Aquaculture, Ecological

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Article Outline

Glossary

Biofloc A mixture of detritus, bacteria, and other microscopic organisms that aggregates in flocs, which are used for controlling water quality and enhancing the delivery of natural foods to omnivorous species in aquaculture.

Ecosystem An area of the natural environment in which the structure and functions of the physical (rocks, soil, etc.) and natural (all living organisms) environments are considered together in interacting food webs.

Escapees The unintended releases of cultured organisms from captivity into the wild.

Polyculture The practice of making compatible the culture of multiple species in the same physical space by stocking or planting organisms having different food, spatial, or temporal niches.

Resilience The ability of a natural or aquaculture system to absorb abrupt changes or disturbances without collapsing. A resilient aquaculture ecosystem can withstand physical and economic shocks and rebuild itself.

Stewardship An ethic that engages all affected stakeholders in the cooperative planning and management of the environmental quality to prevent degradation and facilitate recovery in the interest of long-term sustainability.

Watershed An area of land where all of the water that is under it or drains off of it goes into the same place.

Definition of Ecological Aquaculture

Ecological aquaculture is an alternative model of aquaculture development that uses ecological principles as the paradigm for the development of aquaculture [1, 2]. 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 integrated "aquaculture ecosystems" designed to deliver both economic and social profit (Fig. 1).

Ecological aquaculture incorporates at the outset – and not as an afterthought – planning for not only the sustainable production of aquatic foods, but also for innovation [3], community development, and the wider social, economic, and environmental contexts of aquaculture at diverse scales, both large and small, and at the commercial, school, and homeowner scales [4, 5]. Ecological aquaculture also uses the "aquaculture toolbox" [6] to play vital roles in non-food, natural ecosystem rehabilitation, reclamation, and enhancement.

Introduction

The roots of ecological aquaculture are in Asia [7, 8]. In this century, however, Asia, especially China, during the period from 1980s to present has chosen the industrial model of aquaculture development, and has dismantled much of its rich ecological aquaculture heritage, and choosing instead to intensify and import vast quantities of feedstuffs. As a result of intensification and the use of imported feeds, freshwater aquaculture yields from China have increased 10X in just 20 years, and comprise the world's largest aquaculture industries [9].

The FAO ecosystems approach to aquaculture [10] creates a new code for global aquaculture development, combining into one common framework the two most

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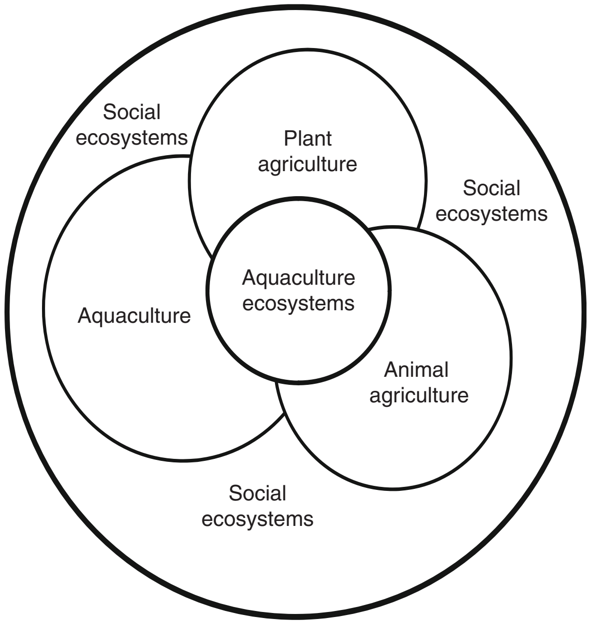

Aquaculture, Ecological. Figure 1
Aquaculture ecosystems mimic the form and functions of natural ecosystems, but are a sophisticated, knowledge-based designed farming ecosystem that are planned as combinations of land and water-based aquatic plant, agronomic, algal, and animal subunits, which are embedded into the larger context of human social systems

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.

Key Principles

There are seven principles of ecological aquaculture:

1. **Ecological aquaculture systems are "aquaculture ecosystems" that mimic the form and functions of natural ecosystems.**

   Ecological aquaculture farms are designed, farming ecosystems. Sophisticated site planning occurs so that farms "fit with nature" and do not displace or disrupt invaluable natural aquatic ecosystems or conservation areas. If localized displacement or degradation does occur, active support of innovative, collaborative research and development programs for ecosystems redesign, relocation, rehabilitation, and enhancement efforts are initiated and supported by the ecological aquaculture farms throughout the life of their farming operations.

