Taxonomy of Aquaculture

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The green revolution took off without considering the knock-on impacts on the environment, society and economies. The blue revolution needs to be planned in a much more comprehensive manner.
Costa-Pierce (2003)

Introduction

Costa-Pierce (2002) defined "ecological aquaculture" as an alternative model that uses ecological principles and ecosystems thinking as the fundamental organizing paradigm for the development of aquaculture. Ecological aquaculture incorporates—at the outset—the principles of natural and social ecology, planning for community development, and concerns for the wider social, economic, and environmental contexts of aquaculture". Ecological aquaculture plans for both economic and social profit.

Ecological aquaculture is the study of aquaculture ecosystems; thus it is a branch of ecosystems ecology (Costa-Pierce, 2002, 2003). Ecosystems ecology seeks to understand the structure and functions (services) of natural and social ecosystems and how they interact (Odum, 1969; Odum, 1971; Hagen, 1992). Ecosystems science is the practical application of ecological theory to urgent societal issues needed for environmental management. It includes the scientific study of conservation and management of natural, human-dominated and man-made ecosystems, habitats, and species; restoration ecology and regenerative studies; urban and industrial ecology; and the role of ecological research in global and sustainability problems.

Aquaculture ecosystems exhibit the kinds of classic characteristics discussed by these pioneers of ecosystems ecology, namely:

(a) aquaculture ecosystems have defined boundaries, but these boundaries are fluid and may fluctuate over time. These boundaries are oftentimes defined within the constructs of human minds; and,

(b) organisms cultured within aquaculture ecosystems are dependent on both ecosystem level biophysical processes and human management.

An ecological classification of aquaculture systems is given in Table 1. Such taxonomies of aquaculture are sorely needed so that professionals can develop a more common language when they speak about "aquaculture" and its potential environmental and social impacts.

Ecosystem science can examine in detail these functional hierarchies of aquaculture ecosystems, especially the material, cash, and nutrient flows. For example, a major concern is that stand alone, intensive cage aquaculture systems located in open waters add a new source of untreated aquatic pollution to already overburdened natural ecosystems. Not unexpectedly, such aquaculture systems that have a high intensity of production, and discharge waste with no treatment whatsoever to oligotrophic ecosystems have the greatest potential for nutrient impacts on the environment. The amount of dependence on the natural environment for waste assimilation—and thus the level of ecological goods, services and subsidies that are provided—is directly related to the amount of on-site treatment of wastes that is performed.

However, while super-intensive, flow-through aquaculture systems have potentially the highest nutrient impact on natural ecosystems, impacts from such systems can be insignificant if complete, on-site waste treatment occurs. Therefore, super-intensive aquaculture cannot always be assumed to have major nutrient impacts that impair natural aquatic ecosystem structure and functions. The place to start in these analyses are summaries of functional data on aquaculture ecosystems which will allow ecologists to develop more rigorous simulation models that can be tested with empirical research on the nutrient impacts of floating cage and raft aquaculture, recirculating systems, and semi-intensive pond systems.

Social ecology analyses of aquaculture's functional hierarchies are also needed. For example, if aquaculture systems are located completely within natural environments (cages, rafts) and are not required to treat their wastes, the public is subsidizing the environmental costs of these operations at the level of: (a) the additional capital costs for complete waste treatment, (b) the operating costs for treatment facilities, and (c) the interest on loans received to purchase and operate waste treatment systems. These subsidies need to be compared with other available public policy options to sustain a working coast. In Norway, for example, aquaculture provides an estimated 3,500 direct jobs and 40,000 to 45,000 total jobs in support services, etc. (Ludvigsen, 2002). Many small, rural coastal communities are sustained by the taxes provided by these intensive operations. The issue for analysis is the weighing of the social and ecological costs/benefits of both environmental and social subsidies.

Aquaculture is as diverse a field of endeavor as agriculture. There are far too many misguided discussions when the merits of aquaculture are being debated. And, this comment is applicable not only to coastal landowners, fishing interests or other water dependent users, but also applies to narrowly trained capture fisheries professionals who routinely wade into discussions about the merits of aquaculture but are totally mis-informed!

