aquaculture, recent trends analyses have suggested that aquaculture is turning from the ocean to land-based agriculture to provide its protein feeds and oils. As such, more sophisticated, ecologically planned and designed "aquaculture ecosystems" will 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 that is inclusive of all stakeholders and decision makers in fisheries, agriculture, and ecosystems conservation and restoration.

The successful application of new knowledge and breakthrough technologies, which are likely to occur with ever-increasing frequency, will require an entirely new interdisciplinary approach to policy-making: one that operates in an agile problem-solving environment and works effectively at the interface where science and technology meet business and public policy. It must be rooted in a vastly improved understanding of people, organizations, cultures, and nations and be implemented by innovative strategies and new methods of communication (Lane, 2006).

Aquaculture Is Not a Global Panacea for Seafood

The Food and Agriculture Organization (FAO, 2009) "State of World Fisheries and Aquaculture 2008 Report" received much press due to its loud pronouncement that aquaculture now contributes about half of the world's seafood. This release was celebrated by global aquaculture advocates and policy makers but also was met with consternation among some capture fisheries and environmental NGO circles. At aquaculture conventions worldwide, this news was greeted with much boasting—the kind of which is routine among keynote speakers at aquaculture gatherings—which recant a tale that reads like, "because the world capture fisheries are dead or all collapsing, that the world must turn rapidly away from hunting the seas, to farming them, and that aquaculture must (and will) grow at a breathtaking pace everywhere."

However, if we look more closely at the FAO (2009) statistics, we do not have the massive development of aquaculture all over planet Earth everywhere outside of China. Aquaculture's growth is restricted to very few places and countries. With potentially billions of dollars of multilateral and bilateral aid at stake in global aquaculture development, it is important to reanalyze the data which show the following:

(1) The world is not eating half of its seafood from aquaculture. The world has watched, and is watching, a blue revolution … in China. In 2006, China accounted for 67% of all global aquaculture production, 34.4 million metric tons [MMT] of a total world aquaculture production of 51.7 MMT. In addition, Chinese aquaculture production is largely feeding China (FAO, 2009), not the world. For the rest of the world, aquaculture production in 2006 was just 17.2 MMT (FAO, 2009). Therefore, outside of China, aquaculture provided just 23% of world fisheries production, not 47%. In addition, most global aquaculture production remains—for all the controversies over shrimp and salmon—freshwater fish (54%) and mollusks (27%) (FAO, 2009). Especially for mariculture, there are major concerns that it will not experience the phenomenal growth that has occurred for freshwater aquaculture due to user conflicts, lack of suitable sites, water quality degradation, and the high cost and availabilities of feedstuffs.

(2) Global capture fisheries are not "dead." Albeit of great concern due to mismanagement and alarming global trends, especially so since global marine capture fisheries production peaked in the late 1980s (Watson and Pauly, 2001; Pauly et al., 2003), capture fisheries still provide an estimated 81.9 MMT (FAO, 2009) and are the major animal protein source for the majority of seafood-eating peoples of the planet, especially for the world's poor (Hall et al., 2010).

(3) With a few notable exceptions, such as Norway, aquaculture development in the rich countries is very limited in scope and has not occurred to any significant degree. All of Europe and North America provide less than 5% of global aquaculture production (FAO, 2009). The share of world aquaculture production for the 27 nations of the European Union has dropped over the past 10 years from 4% to 2%. In the United States, production declines have been occurred over the past 5 years in farmed catfish, trout, and shrimp, with positive trends only for shellfish aquaculture and salmon aquaculture in Maine. New land-based and coastal sites are limited as the global population has shifted from 97% rural in 1800 to 50% rural in 2007 (United Nations, 2008). In the rich countries, aquaculture development has been slowed by user conflicts and access to sites, obtuse and ever-changing regulatory regimes, lack of government investments at a meaningful commercial scale, consumer disinterest, and a lack of aquaculture education by local, coastal, and other environmental decision makers.

(4) With a few notable exceptions such as Brazil, Bangladesh, India, Vietnam, and Egypt, aquaculture development in the world's poorest nations has not occurred. In Africa, 200 million people have between 22% and 70% of their dietary animal protein from fish, whereas in developed countries the average is just 13% (Heck et al., 2007). Africa provides only 1% of the world's aquaculture production ad less than 5% of Africa's fish production, with most development concentrated in Egypt where aquaculture production has grown 10-fold since the 1990's (FAO, 2009).

To meet seafood demands due to projected population growth to 2030, FAO (2009) has estimated that at least an additional 40 MMT of aquatic food will be required to maintain the current per capita consumption. This forecasts that world aquaculture production will exceed 90 million tons and surpass global capture fisheries production. I argue that such an expansion of aquaculture globally in the rich and poor countries outside of China might not occur because of the following:

(1) The current industrial aquaculture development paradigm is inadequate at all levels of government and that without major government subsidies, aquaculture will not spread as rapidly in the next two decades as it has in the past two unless ecological aquaculture as an alternative development model for aquaculture becomes the dominant development model.

(2) Most national decision makers are unaware of and are not planning for the magnitude of the world's coastal urban, land, energy, and water crises, and the implications on food production of these vast societal challenges that need to occur—Brown (2009) calls this "mobilizing to save civilization"—and are continuing to be duped by "20th century thinking" into believing that there are vast areas of a virgin ocean planet and adequate feedstuffs just waiting for a large

expansion of “fed aquaculture” developments, which there are not.

(3) Professional, regulatory “decision-maker communities” in aquaculture and fisheries are so separate structurally and functionally in many countries to the point that they have lost track of their common goal of delivering environmentally friendly, safe, sustainable seafood to the people they serve. Professional fisheries managers are working everywhere to recover damaged capture fisheries in both developed and developing nations. Recovered fisheries will add price and volume competition to aquaculture in many regions of the world, in some cases making aquaculture development not economically feasible, a fact which may not be captured in global statistics. The world will need all the fish it can produce sustainably from capture fisheries as well as develop aquaculture. Management conflicts and educational deficiencies between fisheries and aquaculture managers will need to end as products that sustain livelihoods will be needed from both.

There is an urgent need for institutions that train the next generation of professional stewards in a new “sustainable seafood” paradigm (Smith et al., 2010). This would result in the development of a cadre of decision makers who could conduct the integrated planning for aquaculture, fisheries, ecosystems, and their allied regional social infrastructures. The target areas of the world where this is most needed are ones where aquatic food are the most important contributors to livelihoods and human well-being and where aquaculture development has the greatest potential to be developed without displacing capture fisheries.

Ecological Aquaculture as an Alternative Development Model for Aquaculture

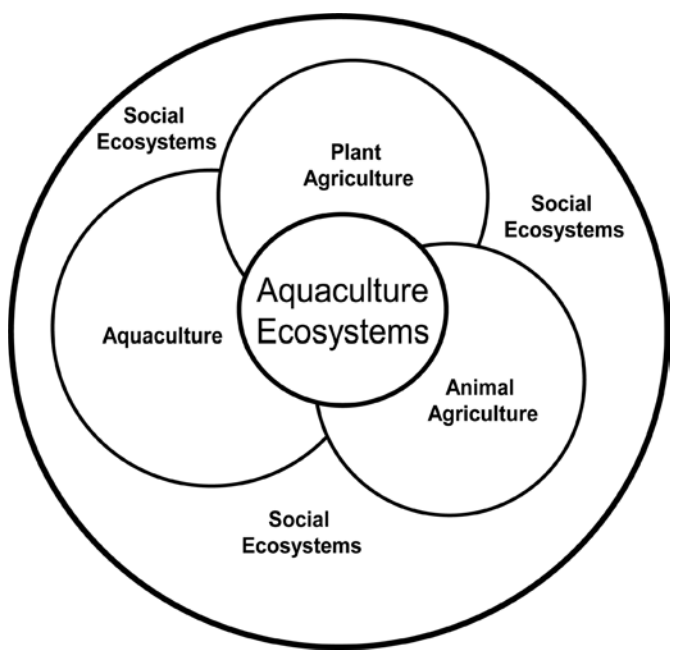
Ecological aquaculture, the cultivation of essential aquatic proteins vital to human health, longevity, and community sustainability, is an integral part of our common planetary wisdom and cultural heritage, an essential part of our past, and a vital part of our future evolution as a sophisticated species living in peace with the Earth’s invaluable, complex aquatic ecosystems.

Ecological aquaculture is an alternative model of aquaculture development that not only brings the technical aspects of ecosystems design and ecological principles to aquaculture but also incorporates—at the outset—social ecology, planning for community development, and concerns for the wider social, economic, and environmental contexts of aquaculture. Ecological aquaculture plans for and evaluates both the economic and the social profit of aquaculture. It uses the science and practices of natural and social ecology to better plan for aquaculture as a means for sustainable community development and working waterfronts (Costa-Pierce, 2002a, 2003, 2008a).

Ecological aquaculture plans, designs, develops, monitors, and evaluates aquatic farming ecosystems that preserve and enhance the form and functions of the natural and social environments in which they are situated. Ecological aquaculture farms are “aquaculture ecosystems” (Figure 1). Aquaculture depends on inputs connected to various food, processing, transportation, and other sectors of society. In turn, aquaculture ecosystems

FIGURE 1

Aquaculture ecosystems mimic the form and functions of natural ecosystems. These sophisticated, knowledge-based, designed, farming ecosystems are planned as combinations of land and water-based agronomic, algal, and animal subunits that are embedded into the larger context of human social systems.



can produce valuable, uncontaminated waste waters and fish wastes, which can be important inputs to ecologically designed aquatic and terrestrial ecological farming systems. These integrated food production systems can be planned and organized at all levels of society as socially responsible businesses, schools, family farms, or community-based operations. Ecological aquaculture also uses the "aquaculture toolbox" to play vital roles in nonfood, natural ecosystem rehabilitation, reclamation, and enhancement (Costa-Pierce and Bridger, 2002).

Ecological aquaculture takes a global view, integrating ecological science and sharing technological information in a sophisticated, knowledge-based manner, promoting innovation and efficiency in the global marketplace by incorporating social and environmental costs, not externalizing them (Culver and Castle, 2008). Thus, ecological aquaculture plans not only for seafood production and economic profit but also for social profit by developing social capital and social networks that promote business, education, and community stewardship practices.

Ecological Aquaculture Throughout the History of Human Development

> *Before it became the New World, the Western Hemisphere was vastly more populous and sophisticated than has been thought—an altogether more salubrious place to live at the time than, say, Europe (Mann, 2005).*

Aquaculture has a long, fascinating pre-history with well-documented "blue revolutions" occurring throughout human history (Table 1). Thus, in contrast to the popular press in the West, "blue revolutions" are nothing new and have occurred throughout human history. In this light, societies worldwide are embroiled only in aquacultures' latest and likely its most important "industrial" iteration. However, few, if any, of these seminal moments in the history of aquatic peoples have ever been studied by professional anthropologists or archeologists. Notable exceptions are the works of Beveridge and Little (2002) and Edwards (2009) who studied in depth the roots of Asian and European aquaculture as important parts of our common, historical "food-producing wisdom."

The field of "aquaculture anthropology" does not exist yet to formulate a unifying theory of how aquaculture

TABLE 1

Documented "blue revolutions" in aquaculture societies from antiquity to historical times. There have been many blue revolutions throughout human history.