2. **Ecological aquaculture is integrated with communities to maximize not only local but also regional economic and social multiplier effects in order to provide maximal job creation and training, and create "aquaculture communities" that are an essential part of vibrant, working waterfronts.**

   Ecological aquaculture operations export to earn profits but also promote and market products locally to contribute to the development of society. Ecological aquaculture operations are committed to building the "culture" of aquaculture in order that "aquaculture communities" can develop and evolve as a source of innovation, education, and local pride. Aquaculture development as a means of community development can result in numerous, innovative economic and social multiplier effects such as aquaculture restaurants, marketing of "sustainable seafoods" that are branded as local and bioregional, and aquaculture tourism.

3. **Ecological aquaculture results in economic profit by practicing trophic efficiency to ensure that aquaculture is humanity's most efficient protein producer.**

   Non-fed, shellfish and algae culture are preferred choices for ecological aquaculture developments. In fed aquaculture, fish meals/oils are not used as either the major protein or energy sources, but are included in animal diets to solve issues of diet palatability only; and, if used, fish meals and oils originate from certified, sustainable fishmeal/oil fisheries only. Fed aquaculture ecosystems rely on protein and oil sources from agricultural sources and seafood processing wastes, and include science innovations such as the development of detrital food webs ("bioflocs") to feed cultured, aquatic organisms.

4. **Ecological aquaculture results in social profit by integrating aquaculture developments into global fisheries, food, and poverty alleviation programs.**

   Ecological aquaculture is part of the global movement to eliminate extreme hunger and starvation (Millennium Development Goal #1) by being a part of comprehensive plans for sustainable fisheries for poverty alleviation. Ecological aquaculture uses alternative feeds to support programs to deliver more of the world's feed fisheries (sardines, anchovies, mackerels, etc.) away from aquaculture to the world's poor.

5. **Ecological aquaculture practices nutrient management by using ecosystems design, reuse, and recycling, and does not discharge any nutrient or chemical pollution causing irreversible damage to natural aquatic or terrestrial ecosystems.**

   No harmful metals, chemicals, or pharmaceuticals potentially harmful to long-term human or ecosystem health are used in the ecological aquaculture production processes. Ecological aquaculture farms have "sustainability strategic and implementation plans" in place to develop comprehensive, full cycle reuse, and recycling systems for all farming operations.

6. **Ecological aquaculture uses native species/strains, and does not contribute to "biological" pollution.**

   Escapees from aquaculture, especially aquarium operations, have severely impacted aquatic ecosystems worldwide. Exotics species/strains can be good choices only if long-term monitoring data and scientific research indicate that exotic species are unlikely to establish; if exotic species are widely established and provide economic and social profit without irreversible environmental harm; or, the use of native species puts at risk indigenous genetic diversity. Ecological aquaculture operations ensure that innovative engineering and complete escapement technologies are used; that control and recovery procedures are in place; that active research and development programs provide alternatives and new options; and that complete, transparent, public documentation and information are available.

7. **Ecological aquaculture is a global partner, producing information for the world, avoiding the proprietary.**

   Ecological aquaculture farms are aquaculture ecosystems that go beyond "meeting the regulations." They are sites of collaboration, leadership development, and innovation. They are outstanding community citizens and models of stewardship [4]. Successful leadership development triggers developments of innovation and more efficient aquaculture-related technology, and more ecologically appropriate legislation and regulations.

The FAO Ecological Approach to Aquaculture (EAA)

In 2006, the Fisheries and Aquaculture Department of Food and Agriculture Organization (FAO) recognized the need to develop an ecosystem-based management approach to aquaculture similar to the Code of Conduct for Responsible Fisheries. FAO [10] suggested that an ecological approach to aquaculture (EAA) 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.

In 2008, FAO defined an EAA as: A strategy for the integration of the activity within the wider ecosystem such that it promotes sustainable development, equity, and resilience of interlinked social-ecological systems. An ecosystem approach to aquaculture, similar to other systems approaches to management, accounts for a complete range of stakeholders, spheres of influences, and other interlinked processes. Applying an ecosystem-based approach must plan for physical, ecological, social, and economic systems as a part of community development, taking into account stakeholders in the wider social, economic, and environmental contexts of aquaculture [10]. FAO developed three principles and key issues at different scales of society:

Principle 1: Aquaculture development and management should take account of the full range of ecosystem functions and services, and should not threaten the sustained delivery of these to society.