There are a wide diversity of systems and species which can be classified in many different ways, from non-fed, photosynthetic, marine-agronomic type operations, to publicly-funded aquaculture hatcheries for fisheries enhancement (Alaska salmon, coral reef, eelgrass, mangrove and oyster restoration), and intensive, feedlot-type industrial aquaculture production systems in open waters. Worldwide, the most common type of aquaculture system remains the classic earthen ponds growing omnivorous fish species that were either produced in hatcheries or collected from the wild, and cultivated in ponds being fed supplemental feeds on an exact feeding schedule (Edwards, 2015). Most of these pond systems are located in Asia, and are open systems having little or no capital investments in waste treatment facilities (but they may be completely integrated operationally so that no aquaculture wastes are discharged, but these classic integrated systems are disappearing in Asia [Edwards, 2015]).

A classic understanding of ecological systems has emerged (Allen and Starr, 1982; Allen and Hoekstra, 1992; O'Neill et al., 1986) which is the recognition that complex systems are: (a) hierarchical in nature; (b) have different properties and dynamics occurring at different scales of organization; and (c) have inherent uncertainties that require ecologists to incorporate and build in—not to exclude—uncertainty. The notion of hierarchy requires that a study of ecosystems first consider the types of systems and the ecological hierarchies (scales) that exist in order to determine the appropriate means of investigation (Table 1).

Aquaculture Social-Ecological Systems

Ensuring that accelerated aquaculture developments be done in an ecological manner is much more than a simple technological exercise—it is an exercise in multi-disciplinary, multi-institutional social-ecological scholarship. Millions of people whose lives depend upon harvesting marine resources from fishing and farming require that a planned aquatic foods system *include* them, and helps ensure their futures. Behavioral changes will be required that can be accomplished through social investments, strategic subsidies, and market mechanisms that facilitate change in consumer behaviors.

Jamieson (1996) believes the most effective strategy for sustainability is not technological, but solutions "located in their source: humans, their behavior, and their institutions". In this regard, development of ecological aquaculture is essentially a conscious exercise in social engineering.

One major stumbling block is the lack of rigorous, comprehensive, multi-disciplinary scientific analyses of aquaculture which define in a more holistic manner a social-ecological framework for analysis, impacts on the production "chain", and critically important resource input/output and cost/benefit issues. The broader issue is that the future sustainability of both wild and farmed stocks depends upon many of the same marine and agricultural resources—from food to habitats. Although capture fisheries, aquaculture and terrestrial agriculture operations are researched, planned, and managed as if they were independent entities, they share common concerns about environmental disruptions, genetic and habitat diversity, feeds, and the sustainability of protein meal/oils and industries, among other shared concerns.

The future challenge for planners—who clearly need to accelerate aquaculture development—is to plan for new production—not only technically, but also as community development— and consider the social ecology of aquaculture developments.

But, to date, macro-economic factors have been the main controllers of aquaculture developments, with environmental and social costs externalized (Bailey et al. 1996).

Proper planning for ecological aquaculture internalizes all of nature's and society's costs as part of an entire regional development activity that plans for the regional impacts of the entire "aquaculture production network"(Costa-Pierce, 2010) that connects aquatic seed and feed production centers and markets in order to maximize local social-economic multiplier effects.

From a social-ecological systems perspective, the most important ecological classifications of aquaculture ecosystems are: (a) their location within or separate from the environment, (b) their levels of operational intensities (management, feeds, water flows, etc.), and (c) the level of system's integration.

In the 21st century, aquaculture developers will need to spend as much time on technological advances coming to the field as they do in designing ecological approaches that clearly exhibit stewardship of the environment and coastal societies. The degraded state of aquatic ecosystems worldwide, combined with public concerns about adding new sources of pollution to already overburdened aquatic ecosystems require: a) comprehensive planning for aquaculture in the future of sustainable fisheries, b) integration of aquaculture into plans for restoration of coastal ecosystems and the future of coastal communities, and c) increased market development of environmentally (and socially) certified commodities.

For example, to understand a type of aquaculture ecosystem, studies of the natural and social ecology of the system at the species, community, ecosystem, and regional scales are required. Applying the notion of complexity to aquaculture ecosystems suggests new roles for ecosystems science in the evolution over time towards sustainability of aquaculture ecosystems. An investigator must first take great care to ecologically classify the structure and functioning of the aquaculture system and scales of investigation necessary to deal with research issues in both a natural and social ecological context.