Places, Regions, and Approximate Dates	Aquaculture Social Ecologies and Ecohistories	References
Egypt (New Kingdom, 4,000 years ago)	Tombs show tilapia being cultured in drainable fishponds integrated with agriculture	Chimits (1957)
China (Zhou Dynasty at least 2,300 years ago)	Aquaculture monograph by Fan Li published; evidence of integration of fish and rice 8,000 years ago; in Tang Dynasty, sophisticated multispecies carp polycultures are developed resulting in significant increases in food (fish and crops) per unit area	Beveridge and Little (2002); Edwards (2004, 2006); Lu and Li (2006)
Europe (Etruscans and Romans 2,100–2,200 years ago)	Start of "vallicoltura" coastal aquaculture by the Etruscans on Adriatic and Tyrrhenian coasts; Roman literature describes that fish in ponds were commonplace	Beveridge and Little (2002)
Bolivia (Beni Province, 2,000 years ago)	The Beni is ~30,000 square miles of raised agricultural fields integrated with fish/irrigation canals	Mann (2005, 2008)
Cambodia (more than 1,000 years ago)	Traditional integrated agriculture/aquaculture systems may have developed first in Cambodia	Edwards et al. (1997)
Mexico (Valley of Mexico City, 1000–1400 AD, but could stretch back 6,000 years ago)	Chinampas floating garden islands in lakes that were separated by channels where fish were grown	Aghajanian (2007)
Indonesia (West Java, 1200–1400 AD)	Milkfish in coastal ponds	Schuster (1952)
Hawai'i (from Polynesian settlement to 1778)	The ahupua'a aquaculture ecosystems sustained a high population density of islanders until European contact	Costa-Pierce (1987, 2002b)

develops and how it evolves into the human development equation of seafood-eating peoples. The late pioneering anthropologist Claude Levi-Strauss (1958) brought the idea of "structuralism" to anthropology, which is the concept that societies throughout history follow universal patterns of behavior. In tribute to him, I have formulated a simple anthropological theory on the evolutionary, "social ecology" of aquaculture that

> *whenever the demands of seafood-eating peoples exceeded the abilities of their indigenous aquatic ecosystems to adequately provide for them, these cultures, throughout the world, have developed aquaculture.*

Modern aquaculture has few if any connections to its ancient past. And all too often, there are no connections made even to its recent past! As a consequence, many proposals for modern aquaculture developments are all too frequently marketed as "new" or "pioneering" and, at worst, duplicative of past efforts. When this neglect occurs, society loses, and the aquaculture profession limps along, losing opportunities to aggregate and deliver "teachable moments." Another way of saying it is that the world loses important opportunities to "evolve the blue revolution" and develop the background, baselines, and place-based ecological and social contexts of aquaculture so that more informed decisions can be made by politicians, investors, and communities.

However, although the roots of ecological aquaculture are in Asia (Ruddle and Zhong, 1988; Edwards, 2009), there is a new model that has developed in this cradle of aquaculture history. Fast forwarding to the present has seen many Asia countries, especially China in the 1990s to the present choose to pursue an industrial model of aquaculture development, intensifying and importing vast quantities of feedstuffs for formulated feeds (Tacon and Metian, 2008). As a result, freshwater aquaculture yields in China have increased approximately 10× in just 20 years (FAO, 2009). Intensification has led to many benefits in income and employment for aquafarmers (Edwards, 2002) but has also led to widespread water pollution and a dismantling of much of its rich ecological aquaculture heritage.

An Ecological Approach to Aquaculture

In 2006, the Fisheries and Aquaculture Department of FAO recognized the need to develop an ecosystem-based management approach to aquaculture similar to the Code of Conduct for Responsible Fisheries. FAO suggested that an ecological approach to aquaculture would have three main objectives: human well-being, ecological well-being, and the ability to achieve both via effective governance, within a hierarchical framework that was scalable at the farm, regional, and global levels (Soto et al., 2008).

In 2008, FAO defined an EAA as "a strategy for the integration of aquaculture within the wider ecosystem such that it promotes sustainable development, equity, and resilience of interlinked social–ecological systems." An ecosystems approach to aquaculture (EAA), similar to other systems approaches to natural resources management, accounts for a complete range of stakeholders, spheres of influences, and other interlinked processes. Applying an ecosystem-based approach requires planning for physical, ecological, social, and economic systems as a part of community development, taking into account stakeholders in the wider social, economic, and environmental spheres that affect aquaculture (Soto et al., 2008). FAO developed three principles and key issues for an EAA at different scales of society:

> *Principle 1: Aquaculture should be developed in the context of ecosystem functions and services (including biodiversity) with no degradation of these beyond their resilience capacity.*

The key issue is to estimate resilience capacity, or the limits to "acceptable environmental change." A range of terms has been used to estimate the limits to environmental change, including "environmental carrying capacity," "environmental capacity," "limits to ecosystem functions," "ecosystem health," "ecosystem integrity," and "fully functioning ecosystems," all of which are subject to a specific social/cultural/political context (Hambrey and Senior, 2007). Conventional environmental impact assessments touch on just some of these issues. Application of the precautionary approach is important but is inadequate and oftentimes misused by decision makers in aquaculture; rather, the use of aquaculture risk assessments is becoming more widespread (GESAMP, 2008).

> *Principle 2: Aquaculture should improve human well-being and equity for all relevant stakeholders.*

Aquaculture should provide equal opportunities for development, which requires that its benefits be more widely shared, especially locally so that it does not bring detriment to any sector of society, especially the poor. Aquaculture should promote both food security and safety as key components of human well-being, especially for the world's poor in developing countries.

Principle 3: Aquaculture should be developed in the context of other sectors, policies and goals.

Interactions between aquaculture and its influences on the surrounding natural and social environment must be recognized. Aquaculture often has a smaller impact than other human activities, for example, agriculture and industry, but it does not take place in isolation. There are many opportunities to couple aquaculture activities with other primary producing sectors to promote materials and energy recycling and the better use of resources in general.

Applying an Ecological Aquaculture Approach at Different Scales of Society

There are three physical scales important in the planning for and assessment progress toward an ecosystem approach to aquaculture: farm scale, watershed/aquaculture zone, and global. Each of these has important planning and assessment needs.

Farm Scale

Planning for aquaculture farms is easily defined physically and could be few meters beyond the boundaries of farming structures; however, the increasing size and intensity of some farms (e.g., large-scale shrimp farming or salmon farming) could affect an entire water body or watershed. Assessment of an EAA at the farm scale entails an evaluation of planning and implementation of "triple bottom line" programs—ecological, economic and social programs—that in a comprehensive manner account for impacts to the wider ecosystem and social impacts of farm-level aquaculture developments, including use of better ("best") management practices, and use of restoration, remediation, and mitigation methods. Proper site selection, levels of production intensity, use of species (exotic vs. native), use of appropriate farming systems technologies, and knowledge of economic and social impacts at the farm level should be considered.

For fed aquaculture, there are many concerns as to the current trajectory and growth of the large-scale aquaculture industries. "Classic" concerns over the current aquaculture development models are being modified rapidly by advances that will affect the widespread adoption of ecological aquaculture which, if projected to 2050, confirm that large-scale aquaculture may move fully toward ecological aquaculture approaches (Table 2). There are numerous, well-documented, emerging success stories in ecological aquaculture (Table 3).

Watershed/Aquaculture Zone Scale

Planning for an EAA at watersheds/aquaculture scale is relevant to common ecosystem and social issues such as diseases, trade in seed and feeds, climatic and landscape conditions, urban/rural development, etc. Assessment of an EAA at this scale is a two phase process and will include, at phase I, assessments of the following:

(1) inclusion of aquaculture as a part of regional governance frameworks, for example, the overall framework of integrated coastal zone management or integrated watershed, land–water resource management planning and implementation. Assessments take into account existing scenarios, user competition and conflicts for land and water uses, and comparisons of alternatives for human development;
(2) impacts of aquaculture on regional issues such as escapees, disease transmission, and sources of contamination to/from aquaculture; and
(3) social considerations such as comprehensive planning for all of the possible beneficial multiplier effects of aquaculture on jobs and the regional economy, and considerations of aquaculture's impacts on indigenous communities.

At phase II, progress toward a full implementation of an EAA at watersheds/aquaculture zone scale can be assessed by measuring the

(1) abilities of governments to implement new methods of coastal and water governance to include ecological aquaculture;
(2) development of ecological aquaculture approaches that allow agencies responsible for permitting aquaculture to consider and manage activities impacting aquaculture and aquatic ecosystems (e.g., capture fisheries, coastal zone development, watershed management organizations, agriculture, forestry, and industrial developments) more holistically, such as new mechanisms to communicate, cooperate, and collaborate across sectors; and
(3) design of ecological aquaculture management zones and parks that encourage aquaculture education, research, and the development

TABLE 2

Major issues with fed aquaculture today (2010) and projections of these to 2050.

Issues	Concerns	Modern Developments (2010)	Trajectory of Issues to 2050
Feeds/no net gain	Schroeder (1980) documents pond can be a net consumer rather than a producer of animal protein. Fishing down and farming up marine food webs (Naylor et al., 2000; Pauly et al., 1998a,b)	Food conversion rates improve to ~1:1; fish in/out (FIFO) ratios drop to ~1.7; domestication of farmed species turns carnivores into domesticated omnivores	FIFO ratios drop to 1 or less; aquaculture uses ~50% of world's fish meal and oil with balance met by agricultural meals/oils
Feeds/ocean sustainability	Integrity of marine ecosystems damaged by high removal rates of feed species by fishing for terrestrial animal, pet, and aquaculture feeds	Aquaculture use dropping due to rapid cost increases in meals/oils; poverty/social concerns recognized	Ecosystem modeling parcels out science-based removal rates/ allocations for aquaculture and ecosystems
Feeds/poverty	Massive poverty and hunger in fish meal/oil producing countries	New recognition in Peru; new international attention to role of meal/oil fisheries and fed aquaculture in poverty alleviation	Governments move to develop seafood products to prioritize human needs/ alleviate poverty
Habitat destruction	Mangrove destruction and water diversions disrupt nearshore and riverine ecosystems (Pullin, 1993)	Some nations (e.g., Thailand) develop policies to prevent damage by proper siting and to rehabilitate damage of shrimp farms	Governments worldwide ban developments in sensitive conservation areas; widespread use of carrying capacity models (McKinsey et al., 2006) and ecological valuation for decision-making
Eutrophication	Intensive aquaculture operations are feedlots producing nutrient pollution loads comparable to human sewage (Folke et al., 1994)	Complete feeds, automated feed delivery systems and nutrition research deliver less pollution; wastes are primarily in the form of soluble nutrients and feces, not waste feeds; documentation that human sewage contains human pathogens that are not present in aquaculture wastes	Development of land-based recirculating systems; widespread use of land-based integrated aquaculture and water-based Integrated Multi-trophic Aquaculture systems
Energy	Intensive aquaculture operations are energy intensive comparable to industrial agriculture and fisheries	Scattered R&D in energy use, mostly Life Cycle Analyses in aquaculture; little/no movement toward use of renewables	Renewable energy systems used

of innovations and partnerships and also emphasize streamlined permitting of integrated aquaculture, polyculture, or innovative, integrated aquaculture–fisheries businesses and initiatives.

Global Scale

Planning for an EAA at a global scale considers aspects of transnational and multinational issues for global commodities (e.g., salmon and shrimp). Assessment of progress toward an EAA at the global level entails evaluation of issues such as: availabilities of fisheries and agriculture feedstocks for formulating aquaculture feeds and impacts on distant marine and social ecosystems, the economic and social impacts of aquaculture on fisheries and agriculture resources, impacts of aquaculture on markets, and impacts of globalization on social sustainability (social capital, goods, and social opportunities). Applications of tools such as lifecycle assessments of aquaculture commodities and the use of innovative social enterprise management guidelines and tools (Dees and Backman, 1994) are useful to determine impacts at the global scale.