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 function," "ecosystem health," "ecosystem integrity," "fully functioning ecosystems," all of which are subject to a specific social/cultural/political context [11]. Conventional environmental impact assessments touch on just some of these issues. Application of the precautionary approach is important but inadequate in aquaculture; use of aquaculture risk assessment is becoming widespread [12].

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

Aquaculture should provide equal opportunities for development, which requires its benefits to 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.

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, e.g., agriculture and industry, but it does not take place in isolation. There are many opportunities to couple aquaculture activities with other primary producing sectors in order 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 the current trajectory and growth of the large-scale aquaculture industries. 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 1). There are a growing number of well-documented success stories in ecological aquaculture (Table 2).

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

1. Inclusion of aquaculture as a part of regional governance frameworks, e.g., 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.
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

Aquaculture, Ecological. Table 1 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 [28] 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. [29]; Pauly [30])	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	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 & fed aquaculture in poverty alleviation	Governments move to develop food products/prioritize human needs
Habitat destruction	Mangrove destruction and water diversions disrupt nearshore and riverine ecosystems (Macintosh and Phillips [31]; Pullin et al. [32]	Some nations (ex. 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 (McKindsey et al. [33]) and ecological valuation for decision-making
Eutrophication	Intensive aquaculture operations are feedlots producing nutrient pollution loads comparable to human sewage (Folke et al. [21]; Costa-Pierce [34])	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	Development of land-based recirculating systems; widespread use of land-based integrated aquaculture and water-based IMTA systems
Energy	Intensive aquaculture operations are energy intensive comparable to industrial agriculture and fisheries (Weatherly and Cogger [35])	Scattered R&D in energy use, mostly Life Cycle Analyzes in aquaculture; little/no movement toward use of renewables	Renewable energy systems used

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
3. Design of ecological aquaculture management zones and parks that encourage aquaculture education, research, and development 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

Aquaculture, Ecological. Table 2 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" (GIAHS)	FAO [9]; Dela Cruz et al. [36]
Asia (China, Thailand, Cambodia, Vietnam, Indonesia)	Integrated aquaculture benefits millions of rural people	Edwards [8]
Asia (China)	Integrated Multi-trophic Aquaculture (IMTA) of fish, shellfish, and seaweeds bioremediates and increases total yields up to 50%	Zhou et al. [37]
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 [38]
Canada	IMTA has been adopted by Cooke Aquaculture, the largest salmon aquaculture company in eastern Canada	Chopin et al. [39]; Chopin [40]; Ridler et al. [41, 42]
Canada & USA	Shellfish aquaculture has become widely accepted as environmentally friendly and socially acceptable	National Academy [43, 44]
Tanzania	Seaweed and shellfish aquaculture	Seaweed grown by ~2,000 producers most women; new half-pearl industry growing

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 are useful to determine impacts at the global scale.

Social Ecology of Aquaculture

Many analysts are calling for more integrated, multidisciplinary ways of developing ecologically and socially responsible food, energy, water, and waste systems to meet society's needs [13]. Among the first was Lubchenco [14] 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.

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" [15]. Keen et al. [16] believe 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 [17]. 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 [18, 19].

Folke et al. [20] challenge our education system to continually adapt to the emergence of such new questions and changing social compacts as aquaculture. Any rapid 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. Bransford et al. [22] 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.

An Ecological Aquaculture 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 can "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 [23].

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 other's 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 [24] 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 [25] have used 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; as analysts report that such work is the highest impact science being published today [26].

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, to:

1. Become an integral part of a community and a region.
2. Plan for community development by working with leaders to provide needed inputs and recycle wastes.
3. 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.
4. 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 USA, Dicks et al. [27] found that aquaculture production accounted for just 8% of the income and ~16,500 jobs. Aquaculture goods and services accounted for 92% of the income and ~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 – to say nothing about employing local professionals (most industrial aquaculture operations import high paying professionals from the outside). In the vast majority of cases, feed 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, and one that is important for the future food security and environment of the planet, requires the much more comprehensive planning in order to evolve a new social contract with society.