A particular concern is the neglect of investigations on the social ecology of aquaculture ecosystems. As one example, ecology research on the natural ecology of aquaculture ecosystems in central Africa focused on group training in scientific production methods. Training courses were attended by village leaders who were men; social science research investigations, however, found that the actual managers of the pond aquaculture ecosystems were children (ICLARM, 1991).

The challenge for researchers studying aquaculture ecosystems is to abandon the normal approach of hypothesis testing and analytical searching for the correct model for solving a problem. Instead we must develop a manner of investigation that uses a diversity of different perspectives and models, brings different players to the table, and synthesizes the different natural and social ecological methods together in order to achieve understanding. The values of various stakeholders and community members will play an essential role in the decision making process. The role of the scientists will be to inform the decision makers about the ecological options, the tradeoffs and uncertainties involved, and various strategies for influencing what happens. However, ecologists cannot predict with complete certainty what will happen in this situation, nor can they inform us about the “correct” way to proceed.

Thus, the role of science in decision-making for sustainability changes from problem solver, in the sense of providing a solution for the situation, to the role of facilitating understanding about the bio-physical and social realities of the situation, and in so doing contributing to its resolution (Ulanowicz, 1997).

Vital to establishing a framework for more comprehensive natural and social ecological analyses of aquaculture ecosystems are the recognition of three important guidelines that will help investigators determines aquaculture’s hierarchies:

- Aquaculture is not a uniform “industry” or a standard set of practices easy to classify, codify, label or regulate. It is very important to always define the structure, functions and hierarchical placement of an aquaculture system before addressing its social and environmental connections and impacts. Unfortunately, this simple point is not widely practiced by many “analysts” of the field. Indeed, analyses of “aquaculture” cannot be scientifically credible unless directed to the actual ecological structure and functional type of aquaculture ecosystem to which is being referred.

- There are intimate—albeit largely unplanned— connections between capture fisheries, enhanced fisheries (“ranching”), and culture fisheries (“aquaculture”), and greater recognition is needed regarding the vital contribution of culture fisheries (aquaculture) and enhanced fisheries (ranching) to global fisheries production (Costa-Pierce, 2010).

- The success of aquaculture is dependent not only on its technical needs for hatcheries to produce seed, and feed mills to produce feeds, but also on markets, equipment, and the

> capacities and capabilities of the entire seafood infrastructure. Determinations of the costs and benefits of aquaculture require more comprehensive ecological analyses of the entire "aquaculture production network" (the "support network") for a particular aquaculture species.

Table 2 is an attempt at developing a better social-ecological systems classification system for the wide variety of aquaculture ecosystems.

Taxonomy of Aquaculture: "New" Rubrics

There are many important "new" rubrics in aquaculture today competing as fundamental organizing paradigms for the academic organization of the field of aquaculture. Among these are "Sustainable Aquaculture" and IMTA (Integrated Multi-Trophic Aquaculture).

It is worthwhile to explore the merits and opportunities of these paradigms, especially so as the young field of ecological aquaculture emerges from its parallel sisters of agroecology and agroecosystems (Gliessman, 1998; Altieri, 2002).

Sustainable Aquaculture (Costa-Pierce and Page, 2012)

There are far too many definitions of "sustainability" as the concept applies to aquaculture. The most popular definition of "sustainable development" is to "meet present needs without compromising the ability of future generations to meet their needs" adopted at a United Nations conference in 1987. The many definitions of sustainability all embody common the concepts of "stewardship", "design with nature," plus incorporate recent concepts of the "precautionary principle", and "carrying capacity". Sustainability science (Kates et al., 2001) uses the wisdom from multiple disciplines in decision-making (e.g. it is "transdisciplinary"). In aquaculture, sustainability science is used to undertake more comprehensive planning for multiple impacts on multiple time and spatial scales to better understand and plan for the consequences of development options (see Table 1 in *Costa-Pierce and Page, 2012*).

Most definitions of sustainability are synonymous with "environmental sustainability" of air, water, and land systems. Sustainability is however a concept broader than examining the site-specific environmental impacts of externalities in planning for site-specific developments; it also accounts for systematic impacts off site, and impacts to combined human-environmental systems for food, water, waste, energy, and shelter.