Systems Ecology of Aquaculture

In the worldwide effort to increase food production, aquaculture

TABLE 3

Global success stories in ecological aquaculture.

Region/Countries	Aquaculture Ecosystems	References
Asia (China, Vietnam, Indonesia)	Rice-fish culture benefits millions of rural people; rice-fish aquaculture ecosystems have been designated as a "Globally Important Agricultural Heritage System"	World Fish Center (2008); FAO (2009); Lu and Li (2006); Dela Cruz et al. (1992)
Asia (China, Thailand, Cambodia, Vietnam, Indonesia)	Integrated aquaculture benefits millions of rural people	Edwards (2009)
Asia (China)	Integrated Multi-trophic Aquaculture of fish, shellfish, and seaweeds bioremediates and increases total yields up to 50%	Zhou et al. (2006)
Egypt	Integrated aquaculture produced over 650,000 tons of tilapia in 2008, ~60% of total fish production; provision of cheap source of fish at approx. same cost as poultry	McGrath (2009)
Canada	Integrated Multi-trophic Aquaculture has been adopted by Cooke Aquaculture, the largest salmon aquaculture company in eastern Canada	Chopin et al. (2001); Chopin (2006); Ridler et al. (2006, 2007)
Canada and United States	Shellfish aquaculture has become widely accepted as environmentally friendly and socially acceptable	National Research Council (2010)
Tanzania	Seaweed and shellfish aquaculture	Seaweed grown by ~2,000 producers most women; new half-pearl industry growing (2009)

merits more attention than raising grain-fed cattle (Goodland and Pimental, 2000).

Aquaculture needs to adopt an ecosystems approach, use ecological principles and methods, incorporate ecosystem-based management concepts and guidelines (see McLeod and Leslie, 2009), and use of systems ecology, ecological modeling, and ecological economics methods in its design, operations, and communications. Using such guidance and tools, the possibilities for designing productive aquaculture ecosystems are many since aquaculture can encompass the wide availability of species, environments, and cultures.

There are well-developed examples of aquaculture ecosystems, both land and water based, mostly in Asia (Costa-Pierce, 2008b; 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 scale ecological models that have a tight integration between aquaculture and agriculture (Rakocy, 2002; Costa-Pierce and Desbonnet, 2005; Costa-Pierce, 2008b).

At the watershed/aquaculture zone scale (Soto et al., 2008), there are few examples of ecological approaches to well-planned, larger scale developments. Most attention is paid to environmental impact assessments (Black, 2001). The best examples globally of an ecological approach to aquaculture at the watershed/aquaculture zone scale are from Israel and Australia. Both nations face severe land, water, and energy constraints. 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). These aquaculture ecosystems are productive, semi-intensive enterprises that are water and land efficient, and are net energy and material gains to society which follow principles similar to the fields of agroecology and agroecosystems (Pimentel and Pimentel, 2003).

In Australia (Fletcher et al., 2004a), an approach to aquaculture development was built as part of a larger, national effort in fisheries to develop an Ecologically Sustainable Development (ESD) framework (Fletcher et al., 2004b). The Australian ESD framework identified important issues, developed comprehensive reports for each issue, and then prioritized each using risk assessments. The ESD process employed extensive community consultation that considered social and environmental values, considered all other marine users and their management plans for their operational, environmental, and administrative attributes, then proposed development and monitoring plans. As a result of this well-articulated process, nine marine aquaculture zones of 2,400 ha in Port Phillip Bay and Westernport, Victoria, Australia were permitted. The Australian ESD approach combined analytical and participatory methods and developed plans that considered both ecosystem and human well-being, then developed implementation strategies by designing and enhancing an effective governance systems for the expansion of aquaculture.

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). Since fish products are the most widely traded products globally, there have been concerns raised as to the global benefits of not only industrial aquaculture but also the merits in general of all aquaculture development. Naylor et al. (2000) raised the issue of fed aquaculture being a net loss of protein to humanity; however, they were not the first to do so—20 years earlier, Schroeder (1980) commented that the "pond can consume fish." There are a number of concerns about the trajectory of modern industrial aquaculture; however, it is important to recognize the merits of aquaculture in comparison to other methods of large-scale food production. There has been neglect to complete comparative production and energy efficiencies of aquaculture versus other large-scale capture fisheries and terrestrial animal protein production alternatives (Naylor et al., 2000). Fish have the highest protein content in their flesh of all food animals (Smil, 2002). 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 and the research, policy, and regulatory challenges that need to be put into place to make a more ecological approach to future aquaculture development.

Farmed (fed) fish are inherently more efficient than any terrestrial farmed animals. They are cold-blooded (poikilotherms) and thus have to divert less of their ingested food energy to maintain body temperatures in comparison to farmed, land animals. In addition, fish are neutrally buoyant in their watery world and thus do not devote as much food energy to maintain bones/posture against gravity as do land animals. Thus, they can devote more ingested food energy to flesh and therefore have a much higher meat/bone ratio (and meat "dress out" percentages). There are inherent differences processing stored energy between terrestrial and aquatic ecosystems. On land, primary producers (plants) convert sunlight into plant structures to a larger degree in comparison to aquatic plants, and land plants store more energy as starches. Aquatic plants (algae) store oils (lipids) as their primary energy sources. Fish convert these lipids much more efficiently than do land animals converting starch and other carbohydrates (Cowey et al., 1985). No other food animal converts feed to body tissue as efficiently as fish (Smil, 2000).

Aquatic animals use nitrogen much more efficiently than terrestrial animals. Nitrogen use efficiency for beef is 5%, pork is 15%, whereas shrimp are 20% and fish are 30% efficient (Smil, 2002). As a result, aquatic animals release two to three times less nitrogen to the environment in comparison to terrestrial animal food production systems.

Mass and Energy Balances

Comparisons of energy and production efficiencies of aquaculture versus an array of fisheries and terrestrial agriculture systems show that fed aquaculture is an efficient mass producer of animal protein (Table 4). 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 tilapia and catfish use less than 3 kg to add 1 kg of edible weight.

Energy use in low trophic level aquaculture (seaweeds, carps, tilapias, and mussels) is comparable with energy usages in vegetable, sheep, and rangeland beef agriculture (Table 5). Highest energy use is in cage and shrimp aquaculture comparable with intensive agriculture feedlots, with extreme energy use reported for some aquaculture operations in Thailand (Table 5). Capture fisheries are inefficient in comparison with pond aquaculture. 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 five times the amount of energy. Energy costs for intensive salmon cages are less than lobster and shrimp fishing but are comparable to beef production in feedlots (Table 5). Ayer and

TABLE 4

Production efficiencies of edible proteins from some aquaculture systems compared with some animal agriculture systems (modified from Costa-Pierce, 2002c).

Food Systems	Food Conversion Ratios (kg dry feed/kg wet weight gain ±1 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
Freshwater prawns	2.0(0.2)	45	4.4
Marine shrimp	2.5(0.5)	56	4.5
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

Tyedmers (2009) completed a life cycle assessment of alternative grow-out technologies for salmon systems in Canada. They found that for net pens, feeds comprised 87% of total energy use and fuel/electricity 13%. Energy use in land-based recirculating systems was completely opposite: 10% used in feeds and 90% in fossil fuels and electricity.

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 3.20 (Pauly et al., 1998b). 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). Duarte et al. (2009) recently estimated a mean trophic level of 1.9 for mariculture and 1.0 for agriculture and livestock. 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. (1998b) state are "0 to 1.5 levels above that of lions." However, in the wild, salmon are not top level carnivores because salmon are consumed by whales, sea lions, and other marine predators and thus cannot be compared to lions. In aquaculture systems, salmon eat agricultural and fish meals and oils so it cannot be classified at same trophic level "lions," rather they are feeding as farmed omnivores.

Most recent debates over the efficiencies of fed aquaculture have focused on "fish in/fish out" (FIFO) ratios. 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, halibut, sole, cod, hake, haddock, redfish, sea bass, congers, tuna, bonito, and billfish, Naylor et al. (2000) reported >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 deemed to be net producers using less wild fish than produced. At the time, these data were widely criticized by aquaculture scientists and producers as not accounting for the latest advances in aquaculture, as authors chose to calculate FIFO ratios using food conversion ratios for farmed marine fish and farmed salmon of 5:1 and 3:1 (Naylor et al., 2000). In contrast, rapid advances in aquaculture feeds, feed management technologies, and nutrition science had decreased food conversion ratios to approximately 1.5:1 for farmed marine fish and approximately 1.2:1 for farmed salmon (Tacon, 2005).

Jackson (2009) presented more recent FIFO data for all global aquaculture and for farmed salmon. These calculations showed that global aquaculture, as currently practiced, is a net benefit to humanity, not a loss. 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. 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 was produced, confirming the Naylor et al. (2000) concern that some aquaculture systems were a net loss of protein to society from the FIFO perspective. Kaushik and Troell (2010) criticized calculations of Jackson (2009) recalculating a global FIFO

TABLE 5

Ranking of fossil fuel protein production efficiencies for various aquatic and terrestrial food production systems (summarized from Costa-Pierce, 2002c; Troell et al., 2004; where multiple studies exist they are both listed).

Food Production Systems	Fossil Fuel Energy Input/Protein Output (kcal)
Low energy use	1–20
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 and Ireland	8–24
Rangeland beef	10
Sheep agriculture	10
North Atlantic cod fisheries	10–12
Mussel aquaculture, European longlines	10–12
U.S. dairy	14
Tilapia aquaculture, Africa semi-intensive	18
High energy use	20–50
Cod capture fisheries	20
Rainbow trout raised in cages	24
U.S. 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 and Sweden	up to 50 (range 40–50)
Extreme use	>50
North Atlantic flatfish fisheries	53
Sea bass cage aquaculture, Thailand	67
Shrimp aquaculture, Thailand ponds	70
Feedlot beef	up to 78 (range 20–78)
Oyster aquaculture, intensive tanks, United States	136
North Atlantic lobster capture fisheries	up to 192 (range 38–59)
Shrimp capture fisheries	up to 198 (range 17–53)

of 0.7 for fed aquaculture; in addition, they emphasized the need to consider the environmental performances of aquaculture systems as more comprehensively assessed from life cycle and equity approaches (Ayer and Tyedmers, 2009) were more appropriate measures of resource use and stewardship in aquaculture. 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 (Tacon and Metian, 2008).

Nonfed Aquaculture

Concerns and constraints regarding the expansion of global aquaculture are much different for fed and nonfed aquaculture. Indeed, for nonfed shellfish aquaculture, there has been a convergence over the past 10 years or so around the notion that user conflicts in shellfish aquaculture have been resolved due to not only technological advances but also 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, 2008a). Included in this "evolution" of shellfish aquaculture are the following:

(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 and aquaculture user communities,

(6) publication of global comparisons with fed aquaculture indicating a strong movement in shellfish aquaculture globally toward an adoption of ecological approaches to aquaculture at all scales of society (Costa-Pierce, 2008a).

Social Ecology of Aquaculture: Need for New Institutions with a New Social Contract

> *Institutions that can translate knowledge into action, such as nongovernmental organizations, extension arms of universities, and community user groups, are very few and have a weak capacity to meet contemporary needs. Universities in the developing world, generating knowledge for knowledge's sake or, more often, duplicating knowledge, are not moving fast enough to develop programs to meet new challenges. The reallocation of resources by bilateral donor agencies and foundations from short-term projects to new institutions that genuinely address long-term capacity-building could also reverse the present economic and environmental trends (Bawa et al., 2008).*

Many analysts are calling for new, more integrated, multidisciplinary ways of developing more ecologically and socially responsible food, energy, water, and waste systems to meet society's needs (Brown, 2009). Among the first was Lubchenco (1998), who called for a new social contract for science and society. Industrial aquaculture in its current development phase does not have a social contract or social license to expand in many areas of the world, especially at the watershed/aquaculture zone and global scales.