Future Directions

By 2030, fed aquaculture will turn from the ocean to land-based agriculture to provide its feeds and oils. As such, more sophisticated, ecologically designed and integrated aquaculture systems 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, ecosystems conservation, and restoration.

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.

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, require aquaculture to develop ecosystems approaches; sustainable operating procedures; and to articulate a sustainable, ecological pedagogy. The fact that an ecological aquaculture approach can ensure 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 massive globalization of seafood trade has meant less dependence on local natural and social ecosystems, and has resulted in some virulent opposition to aquaculture development, especially as industrial aquaculture has removed the local sources of production and markets, and jobs have been externalized. One major consequence of this globalization has been the increased dependence of industrial, "fed" aquaculture on the southeastern Pacific Ocean marine ecosystem for 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 ecosystems approach to aquaculture 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 [5].

An ecological aquaculture approach to comprehensive planning for aquaculture at many different scales will integrate aquaculture into plans for not only environmental benefit and the restoration of coastal ecosystems, but also local market developments and the future of coastal communities. As such, ecological aquaculture can move aquaculture beyond endless user conflicts, and could stabilize the regulatory environment and ensure a more equitable process of ecosocial design of aquaculture for the future.

Bibliography

Primary Literature

1. Costa-Pierce B (2002) Ecological aquaculture. Blackwell, Oxford
2. Costa-Pierce B (2003) Use of ecosystems science in ecological aquaculture. Bull Aquacul Assoc Canada 103(2):32–40
3. Culver K, Castle D (2008) Aquaculture, innovation and social transformation. Springer, New York
4. Costa-Pierce B (2008a) An ecosystem approach to marine aquaculture: a global review. In: Soto D (ed) Building an ecosystem approach to aquaculture, vol 14, FAO fisheries and aquaculture proceedings. FAO, Rome, pp 81–116