Implementation of more sustainable aquatic food production systems requires knowledge about how ecosystems are utilized and how conflicts among social groups are addressed. A baseline of response to social-ecological changes (Olsen et al., 2009) is the foundation for the implementation of more sustainable aquatic food systems. The practice of adaptive management must be included as responses to changes in the condition of ecosystems in which new aquatic food production is conducted requires incorporation of an iterative learning process.

The use of sustainability science in aquaculture marks the path toward encouraging a long-term perspective and an appreciation of the roles played not only by ecologists, but also by civil societies, markets, and governments in adapting to food systems and ecosystems changes. The use of sustainability science in aquaculture is an approach that is fundamentally a knowledgebased enterprise that incorporates baseline information on natural and human ecosystems, then develops, evaluates, encourages, and communicates imagination, ingenuity, and innovation at both the individual and institutional levels.

Sustainability science information is designed for use by teams of aquaculture professionals working to apply the principles of ecosystem-based management. Information obtained is typically cross sectoral as interdisciplinary groups are needed that are educated in such diverse fields as the natural and social sciences, law, and business. Applying the notions of sustainability science in aquaculture is intended to inspire the long term engagement of governmental agencies, businesses, non-governmental groups and academics.

The goal would be to achieve the highest form of sustainable food systems development of any other comparable known protein production food system by using the concepts of sustainability science and through the many forms of stewardship. At present, there is a paucity of information targeted specifically for those engaged in aquaculture programs and projects in places where the ability of government to regulate and direct the processes of ecosystem change is weak or severely constrained.

IMTA (Integrated Multi-Trophic Aquaculture)
(modified after Edwards, 2015)

IMTA is a rubric invented by Thierry Chopin of the University of New Brunswick in Canada (Chopin 2012). The idea arose from a Northern temperate species assemblage of fed salmon in cages with "inorganic extractive" seaweeds and "organic extractive" mollusks. The idea is not new and essentially is a marine polyculture, or as referred to by Costa-Pierce (2003), in a far less attractive way, as "janitorial polyculture". There remain scientific questions in regard to ecological and economic merits of marine "IMTA" for industrial salmon farming as practiced in Canada, Norway, etc.

Published Results	References
Mussels cannot capture all of the organic particles (feces, detritus, etc.) discharged from intensive salmon cages	Navarrete-Mier et al., 2010; Cranford et al. (2013); Reid et al. (2013a)
The size of seaweed systems needed to absorb all soluble inorganic nutrients from salmon cages would exceed the space available	Reid et al. (2013b)

In Asia, and especially in China, coastal aquaculture has been dominated by the production of seaweeds and shellfish. more recently finfish cage culture has been sequentially developed on a commercial scale in coastal bays (see Fang and Lui, 2013 and Fang et al., 2013 cited in Edwards, 2015). This was not in any way an ecologically designed system purposefully planned as an aquaculture ecosystem (Reid et al., 2013b). Rather, the addition of fish cages was to add additional economic value into existing aquaculture enterprises, where space was at a premium die to intense social-economic competition for emerging export markets. There are no underlying ecological or social innovations in this Chinese example cited in western publications. Indeed the addition of fish cages is a movement of these farmers to reach the full productive carrying capacity of a limited ocean space (McKindsey et al., 2006). Time will tell if they've exceeded it!

As stated by Edwards (2015), "Experimentation and financial modeling have demonstrated the feasibility of open water integration of finfish with seaweed and shellfish culture and have appeared to demonstrate attractive returns for investors but more data are required to demonstrate 'real world' viability, as Bunting (2013) wrote, 'empirical evidence to substantiate claims concerning production rates, management demands, financial returns and economic performance is limited'. "There should be an evaluation of the full value of IMTA component species, with the economic values of the environmental and societal services provided by the extractive species both recognized and accounted for to facilitate open-water IMTA becoming a widespread commercially viable system".