> *The only way aquaculture will acquire a new social contract and grow production into the future is by embracing the "sustainability transition"* (Figure 2) *and move quickly toward an ecological approach to aquaculture that promotes ecological intensification on existing sites, not by massively developing new areas.*

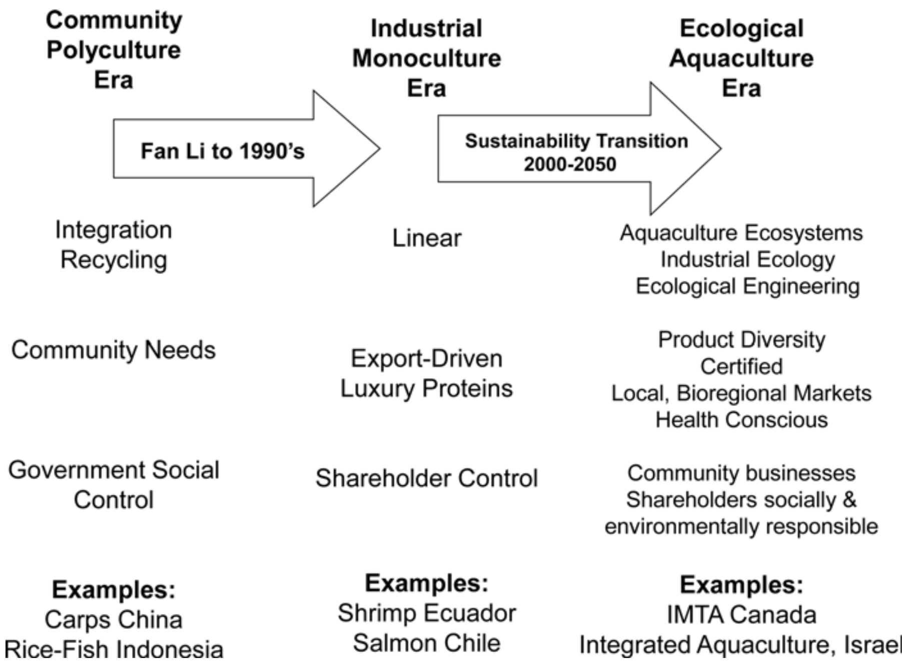
Emerging fields such as ecological aquaculture and agroecology before it (Gliessman, 1998; Altieri, 2002) are examples of "sustainability science," fields that address a broad and deep range of cross cutting issues that integrate many different types of information and tightly couple research with practice (Kates et al., 2001). An ecological aquaculture approach is fundamentally a sophisticated, knowledge-based enterprise that develops baseline information on natural and human ecosystems, then develops, evaluates, encourages, and communicates imagination, ingenuity, and innovation at both the individual and institutional levels (Culver and Castle, 2008). Although there is much information on the natural ecology of food-producing ecosystems, there are few comprehensive frameworks for capturing the necessary social ecology of aquaculture. Cadenasso et al. (2006) have developed a "human ecosystem framework" that could be a model for aquaculture which could assist in organizing multidisciplinary, social–ecological approaches to development.

Just as important are social investments in aquaculture at the individual level. Aquaculture has an urgent need for developing and engaging leaders who are well trained and experienced decision makers who are "honest brokers of policy alternatives" (Pilke, 2007). Keen et al. (2005) believe that transformation toward more sustainable practices will be much more likely if the individuals who make up society can accept change and modify their personal behaviors (Huckle and Sterling, 1996). Changes in the behavior of individuals can "scope up" and result in larger changes at the community and societal scales by employing a combination of trust building, favorable performance, accountability, flexibility and innovation, and the inclusion of stakeholders in strategic planning (Brehm and Rahn, 1997; Knack, 2002; UNESCO, 2005; UNICEF, 2006).

Folke et al. (2005) challenge our education system to continually adapt to the emergence of such new questions and changing social compacts as aquaculture. Any rapid

FIGURE 2

Three eras of historical aquaculture development. Humanity entered, for all food-producing industries, the sustainability transition at the turn of the 21st century as population growth, urbanization, resource constraints, and climate change have affected all industrial inputs and outputs (Brown, 2009).



progress toward an ecological approach to aquaculture will require development of education programs that promote broad awareness, recognition, and implications of new approaches to aquaculture and the creation of new institutions (Huckle and Sterling, 1996; Bawa et al., 2008). Bransford et al. (2000) suggest that for such subfields of sustainability science as aquaculture, more attention needs to be given to educating the next generation of leaders by teaching metacognitive skills such as practicing different ways of thinking in a variety of contexts, with less emphasis being placed on trying to fill students with a large volume of facts and knowledge.

A Strategy for the "Triple Bottom Line"

Aquaculture development plans will be incomplete unless both economic and social goals are articulated and agreed upon, at the outset, in transparent, participatory processes. Only then can aquaculture "evolve" as an integral part of—not separate from—farmers, fishermen, sustainable community development, and the future of "working waterfronts." Aquaculture's success cannot simply be defined as having successfully developed the hatchery, feed, and marketing components of a business plan—the old alignment of the "seed, feed, and the need." Rather, sustainable, ecological aquaculture nurtures "society's success" for the "triple bottom line" of economic, environmental, and social profit (Savitz, 2006) (Figure 3).

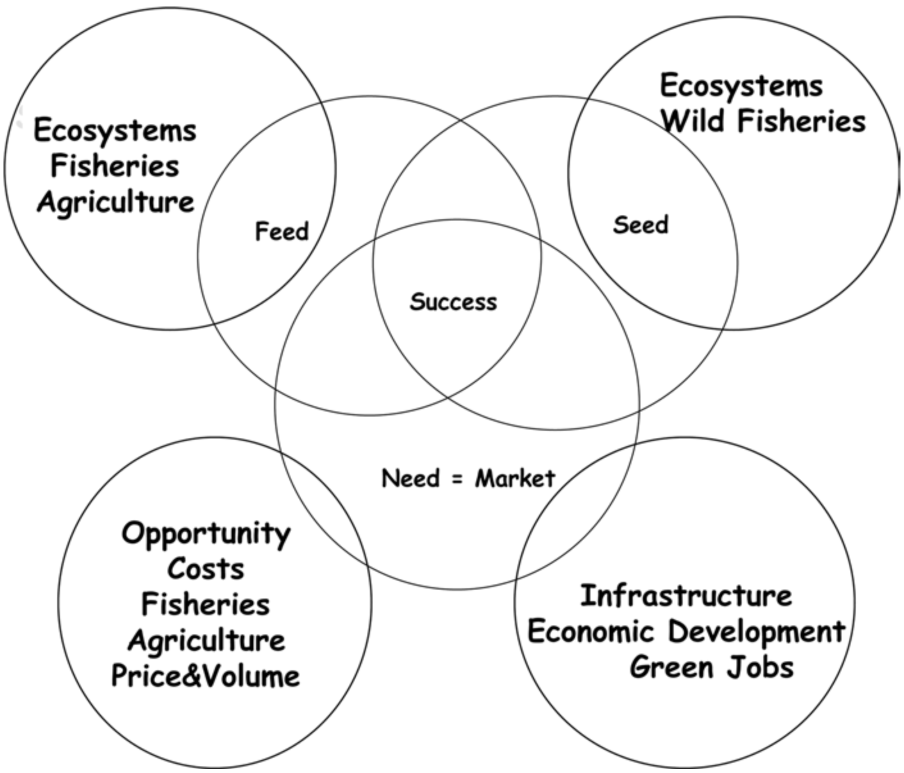
Adversarial social processes occur in jurisdictions where aquaculture is not being developed using a social–ecological "ecosystem approach." In these places, the blue revolution is being televised, tweeted, and blogged. Adversarial processes (conflicts) occur when stakeholders do not recognize each others interests as legitimate. These processes increase conflict, thrive on uncertainty, have poor communication, are exclusive, divisive, opaque, and closed, and lack trust. Collaborative processes must be created that create trust through shared learning and ownership, creative problem solving, joint fact finding, and employ adaptive management. Robertson and Hull (2003) call this a "public ecology" that has both process and content that emphasizes the participation of extended peer communities of research specialists, policy makers, and concerned citizens. Dasgupta and Maler (2004) are others also have tools developed by economists and ecologists to valuate choices in the midst of this complexity. In general, since aquaculture is such a dynamic, evolutionary field, managers, policy makers, and community leaders need to participate to allow understanding of new and emerging problems and to stimulate multidisciplinary research. Analysts report that such work is the highest impact science being published today (Jones et al., 2008).

Clear, unambiguous linkages between aquaculture and the environment must be created and fostered, and the complementary roles of aquaculture in contributing to environmental sustainability, rehabilitation, and enhancement must be developed and clearly articulated to a highly concerned, increasingly educated and involved public. New aquaculture operations must plan at the outset

(1) to become an integral part of a community and a region,
(2) to plan for community development by working with leaders to

FIGURE 3

Success of aquaculture developments is not only the alignment of the "seed, feed, and 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.



provide needed inputs and recycle wastes,

(3) to create a diversity of unprocessed and value-added products and provide local market access, since in rich societies aquaculture products are high-value discretionary purchases that can easily be rejected by the public, and

(4) to plan for job creation and environmental enhancement on both local and regional scales.

It is well documented that most aquaculture jobs are not directly in production rather in the affiliated service industries. In the United States, Dicks et al. (1996) found that aquaculture production accounted for just 8% of the income and approximately 16,500 jobs. Aquaculture goods and services accounted for 92% of the income and approximately 165,500 jobs (most jobs were in equipment, supplies, feeds, fertilizers, transport, storage, processing). However, most aquaculture development plans focus almost exclusively on production concerns and have little/no comprehensive plans for localization of seed, feed, markets, or other aquaculture service industries that produce the most benefits to local economies. Many industrial aquaculture operations import high paying professionals from the outside, and in many cases, feeds and services are imported to sites, and local people cannot even buy the produce!

An ecological aquaculture development model will create new opportunities for a wider group of professionals to get involved in aquaculture since new advances will be needed not only in technology but also in information, community development, and facilitation. Ecological aquaculture as a "new" field, one important for the future food security and environment of the planet, requires more comprehensive planning to evolve a new social contract with society.

Integrating Aquaculture, Fisheries, and Agriculture to Provide Sustainable Seafood and to Restore Aquatic Ecosystems

The "end of the wild" or the real and perceived mismanagement of the world's capture fisheries cannot be accepted as a future, inevitable conclusion of current trends in seafood production. Nor can the difficulties of sustaining the world's invaluable capture fisheries be used as a justification for encouraging unsustainable aquaculture development at the expense of investments to restore capture fisheries. A protein-hungry planet urgently needs to restore capture fisheries to full health everywhere.

In addition, the survival and sustainability of the world's seafood resources and all of the world's fed aquaculture developments depend on the sustainability of capture fisheries (and, increasingly, agriculture).

The Need to Integrate Aquaculture and Fisheries

Planning for aquaculture developments is poorly incorporated into the overall planning framework for sustainable seafood supplies, fisheries, and coastal zone management, whereas there are vital connections between capture fisheries and aquaculture not only in the ecological realm but also with fisheries management and economics, in seafood markets, and in many social dimensions. Although capture fisheries and aquaculture operations are researched, planned, and managed as if they were independent entities, they both share many common concerns about water quality, genetic diversity in hatchery-raised organisms, feeds, and the sustainability of fish meal/oil fisheries.