5. Costa-Pierce B (2008b) Epilogue. In: Culver K, Castle D (eds) Aquaculture, innovation and social transformation. Springer, New York, pp 315–325
6. Costa-Pierce B, Bridger C (2002) The role of marine aquaculture facilities as habitats and ecosystems. In: Stickney R, McVey J (eds) Responsible marine aquaculture. CABI, Wallingford, pp 105–144
7. Ruddle K, Zhong G (1988) Integrated agriculture-aquaculture in South China: the Dike-Pond system in Zhujiang Delta. Cambridge University Press, Cambridge
8. Edwards P (2009) Traditional Asian aquaculture: definition, status and trends. In: Burnell G, Allan G (eds) New technologies in aquaculture, improving production efficiency, quality and environmental management. Woodhead Publishing Ltd., Cambridge, UK, pp 1029–1063
9. FAO (Food and Agriculture Organization) (2009) The state of world fisheries and aquaculture 2008. Fisheries Department, Food and Agriculture Organization of the United Nations, Rome
10. Soto D et al (2008) Applying an ecosystem-based approach to aquaculture: principles, scales and some management measures. In: Soto D, Aguilar-Manjarrez J, Hishamunda N (eds) Building an ecosystem approach to aquaculture, vol 14, Rome: FAO fisheries and aquaculture proceedings. FAO, Rome
11. Hambrey J, Senior B (2007) Taking forward environmental carrying capacity and ecosystem services. Recommendations for CCW. CCW Policy Research Report No. 07/22
12. Black E (2006) A risk analysis approach to assessment of the potential genetic interactions of non-salmonid marine finfish escapes from aquaculture with local native wild stocks, pp 93–105. In: ICES WGEIM report on the environmental impacts of mariculture, 24–28 April 2006, Narragansett, Rhode Island, USA. ICES, Copenhagen, Denmark. (Available at www.ices.dk/reports/MCC/2006/WGEIM06.pdf)
13. Dees J, Backman E (1994) Social enterprise: private initiatives for the common good. Harvard Business School Publishing, Harvard University, Boston
14. Brown L (2009) Plan B 4.0: mobilizing to save civilization. W. Norton, New York
15. Lubchenco J (1998) Entering the century of the environment: a new social contract for science. Science 279:491–497
16. Pilke R (2007) The honest broker: making sense of science in policy and politics. Cambridge University Press, Cambridge
17. Keen M, Brown V, Dyball B (2005) Social learning in environmental management. Earthscan, London
18. Huckle J, Sterling S (1996) Education for sustainability. Earthscan, London
19. Brehm J, Rahn W (1997) Individual level evidence for the causes and consequences of social capital. Am J Pol Soc 41:999–1023
20. Knack S (2002) Social capital and the quality of government: evidence for the states. Am J Pol Sci 46:772–785
21. Folke C, Hahn T, Olsson P, Norberg J (2005) Adaptive governance of social-ecological systems. Ann Rev Environ Res 30:441–473
22. Bransford J, Brown A, Cocking R (2000) Hoe people learn: brain, mind, experience, and school. National Academy Press, Washington
23. Savitz A (2006) The triple bottom line: how today's best-run companies are achieving economic, social and environmental success – and how you can too. Jossey-Bass/Wiley, New York
24. Robertson D, Hull R (2003) Public ecology: an environmental science and policy for global society. Environ Sci Policy 6:399–410
25. Dasgupta P, Maler K (2004) The economics of non-convex ecosystems. Springer, New York
26. Jones B, Wuchty S, Uzzi B (2008) Multi-university research teams: shifting impact, geography, and stratification in science. Science 322:1259–1262
27. Dicks M, McHugh R, Webb B (1996) Economy-wide impacts of U.S. aquaculture. Oklahoma Agricultural Experiment Station, Norman, 946p
28. Schroeder G (1980) Fish farming in manure loaded ponds. In: Pullin R, Shehadeh Z (eds) Integrated agriculture-aquaculture farming systems. ICLARM, Manila, pp 73–86
29. 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
30. Pauly D (2000) Global change, fisheries, and the integrity of marine ecosystems: the future has already begun. In: Pimental D, Westra L, Noss R (eds) Ecological integrity. Island Press, Washington, DC, pp 227–244
31. Macintosh D, Phillips M (1992) Environmental considerations in shrimp farming. Infofish Int 6:38–92
32. Pullin R (1993) Environment and aquaculture in developing countries. International Center for Living Aquatic Resources Management, Manila
33. 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
34. Costa-Pierce B (1997) Environmental impacts of nutrients discharged from aquaculture: towards the evolution of sustainable, ecological aquaculture systems. In: Baird D, Beveridge M, Kelly L, Muir J (eds) Aquaculture and water resource management. Blackwell, Oxford, UK, pp 81–113
35. Weatherly A, Cogger B (1977) Fish culture: problems and prospects. Science 197:427–430
36. Dela Cruz C, Lightfoot C, Costa-Pierce B, Carangal V, Bimbao M (1992) Rice-fish research and development in Asia. ICLARM, Manila
37. 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
38. McGrath C (2009) Egypt. A big catch feeds millions. Global geopolitics Net Sites/IPS http://globalgeopolitics.net/wordpress/2009/11/01/egypt-a-big-catch-feeds-millions
39. 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
40. Chopin T (2006) Integrated multi-trophic aquaculture. What it is, and why you should care... and don't confuse it with polyculture. Northern Aquacult 12(4):4
41. 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 Aquacult 37(3):43–48
42. 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. Aquacul Econ Manag 11:99–110
43. National Research Council (2009) Shellfish mariculture in Drakes Estero, Point Reyes national seashore. National Academies Press, Washington, California
44. National Research Council (2010) Ecosystem concepts for sustainable bivalve mariculture. National Academies Press, Research Council, Washington

Books and Reviews

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

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

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

Costa-Pierce B, Desbonnet A, Edwards P, Baker D (eds) (2005) Urban Aquaculture. CABI Publishing, Wallingford, UK

Duarte C, Holmer M, Olsen Y, Stot D, Maba N, Guiu J, Black K, Karakassis I (2009) Will the oceans help feed humanity? Bioscience 59:967–976

Gowen R, Bradbury N (1987) The ecological impact of salmonid farming in coastal waters: a review. Ocean Mar Biol Ann Rev 25:563–575

Stickney R, McVey J (2002) Responsible marine aquaculture. CABI, Wallingford

Tacon A, Hasan M, Subasinghe R (2006) Use of fishery resources as feed inputs for aquaculture development: trends and policy implications. FAO fisheries circular No. 1018. Food and Agriculture Organization of the United Nations, Rome

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

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