Aquaculture and capture fisheries are inextricably entwined, a fact most noticeable in the seafood marketplace, where, for example, "white fish" as cod, haddock, and tilapia are equally traded. There are substantial interactions between capture and cultured markets, and price and volume competition between fisheries and aquaculture products occur routinely in the modern marketplace. Competition from imports and from restored or seasonally abundant capture fisheries plus an unpredictable regulatory structure are important reasons why marine fish aquaculture has not received any significant attention by aquaculture investors in the United States.

Planning for sustainable seafood supplies for society must involve the close interactions of both aquaculture and fisheries planners. Little interaction occurs at present, but together they can affect policy decisions that could contribute to more sustainable local food production and jobs creation.

Ensuring sustainable seafood supplies includes planning not only for aquaculture because aquaculture is just one of at least five other means of delivering seafood supplies to societies:

(1) by sustaining capture fisheries,
(2) by expanding the consumption of underused fish,
(3) by using bycatch,
(4) by increasing processing efficiencies, or
(5) by increasing imports.

Increasing imports is a viable option for the rich countries such as the United States and the European Union, 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 (2009) reports that peak oil may be reached by 2030 and that humanity may have already consumed 1,228 of the estimated 2,000 billion barrels of the "ultimate recoverable resource."

Global capture fisheries have been declining since the mid-1980, and many important food fisheries are overfished (Pauly et al., 2003; Myers and Worm, 2003). However, for all the negative press and hype that the "collapse" of global capture fisheries has received, the facts are that capture fisheries are not "dead" everywhere, either globally or regionally, and that the world's fisheries managers are working with industry and governments everywhere, in many cases, better than ever before, to restore capture fisheries. Capture fisheries provide the major source of aquatic protein food to humanity and will so into the future. As a result, they will continue to provide substantial price and volume competition to aquaculture for generations to come, especially in the "white fish" seafood markets.

Globally, the FAO (2009) reported that global capture fisheries production has been stable over the past decade at approximately 92 million tons, with 82 million tons from marine waters and 10 million tons from inland waters. The proportion of fully exploited stocks monitored by the FAO has remained steady at approximately 50% from the mid-1970s to 2007. The proportion of overexploited and depleted stocks has stabilized at 25–30% since the mid-1990s to 2007. Of the stocks monitored by FAO, 2% were underexploited, 18% were moderately exploited, 52% were fully exploited, and 28% were overexploited. Capture fisheries are also not "dead" in the United States. The National Marine Fisheries Service (2009) determined that of the 251 fish stocks or stock complexes it assesses, 210 (84%) are not overfished. Every major fishery in the United States that is overfished is subject to a rigorous and often painful stock recovery plan.

Although capture fisheries production is unlikely to grow but be sustained into the future at current levels, there are three other options that need to be explored by planners for sustainable seafood supplies: (1) expanding the consumption of underused fish, (2) using bycatch as food, and (3) increasing processing efficiencies.

There are many examples of how societies worldwide are working to expand consumption of underused fish such as the Arrowtooth flounder (*Atheresthes stomias*), which has had the highest abundance of any groundfish species in the Gulf of Alaska since the 1970s (Turnock et al., 2005), and are rarely used because of both bycatch and processing issues. Advances in gear conservation engineering for this underused species (halibut excluder grate, Gauvin and Rose, 2008) and advances in gear conservation engineering for other important fisheries unharvestable due to high bycatch levels (such as the cod eliminator for a restored haddock fishery, see Beutel et al., 2008) could bring important new, regional sources of capture fisheries products to some areas over the next 40 years. For example, flatfish fisheries in the North Pacific are now closed before target quotas are reached because of halibut bycatch. Advances in bycatch reduction could be important for this fishery.

Rapid advances in fish processing and utilization can increase supplies of sustainable seafood to societies: surimi, minces, and rendering technologies are just a few of these advances (Blanco et al., 2006). Lastly, although approximately 70% of world fish production is used for human consumption and the remaining 30% is used to produce fish meal and oil, there are important trends in the future uses for the total utilization of fish such as bioactive compounds, pigments, antifreeze proteins, lectins, and leather.

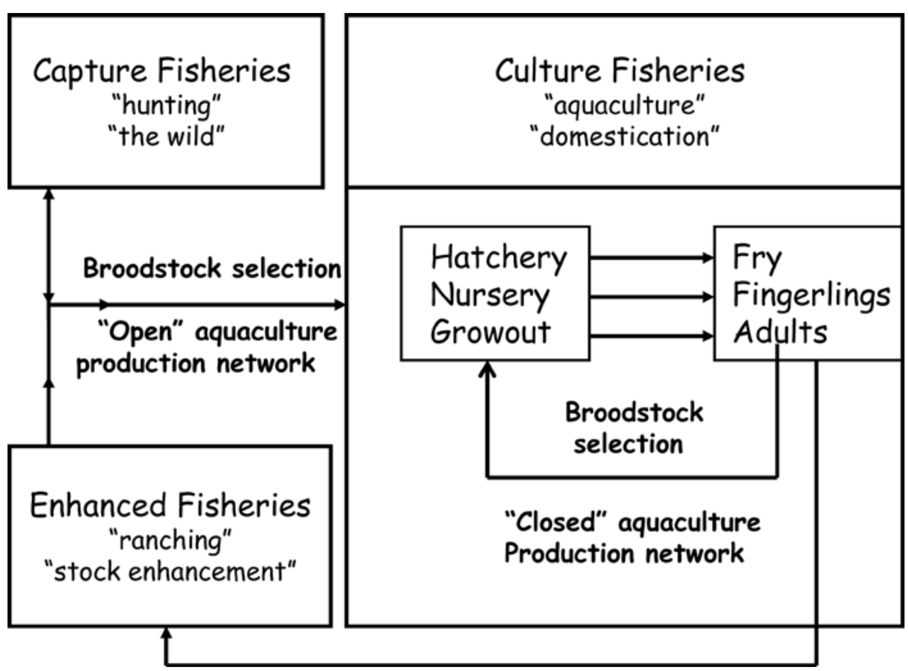
Fisheries and aquaculture today need to be combined into one professional and management field like never before in the history of the planet (Costa-Pierce, 2003). Fisheries science needs to incorporate aquaculture into the longer-term outlook for managing the fisheries of the future. Analyses of the trends in species having aquaculture and capture fisheries components are required along with in-depth examinations of the many functional interdependencies.

> *A more comprehensive planning framework with guidelines for incorporating aquaculture into the planning for sustainable fisheries and coastal zone management is needed to recognize the vital contribution of culture fisheries (aquaculture) and enhanced fisheries (ranching) to capture fisheries production and to enhance aquaculture's efficiencies to protect ecosystems and ecosystem services. There are intimate but little recognized and largely unplanned functional connections between capture fisheries, enhanced fisheries ("ranching"), and culture fisheries ("aquaculture")* (Figure 4).

These connections are important to the future of global fisheries production but are little recognized. For example, Alaska and many of the northern Pacific Rim nations depend on aquaculture to sustain salmon fisheries. Aquaculture hatchery and nursery net pens in Prince William Sound have added millions of salmon to the Pacific Ocean each year since the 1990s. Wertheimer et al. (2004) found that these hatchery salmon did not displace the region's wild pink salmon in Prince William Sound and that hatchery salmon have added to the size of Alaska's "wild" salmon harvest. Beamish and Riddell (2009) report that each year billions of hatchery salmon are added to a "common feeding area" of the northern Pacific Ocean by the United States, Canada, Russia, Japan, and Korea and that the success of hatcheries in adding to the region's fisheries are driven mainly by the interactions of the marine ecosystems responding to climate which, in turn, creates the conditions for good

FIGURE 4

There are fundamental but oftentimes unplanned connections between capture fisheries, enhanced fisheries, and aquaculture ("culture fisheries"). A closed aquaculture production network has little/no connection to the "wild" except for occasional replenishment of broodstock, whereas in an open aquaculture production network, production remains dependent on the wild. Until recently, the largest aquaculture industries in the world, such as carp farming in China, still relied on extraction of stocking materials from rivers. The "aquaculture toolbox" (hatcheries, nursery pens) is also used for the massive annual supplementation of the North Pacific salmon fisheries.



salmon growth or not. The concepts of pristine, "wild" fisheries, and untouched habitats are at odds with the modern fisheries/aquaculture science and management reality. There are important contributions of the use of aquaculture hatcheries to sustain "wild" fisheries. There are many other examples; modern lobster fisheries in the Atlantic are more akin to extensive aquaculture operations. It is time to focus fisheries/aquaculture planning not on fisheries and aquaculture but on food.

The Need to Integrate Aquaculture and Conservation Ecology

Although aquaculture has great potential to expand the production of commercially valuable species, it depends on intact natural ecosystems and ecosystem services. In turn, aquaculture is just a "tool box" with great potential for restoring aquatic ecosystems. There is an unbalanced focus on marine animal husbandry (e.g., "fed" aquaculture) causing a concomitant lack of appreciation for the positive environmental attributes of nonfood aquaculture such as marine agronomy, endangered species aquaculture, and aquaculture for environmental enhancement and rehabilitation, all of which use modern marine hatchery and nursery aquaculture practices.

Aquaculture in its current development is so beset with concerns over the future of fed aquaculture and capture fisheries, that it is oftentimes simplified into kind of a blood sport where battles are fought, and "all fisheries become cod, and all aquaculture, salmon." Missed in the controversies is one of the most important parts of the toolbox-the use of "aquaculture agronomy, restoration, and aquaculture conservation ecology" (Costa-Pierce and Bridger, 2002).

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 approximately 7% of total nitrogen and approximately 10% of total phosphorous discharges (Pitta et al., 1999). Classically, inappropriate siting of cages has been blamed for the destruction of nearshore and benthic aquatic ecosystems (Gowen and Bradbury, 1987). However, Mirto et al. (2009) found that if sea bass/bream cages were sited above sea grass (*Posidonia oceanica*) meadows that sea grasses responded positively to aquaculture discharges and that there were no impacts on benthic biodiversity. These findings raise the possibility that sea grass meadows can be created and enhanced by an ecological engineering systems approach and that evolving a nontoxic, cage ecological aquaculture model for fish production and environmental improvement could evolve in this region.

In this regard, there is little difference between aquaculture and the emerging fields of ecological engineering and industrial ecology. Indeed, tidal wetland, mangrove forest, coral, and sea grass restoration aquaculture—in addition to establishment and maintenance of oyster reefs—are important examples of aquaculture creating, enhancing, and maintaining productive marine ecosystems, habitats, and water quality.

The Need to Integrate Aquaculture and Agriculture

There have been questions as to whether aquaculture contributes to the depletion of world fisheries. This "aquaculture paradox" recognizes the dependence of both wild and farmed fish stocks on many of the same marine and agricultural resources—from food to habitats. Although there is much on-going policy, research, and management concerns on the interactions of marine food fish fisheries ("biomass fisheries") with aquaculture and human welfare, there is little to no planning regarding the future impacts of fed aquaculture on agriculture. Current projections forecast that fed aquaculture may in the future use 50% or less of the world's fish meal (Tacon and Metian, 2008) but expand use of agricultural and other terrestrial sources of feed proteins and oils. Feed alternatives are developing rapidly (Table 6).

Terrestrial proteins and oils from soybeans, sunflowers, and lupins are available at volumes larger than the quantity of global fish meal. Soybeans have high protein content of approximately 28%, peas have approximately 22%, and these have good amino acid profiles. Other abundant cereals have protein contents of only 12–15%. However, processing can create protein concentrates with protein levels of >50% (Bell and Waagbo, 2002). Vegetable oils have very low EPA and DHA levels. However, substitution of plant oils upward of 50% of added dietary oil has not resulted in growth reductions or increased mortalities in fish such as salmon and trout.

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.

TABLE 6

Protein and energy (oil) alternatives for aquaculture and terrestrial animal feeds are developing rapidly.

Alternative Meals/Oils	Notable Research and Developments	References
Soybean meals	Shrimp in semi-intensive culture in ponds could be grown on defattened soybean meal as their sole protein source	Piedad-Pascual et al. (1990); Bell and Waagbo (2002)
Insect meals	Meals made from mass-producing insects in culture; Indonesia constructing 4,000 maggot farms for fish feeds using palm oil by-products in Sumatra and Kalimantan	Ratliff (2008), Infofish International February 2010 (www.infofish.com)
Bacterial protein meals	Bacterial protein meals investigated as protein sources in salmon, rainbow trout, and halibut feeds with comparable results for growth, feed intake, and utilization up to 36% incorporation for salmon and trout	Aas (2006)
Vegetable oils and animal fats	~75% of dietary fish oil can be substituted with alternative lipid sources without significantly affecting growth performance, feed efficiency, and intake for almost all finfish species studied	Turchini et al. (2009)

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 with a 4% decrease in rainfall in land areas cleared for pasture.

Sustainable Seafood for the Poor

In comparison to other sectors of the world food economy fisheries and aquaculture sectors frequently are poorly planned, inadequately funded, and neglected by all levels of government. This neglect occurs in a paradoxical situation: fishing is the largest extractive use of wildlife in the world and aquaculture is the most rapidly growing sector of the global agricultural economy (Costa-Pierce et al., 2003).

Approximately 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. FAO has stated that the world will need to produce 70% more food for an additional 2.3 billion people by 2050. Scarce natural resources will need to be used more efficiently, and there will be a need for proper socioeconomic frameworks to address imbalances and inequities to ensure that everyone in the world has access to the food they need. Food production will have to be carried out in a way that reduces poverty and takes account of natural resource limitations.

The world's population will rise from 6.8 billion to 9.1 billion in 2050, with nearly all population growth occurring in the economically developing countries. Without additional global food strategies, an estimated 370 million people will be hungry in 2050. The magnitude of the problem is most acute in Africa. In 10 African countries of an estimated 316 million persons where aquatic proteins are an important dietary component (Table 7), 216 million live on US$2/day, 88 million are undernourished, and 16 million children younger than 5 years are malnourished (UNICEF 2006; Allison et al., 2009).

Small-scale coastal and inland freshwater fisheries provide more than 90% of the fish consumed in Africa. Over 2.5 million people are involved in fishing and 7.5 million in trading, marketing, and processing. The most important fisheries/aquaculture ecosystems are located on the coasts of west and southern Africa and the river basins of Senegal, Niger, Volta, Congo, Lake Chad, Nile, and Zambezi Rivers. But today, aquaculture provides less than 5% of Africa's fish, with most concentrated in Egypt and Nigeria (Allison et al., 2009).

Aquaculture is a global enterprise with local roots. There are strong concerns that aquaculture is evolving away from its global responsibility to provide net benefits (additional food) for a protein-hungry planet (Goldburg and Naylor, 2005; Alder et al., 2008; Naylor et al., 2009). Greater than 75% of global fisheries are traded.

TABLE 7

There is an urgent need to develop ecologically and socially appropriate and economically viable food and income-generating aquaculture models in these nations in Africa (modified from Allison et al., 2009).

Country	% Total Population Living on Less Than US$ 2/day	Fish Protein/Total Animal Protein in Diets (%)
Ghana	78	66
Senegal	63	43
DR Congo	N/A	43
Nigeria	90	34
Uganda	79	33
Cameroon	50	32
Malawi	76	31
Zambia	87	23
Mozambique	78	22
Mali	90	15

In 2000, more than 60% of fish meal was traded. Only 7% of meat is traded, 17% of wheat, and 5% of rice (FAO, 2009). To tackle this huge challenge, the FAO EAA (Soto et al., 2008) has not only created a new code for responsible global aquaculture development but also combined into one common development framework a global implementation strategy for aquaculture that can be used to measure the trajectory of social responsibility for global aquaculture.

If aquaculture is designed, implemented, and evaluated as aquaculture ecosystems, a new social contract would have a close relationship between aquaculture professionals who not only create an alternative model of aquaculture development but also interact closely with capture fisheries and agriculture to help deliver to the world's poor its needs for nutrient-dense, protein-rich seafood. Components of a global strategy could be as follows:

(1) To allocate more food fish and oils for poverty alleviation and human needs worldwide and allocate less marine resources for feed fish for fed aquaculture so as (a) to increase the ecosystem resilience of the Humboldt ecosystem and (b) to relieve the increasing overdependence of aquaculture countries such as Thailand (shrimp) and Norway (salmon) on this southeastern Pacific Ocean marine ecosystem.

Alder et al. (2008) estimated that about 36% of the world's fisheries catch (30 million tons) are processed into fish meal and oil, mostly to feed farmed fish, chickens, and pigs. Daniel Pauly of the University of British Columbia has stated that "Globally, pigs and chickens alone consume six times the amount of seafood as US consumers and twice that of Japan." Jacquet et al. (2009) reported that Peru exports about half of the world's fish meal from its catch of 5–10 MMT/year of anchovies, whereas 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 food has resulted in a 46% increase in demand for 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 (approximately US$80 million) for programs to supply anchovies to its people. Higher prices for fish used as direct human food for food security will limit processing of fish to meals for terrestrial animal and aquaculture feeds, thereby decreasing the supply of fish meals and oils for global aquaculture trade and development but meeting the Millennium Development Goals of eliminating everywhere extreme hunger and starvation.

(2) To accelerate research into the elucidating functional feed ingredients in fish diets that are showing the potential to eliminate the needs for fish meal and oils in aquaculture.

Skretting Aquaculture Research Centre (2009) reported on research on "functional ingredients" that are contained in fish meals 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 fish meal 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 fish meal and oil. Current research is exploring the extraction of functional ingredients from other nonmarine by-products.

(3) To develop alternative ecological aquaculture models that accelerate the movement toward use of agricultural, algal, bacterial, yeasts meals, and oils.

Aquaculture uses most of the world's fish meal (68%) and fish oil (88%); however, Tacon and Metian (2008) predict that fish meal and oil use in aquaculture will decrease to become high priced, specialty feed ingredients. Currently, about 40% of aquaculture depends on formulated feeds: 100% of salmon, 83% of shrimp, 38% of carp. Research on the use of agricultural meals and oils to replace use of ocean resources especially on the functional components of fish meals/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 that 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.

(4) To develop new governance systems that integrate aquaculture, agriculture, and fisheries using ecosystem-based management approaches that combine production, distribution, and consumption networks that do not institutionalize poverty and hunger but provide new alternative tools and education in multisectoral ecosystem approaches.

The massive environmental change being brought about by the accelerated growth of the world's population has caused profound change to the world's ecosystems. Crutzen and Stoermer (2000) have called this new era the "Anthropocene." In this era, massive quantities of additional foodstuffs will be needed to sustain humanity; nutrient-dense, high-quality aquatic proteins will be especially important. The tools and training of the next generation of transdisciplinary, sustainability scientists will have to be further developed and well used, or serious consequences for the Earth's living systems will result.

Summary

The main points of this paper are that the blue revolution is nothing new, that aquaculture is one of the planet's best choices for expanding new protein production, but that the wildly optimistic scenarios for aquaculture's expansion will not occur unless alternative ecological approaches and ecological intensification of aquaculture are widely adopted. Aquaculture needs to be better integrated into overall fishery societal plans for securing sustainable seafood supplies and restoring damaged, supporting fisheries ecosystems. An ecological aquaculture approach can insure aquaculture is a net gain to humanity, and it could be the key organizing paradigm to form a new social contract for aquaculture worldwide. The overuse and degraded state of nearly all of the world's aquatic ecosystems combined with public concerns about adding any "new" uses or sources of aquatic pollution to already overburdened natural and human systems requires aquaculture to develop ecosystems approaches and sustainable operating procedures and to articulate a sustainable, ecological pedagogy.

For aquaculture development to proceed to the point where it will provide 50% of human protein food in nations outside of China, clear, unambiguous linkages between aquaculture, society, and the environment must be created and fostered, and the complementary roles of aquaculture in contributing to social and environmental sustainability, rehabilitation, and enhancement must be developed and clearly articulated to a highly concerned, increasingly educated, and involved public. The most sustainable growth trajectories for aquaculture are to change dramatically the prevailing aquaculture development model and move rapidly toward more sustainable, social–ecological approaches to development; to shift patterns of production and consumption patterns from global to bioregional food production and job creation; and to develop the indigenous human and institutional capacities that clearly demonstrate to society that "aquaculture is culture."

The massive globalization of seafood trade has meant less dependence on local natural and social ecosystems and has resulted in some well-organized and funded opposition to aquaculture development, albeit small and localized, but opposed especially to large-scale aquaculture. This opposition has grown as local sources of food production, markets, and jobs have been exported and externalized. One major consequence of this globalization has been the increased dependence of industrial, "fed" aquaculture on the southeastern Pacific Ocean marine ecosystem for fish meals 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.

Aquaculture sites are not only economic engines of primary production that meet the regulations of a society but can be sites of innovation and pride if they can be well designed as community-based, aquaculture farming ecosystems. A review of the progress toward such an EAA is necessary to inspire planners and environmental decision makers at many societal scales (national, regional, local) to make use of such innovative approaches. Sophisticated site planning of aquaculture can occur so that farms "fit with nature" and do not displace or disrupt invaluable natural, aquatic ecosystems or conservation areas but contribute to the local economy and society.

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References

Aas, T. 2006. Evaluation of a bacterial protein meal in diets for Atlantic salmon (*Salmo salar*), rainbow trout (*Oncorhynchus mykiss*) and Atlantic halibut (*Hippoglossus hippoglossus*). Ph.D. thesis, Norwegian University of Science and Technology.

Aghajanian, A. 2007. Chinampas: Their Role in Azetc Empire-Building and Expansion. Los Angeles: Indo-European Publishing.

Alder, J., Campbell, B., Karpouzi, V., Kaschner, K., Pauly, D. 2008. Forage fish: From ecosystems to markets. Ann Rev Envir Res. 33:71-714.

Allen, P., Van Dusen, D., Lundy, J., Gliessman, S. 1991. Integrating social, environmental, and economic issues in sustainable agriculture. Am J Altern Agric. 6(1):34-39.

Allison, E., Beveridge, M., van Brakel, M. 2009. Climate change, small-scale fisheries and smallholder aquaculture. In: Fish, Trade and Development, ed. Culberg, M., pp. 73-87. Stockholm: Royal Swedish Academy of Agriculture and Forestry.

Altieri, M. 2002. Agroecology: The science of natural resource management for poor farmers in marginal environments. Agric Ecosyst Environ. 93:1-24.

Ayer, N., Tyedmers, P. 2009. Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture systems in Canada. J Clean Prod. 17:362-373.

Bawa, K., Bachlander, N., Raven, P. 2008. A case for new institutions. Science. 319:136.

Beamish, R.J., Riddell, B. 2009. The future of fisheries science on Canada's west coast is keeping up with the changes. In: The Future of Fisheries Science in North America, eds. Beamish, R.J., Rothschild, B.J., pp. 567-596. New York: Springer Science.

Bell, J., Waagbo, R. 2002. Safe and nutritious aquaculture produce: Benefits and risks of alternative sustainable aquafeeds. In: Aquaculture in the Ecosystem, eds. Holmer, M., Black, K., Duarte, C., Marba, N., Karqakasis, I., pp. 185-226. New York: Springer.

Beutel, D., Skrobe, L., Castro, K., Ruhle, Sr, P., O'Grady, J., Knight, J. 2008. Bycatch reduction in the Northeast USA directed haddock bottom trawl fishery. References and further reading may be available for this article. To view references and further reading you must this article. Fish Res. 94(2): 190-198.

Beveridge, M., Little, D. 2002. The history of aquaculture in traditional societies. In: Ecological Aquaculture: The Evolution of the Blue Revolution, ed. Costa-Pierce, B.A., pp. 3-29. Oxford: Blackwell Science.

Black, K. 2001. Sustainability of aquaculture. In: Environmental impacts of aquaculture, ed. Black, K., pp 199-212. Sheffield: Sheffield Academic Press.

Blanco, M., Sotelo, C.G., Chapela, M.J., Pérez-Martín, R.I. 2006. Towards sustainable and efficient use of fishery resources: present and future trends. Trends Food Sci Technol. 18(1):29-36.

Bransford, J., Brown, A., Cocking, R. 2000. Hoe People Learn: Brain, Mind, Experience, and School. Washington: National Academy Press.

Brehm, J., Rahn, W. 1997. Individual level evidence for the causes and consequences of social capital. Am J Polit Sci. 41:999-1023.

Brown, L. 2009. Plan B 4.0: Mobilizing to Save Civilization. New York: W. Norton and Co.

Byron, C., Alves, D., Bengtson, D., Rheault, R., Costa-Pierce, B. 2008. Working towards consensus: application of shellfish carrying capacity in management of Rhode Island aquaculture. Wakefield, RI: Rhode Island Coastal Resources Management Council.

Cadenasso, M., Pickett, S., Grove, M. 2006. Integrative approaches to investigating human-natural systems: The Baltimore ecosystem study. Nat Sci Soc. 14:4-14.

Chimits, P. 1957. Tilapia in ancient Egypt. FAO Fish Bull. 10:211-215.

Chopin, T. 2006. Integrated multi-trophic aquaculture. What it is, and why you should care … and don't confuse it with polyculture. North Aquac. 12(4):4.

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

Costa, M., Yanagi, S., Souza, P., Ribeiro, A., Rocha, E. 2007. Climate change in Amazonia caused by soybean cropland expansion, as compared to caused by pastureland expansion. Geophys Res Lett. 34(L07706), doi:10.1029/2007GL029271.

Costa-Pierce, B. 1987. Aquaculture in ancient Hawaii. BioScience. 37:320-331.

Costa-Pierce, B. 2002a. Ecological Aquaculture. Oxford: Blackwell Science.

Costa-Pierce, B. 2002b. The ahupua'a aquaculture ecosystems in Hawaii. In: Ecological Aquaculture: The Evolution of the Blue Revolution, ed. Costa-Pierce, B.A., pp. 30-43. Oxford: Blackwell Science.

Costa-Pierce, B. 2002c. Ecology as the paradigm for the future of aquaculture, In: Ecological Aquaculture: The Evolution of the Blue Revolution, ed. Costa-Pierce, B.A., pp. 339-372. Oxford: Blackwell Science.

Costa-Pierce, B.A. 2003. Use of ecosystems science in ecological aquaculture. Bull Aquacul Assoc Canada. 103(2):32-40.

Costa-Pierce, B., Hardy, R., Kapetsky, J. 2003. Review of the Status, Trends and Issues in Global Fisheries and Aquaculture, with Recommendations for USAID Investments. Strategic Partnerships for Agricultural Research and Education (SPARE). Washington: U.S. Agency for International Development.

Costa-Pierce, B., Desbonnet, A. 2005. A future urban ecosystem incorporating urban aquaculture for wastewater treatment and food production. In: Urban Aquaculture, eds. Costa-Pierce, B.A., Desbonnet, A., Edwards, P., Baker, D., pp. 1-14. Wallingford: CABI Publishing.

Costa-Pierce, B. 2008a. Epilogue. In: Aquaculture, Innovation and Social Transformation, eds. Culver, K., Castle, D., pp. 315-325. New York: Springer Science.

Costa-Pierce, B. 2008b. An ecosystem approach to marine aquaculture: A global review. In: Building An Ecosystem Approach to Aquaculture, ed. Soto, D., pp. 81-116. Rome: FAO Fisheries and Aquaculture Proceedings 14. FAO.

Costa-Pierce, B., Bridger, C. 2002. The role of marine aquaculture facilities as habitats and ecosystems. In: Responsible Marine Aquaculture, eds. Stickney, R., McVey, J., pp. 105-144. Wallingford: CABI Publishing.

Cowey, C., Mackie, A., Bell, J. 1985. Nutrition and Feeding in Fish. London: Academic Press.

Crutzen, P., Stoermer, E. 2000. The "Anthropocene." Glob Change Newsl. 41:17-18.

Culver, K., Castle, D. 2008. Aquaculture, Innovation and Social Transformation. New York: Springer.

Dasgupta, P., Maler, K. 2004. The Economics of Non-Convex Ecosystems. New York: Springer.

DeAlteris, J., Kilpatrick, B., Rheault, R. 2004. A comparative evaluation of the habitat value of shellfish aquaculture gear, submerged aquatic vegetation and a non-vegetated seabed. J Shellfish Res. 23:867-874.

Dela Cruz, C., Lightfoot, C., Costa-Pierce, B., Carangal, V., Bimbao, M. 1992. Rice–Fish Research and Development in Asia. Manila: ICLARM.

Dees, J., Backman, E. 1994. Social Enterprise: Private Initiatives for the Common Good. Boston: Harvard Business School Publishing, Harvard University.

Dicks, M., McHugh, R., Webb, B. 1996. Economy-Wide Impacts of U.S. Aquaculture. Norman: Oklahoma Agricultural Experiment Station. 946 pp.

Duarte, C., Holmer, M., Olsen, Y., Stot, D., Maba, N., Guiu, J., Blac, K., Karakassis, I. 2009. Will the oceans help feed humanity? BioScience. 59(11):967-976.

Edwards, P. 2002. Aquaculture for poverty alleviation and food security. Aquac Asia. 7(2):53-56.

Edwards, P. 2004. Traditional Chinese aquaculture and its impact outside China. World Aquac. 35(1):24-27.

Edwards, P. 2006. Recent developments in Chinese inland aquaculture. Aquac Asia. II(4):3-6.

Edwards, P. 2009. Traditional Asian aquaculture. In: New Technologies in Aquaculture, ed. Burnell, G., chap. 34. Cambridge: Woodhead Publishing.

Edwards, P., Little, D., Yakupitiyage, A. 1997. A comparison of traditional and modified artisanal aquaculture systems. Aquac Res. 28:777-788.

Fletcher, W., Chesson, J., Sainsbury, K., Fisher, M., Hundloe, T. 2004a. A flexible and practical framework for reporting on sustainable development for wild capture fisheries. Fish Res. 71:175-183.

Fletcher, W., Chesson, J., Fisher, M., Sainsbury, K., Hundloe, T. 2004b. National ESD Reporting Framework: The 'How To' Guide for Aquaculture. Canberra: FRDC Project 2000/145.1. 88 pp.

Flimlin, G. 2002. Nursery and growout methods for aquacultured shellfish. Northeast Regional Aquaculture Center Publication No. 00-002. College Park, MD: Northeast Regional Aquaculture Center, University of Maryland.

Folke, C., Hahn, T., Olsson, P., Norberg, J. 2005. Adaptive governance of social–ecological systems. Ann Rev Environ Res. 30:441-473.

Folke, C., Kautsky, N., Troell, M. 1994. The cost of eutrophication from salmon farming: Implications for policy. J Environ Manage. 40:173-182.

Food and Agriculture Organization. 2009. The State of World Fisheries and Aquaculture 2008. Rome: Fisheries Department, Food and Agriculture Organization of the United Nations.

Gauvin, J., Rose, C. 2008. Groundfish Forum Experimental Fishing Permit to Test the Effectiveness of a Halibut Excluder. Seattle: Resource Assessment and Engineering Division, National Marine Fisheries Service Alaska Fishery Science Center. Available at: http://www.groundfishforum.org/Project/EFP/HED/HED.html.

GESAMP (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP Joint Group of Experts on Scientific Aspects of Marine Environmental Protection). 2008. Assessment and Communication of Environmental Risks in Coastal Aquaculture. Rome, FAO Reports and Studies GESAMP No. 76. 198 pp.

Gliessman, S. 1998. Agroecology: Ecological Processes in Sustainable Agriculture. Ann Arbor: Ann Arbor Press.

Goldburg, R., Naylor, R. 2005. Future seascapes, fishing, and fish farming. Front Ecol Environ. 3(1):21-28.

Goodland, R., Pimental, D. 2000. Environmental sustainability and integrity in the agriculture sector. In: Ecological Integrity, eds. Pimental, D., Westra, L., Noss, R., pp. 121-38. Washington: Island Press.

Gowen, R., Bradbury, N. 1987. The ecological impact of salmonid farming in coastal waters: A review. Oceanogr Mar Biol Ann Rev. 25:563-575.

Haamer, J. 1996. Improving water quality in a eutrophied fjord system with mussel farming. Ambio. 25:356-362.

Hall, S., Dugan, P., Allison, E., Andrew, N. 2010. The end of the line: who is most at risk from the crisis in global fisheries? Ambio 39:78080, doi:10.1007/s13280-0008-5.

Hambrey, J., Senior, B. 2007. Taking forward environmental carrying capacity and ecosystem services. Recommendations for CCW. CCW Policy Research Report No. 07/22.

Hambrey, J., Edwards, P., Belton, D. 2008. An ecosystems approach to freshwater aquaculture: a global review. In: Building An Ecosystem Approach to Aquaculture, ed. Soto, D., pp. 117-221. Rome: FAO Fisheries and Aquaculture Proceedings 14. FAO.

Heck, S., Bene, C., Reyes-Gaskin, R. 2007. Investing in African fisheries: Building links to the millennium development goals. Fish Fish. 8:211-226.

Hepher, B. 1985. Aquaculture intensification under land and water limitations. GeoJournal. 10:253-259.

Huckle, J., Sterling, S. 1996. Education for sustainability. London: Earthscan.

Jackson, A. 2009. Fish in–fish out (FIFO) ratios explained. Aquac Eur. 34(3):5-10.

Jacquet, J., Hocevar, J., Lai, S., Majluf, P., Pelletier, N., Pitcher, T., Sala, S., Sumaila, R., Pauly, D. 2009. Conserving wild fish in a sea of market-based efforts. Oryx. 44:45-56. doi:10.1017/S0030605309990470.

Jones, B.F., Wuchty, S., Uzzi, B. 2008. Multi-university research teams: Shifting impact, geography, and stratification in science. Science. 322:1259-1262.

Kates, R., Clark, W., Corell, R. 2001. Sustainability science. Science. 292:641-642.

Kaushik, S., Troell, M. 2010. Taking the fish-in fish-out ration a step further. Aquac Eur. 35(1):15-17.

Keen, M., Brown, V., Dyball, B. 2005. Social Learning in Environmental Management. London: Earthscan.

Knack, S. 2002. Social capital and the quality of government: evidence for the states. Am J Polit Sci. 46:772-785.

Lane, N. 2006. Alarm bells should help us refocus. Science. 312(5782):1847.

Langan, R., Horton, C. 2003. Design, operation and economics of submerged long-line mussel culture in the open ocean. Bull Aquacul Assoc Canada. 103(3):11-20.

Levi-Strauss, C. 1958. Anthropologie Structurale [Structural Anthropology]. New York: Penguin Press.

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

Lu, J., Li, X. 2006. Review of rice–fish–farm systems in China. One of the Globally Important Ingenious Agricultural Heritage Systems (GIAHS). Aquaculture. 260:106-113.

Lubchenco, J. 1998. Entering the century of the environment: A new social contract for science. Science. 279:491-497.

Mann, C. 2005. 1491. New Revelations of the Americas Before Columbus. New York: Alfred A. Knopf.

Mann, C.C. 2008. Ancient earthmovers of the Amazon. Science. 321:1148-1152.

McGrath, C. 2009. Egypt. A big catch feeds millions. Global Geopolitics Net Sites/IPS. Available at: http://globalgeopolitics.net/wordpress/2009/11/01/egypt-a-big-catch-feeds-millions (accessed 10 April 2010).

McLeod, K., Leslie, H. 2009. Ecosystem-Based Management for the Oceans. Washington: Island Press. 391 pp.

McKinsey, C., Thetmeyer, H., Landry, T., Silvert, W. 2006. Review of recent carrying capacity models for bivalve culture and recommendations for research and management. Aquaculture. 261(2):451-462.

Mires, D. 2009. Development of inland aquaculture in arid climates: water utilization strategies applied in Israel. Fisheries Manag Ecol. 7:189-195.

Mirto, S., Bianchelli, S., Gambi, C., Krzelj, Pusceddu, A., Scopa, M., Holmer, M., Danovaro, R. 2009. Fish-farm impact on metazoan meiofauna in the Mediterranean Sea: Analysis of regional vs. habitat effects. Mar Environ Res. 69:38-47.

Myers, R., Worm, B. 2003. Rapid worldwide depletion of predatory fish communities. Nature. 423:280-283.

Naing, A., Satoh, S., Tsuchida, N. 2007. Effect of replacements of fishmeal and fish oil on growth and dioxin contents of rainbow trout. Fish Sci. 73:750-759.

National Research Council. 2010. Ecosystem Concepts for Sustainable Bivalve Mariculture. Washington: National Academies Press.

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

Naylor, R., Hardy, R., Bureau, D., Chiu, A., Elliott, M., Farrell, A., Forster, I., Gatlin, D., Goldburg, R., Hua, K., Nichols, P. 2009. Feeding aquaculture in an era of finite resources. Proc Natl Acad Sci USA. 106(36):15103-15110.

Neori, A., Shpigel, M., Ben-Ezra, D. 2000. A sustainable integrated system for culture of fish, seaweed and abalone. Aquaculture. 186:279-291.

National Marine Fisheries Service. 2009. 2008 Report to Congress on the Status of

U.S. Fisheries. Silver Spring: Office of Sustainable Fisheries, National Marine Fisheries Service, National Oceanic and Atmospheric Administration.

Opstvedt, J., Aksnes, A., Hope, B., Pike, I. 2003. Efficiency of feed utilization in Atlantic salmon (*Salmo salar* L.) fed diets with increasing substitution of fish meal with vegetable proteins. Aquaculture. 221:365-379.

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., Torres, F., Jr. 1998a. Fishing down marine food webs. Science. 279:860-869.

Pauly, D., Tyedmers, P., Froese, R., Torres, F., Jr. 1998b. Fishing down and farming up the food web. Conservation Biology in Practice. 2:25.

Pauly, D., Alder, J., Bemmet, E., Christensen, V., Tyedmers, P., Watson, R. 2003. The future of fisheries. Science. 203:1359-1361.

Piedad-Pascual, F., Cruz, E., Sumalangcay, A., Jr. 1990. Supplemental feeding on *Penaeus monodon* juveniles with diets containing various levels of defatted soybean meal. Aquaculture. 89:183-191.

Pilke, R. 2007. The Honest Broker: Making Sense of Science in Policy and Politics. Cambridge: Cambridge University Press.

Pimentel, D., Pimentel, M. 2003. Sustainability of meat-based and plant-based diets and the environment. Am J Clin Nutr. 78(3):660-663.

Pitta, P., Karakassis, I., Tsapakis, M., Zivanovic, S. 1999. Natural vs. mariculture induced variability in nutrients and plankton in Eastern Mediterranean. Hydrobiologia. 391:181-194.

Pullin, R. 1993. Environment and Aquaculture in Developing Countries. Manila: International Center for Living Aquatic Resources Management.

Pullin, R., Froese, R., Pauly, D. 2007. Indicators for the sustainability of aquaculture. In: Ecological and Genetic Implications of Aquaculture Activities, ed. Bert, T. New York: Kluwer Academic Publishers.

Rakocy, J. 2002. An integrated fish and field crop system for arid areas. In: Ecological Aquaculture: The Evolution of the Blue Revolution, ed. Costa-Pierce, B.A., pp. 263-285. Oxford: Blackwell Science.

Ratliff, B. 2008. Producers might put fish on diet of mass-produced insects. Arlington, VA: Delta Farm Press. Available at: http://deltafarmpress.com/mag/farming_producers_put_fish/.

Rheault, R., Rice, M. 1995. Transient gear shellfish aquaculture. World Aquac. 26(1):26-31.

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

Ridler, N., Wowchuk, M., Robinson, B., Barrington, K., Chopin, T., Robinson, S., Page, F., Reid, G., Haya, K. 2007. Integrated Multi-trophic Aquaculture (IMTA): A potential strategic choice for farmers. Aquac Econ Manag. 11:99-110.

Robertson, D.P., Hull, R. 2003. Public ecology: An environmental science and policy for global society. Environ Sci Policy. 6:399-410.

Ruddle, K., Zhong, G. 1988. Integrated Agriculture–Aquaculture in South China: The Dike–Pond System in Zhujiang Delta. Cambridge: Cambridge University Press.

Ryther, J. 1969. Photosynthesis and fish production in the sea. Science. 166:72-76.

Savitz, A.W. 2006. The Triple Bottom Line: How Today's Best-Run Companies Are Achieving Economic, Social and Environmental Success—And How You Can too. New York: Jossey-Bass/Wiley.

Schroeder, G. 1980. Fish farming in manure loaded ponds. In: Integrated Agriculture–Aquaculture Farming Systems ICLARM, Manila, eds. Pullin, R., Shehadeh, Z. Manila, Philippines: International Center for Living Resources Management (ICLARM). pp. 73-86.

Schuster, W. 1952. Fish Culture in Brackish-Water Ponds of Java. Rome: FAO Indo-Pacific Fisheries Council Special Publication No.1.

Shreck, A., Getz, C., Feenstra, G. 2006. Social sustainability, farm labor, and organic agriculture: Findings from an exploratory analysis. Agric Human Values. 24(4):439-449.

Skretting Aquaculture Research Centre. 2009. Revealing the essential functions of vital feed ingredients. Available at: http://www.skretting.com/Internet/SkrettingGlobal/webInternet.nsf/wPrId/D30B62DD93F65CFEC1257663004DA962!OpenDocument (accessed 10 April 2010).

Smil, V. 2000. Feeding the World: A Challenge for the Twenty-First Century. Cambridge, MA: MIT Press.

Smil, V. 2002. Nitrogen and food production: Proteins for human diets. Ambio. 31:125-131.

Smith, M., Roheim, C., Crowder, L., Halpern, B., Turnipseed, M., Anderson, J., Asche, F., Bourillón, L., Guttormsen, G., Khan, A., Liguori, L., McNevin, A., O'Connor, M., Squires, D., Tyedmers, P., Brownstein, C., Carden, K., Klinger, D., Sagarin, R., Selkoe, K. 2010. Sustainability and global seafood. Science 327:784-786.

Soto, D., Aguilar-Manjarrez, J., Brugère, C., Angel, D., Bailey, C., Black, K., Edwards, P., Costa-Pierce, B., Chopin, T., Deudero, S., Freeman, S., Hambrey, J., Hishamunda, N., Knowler, D., Silvert, W., Marba, N., Mathe, S., Norambuena, R., Simard, F., Tett, P., Troell, M., Wainberg, A. 2008. Applying an ecosystem-based approach to aquaculture: principles, scales and some management measures. In: Building an ecosystem approach to aquaculture, eds. Soto, D., Aguilar-Manjarrez, J., Hishamunda, N. FAO/Universitat de les illes Balears Expert Workshop. 7-11 May 2007, Palma de Mallorca, Spain. FAO Fisheries and Aquaculture Proceedings No. 14. Rome: FAO. pp. 15-35.

Tacon, A. 2005. State of Information on Salmon Aquaculture Feed and the Environment. Washington: World Wildlife Fund Salmon Aquaculture Dialogue.

Tacon, A., Metian, M. 2008. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects. Aquaculture. 285:146-158.

Troell, M., Tyedmers, P., Kautsky, N., Ronnback, P. 2004. Aquaculture and energy use. In: Encyclopedia of Energy, vol. 1, pp. 97-108. Netherlands: Elsevier, Inc.

Turchini, G., Bente, E., Torstensen, E., Ng, W. 2009. Fish oil replacement in finfish nutrition. Rev Aquac. 1(1):10-57.

Turnock, B., Wilderbuer, T., Brown, E. 2005. Stock Assessment and Fishery Evaluation: Gulf of Alaska Arrowtooth Flounder. Anchorage, AK: North Pacific Fishery Management Council. 38 pp.

UK Energy Research Centre. 2009. Global Oil Depletion Report 2009. www.ukerc.ac.uk/support/Global%20Oil/%20Depletion.

UNESCO (United Nations Educational, Scientific and Cultural Organization). 2005. United Nations Decade of Education for Sustainable Development 2005–2014. Paris: UNESCO.

UNICEF (United Nations Children's Fund). 2006. China: Education and Child Development. New York: United Nations.

United Nations. 2008. World urbanization prospects: The 2007 revision-Highlights. New York: United Nations Tech Report E.04.XIII.6.

Verdegem, M., Bosma, R., Verreth, H. 2006. Reducing water use for animal production through aquaculture. Water Resources Development. 22(1):101-113.

Watanabe, T. 2002. Strategies for further development of aquatic feeds. Fish Sci. 68:242-252.

Watson, R., Pauly, D. 2001. Systematic distortions in world fisheries catch trends. Nature. 424:534-536.

Wertheimer, A.C., Heard, W.R., Smoker, W.W. 2004. Effects of hatchery releases and environmental variation on wild-stock productivity: consequences for sea ranching of pink salmon in Prince William Sound, Alaska. In: Stock Enhancement and Sea Ranching 2, eds. Leber, K.M., Kitada, S., Svasand, T., Blankenship, H.L., pp. 307-326. Oxford: Blackwell Science.

World Fish Center. 2008. Rice–Fish Culture: A Recipe for Higher Production. Raising Fish in Rice Fields in South and Southeast Asia Using Low-Cost Technology. Available at: http://www.worldfishcenter.org/wfcms/HQ/article.aspx?ID=158 (accessed 10 April 2010).

Zhou, Y., Yang, H., Hu, H., Liu, Y., Mao, Y., Zhou, H., Xu, X., Zhang, F. 2006. Bioredimation potential of the macroalga *Gracilaria lemaneiformis* (Rhodophyta) integrated into fed fish culture in coastal waters of north China. Aquaculture. 252:264-276.