The Merits of Ecological Aquaculture as an Organizing Rubric for the Future of the Blue Revolution

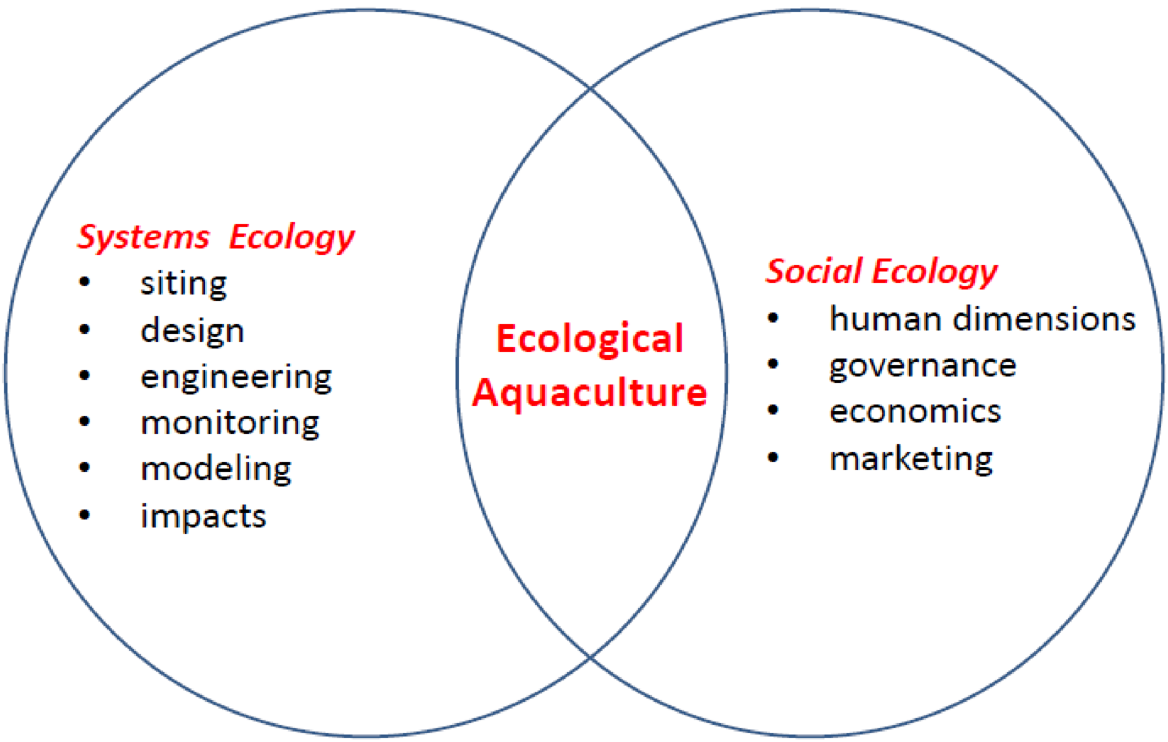

Figure 1. Ecological aquaculture is a transdisciplinary area of applied scholarship, a "pracademic", a blend of professionals working in the practical and the academic, combining the aquaculture sciences with the practical experiences of working with coastal peoples and governance systems.

An alternative model called "ecological aquaculture" is needed that develops clear, unambiguous linkages between aquaculture, the environment and society, and promotes the complementary roles of aquaculture in contributing to environmental sustainability, rehabilitation and enhancement to a highly concerned, increasingly educated and involved public (Figure 1).

Ecological aquaculture brings not only the technical aspects of ecosystems science, ecological methods and systems ecology to aquaculture, but also incorporates the principles of social ecology, social-ecological systems and those connections for the wider social, economic and environmental contexts of aquaculture developments. Sustainable aquaculture is far too broad a concept to obtain any realistic academic traction. IMTA is an obtuse, confusing concept to many, and as reviewed above, remains without a strong scientific or economic foundation. IMTA is also considered by many to be an "assemblage"…a comment at a recent stakeholder meeting was "I can't do IMTA, we have no access to salmon, seaweeds, or mussels".

Ecological aquaculture has the weight of ecosystem ecology behind it. It has the emerging history as being a sister field to agroecology and agroecosystems. It can articulate clear goals, such as…new aquaculture operations must plan at the outset to: 1) become an integral part of a community and a region, 2) plan for social development by working with leaders to provide inputs and recycle wastes, 3) create a diversity of unprocessed and value-added products, and provide for local market access, and 4) plan for job creation and environmental enhancement on local and regional scales.

Table 1. Ecological Classification of Aquaculture Systems (modified from Costa-Pierce, 1996, 2003)

Biophysical System Types	**Functional Attributes**
Levels of Systems Integration	• Stand Alone as Aquaculture • Integrated with Fisheries or Agriculture
Units	• Ponds • Raceways • Tanks • Cages: Floating • Cages: Bottom • Net Pens: Fixed • Rafts: Ropes • Rafts: Nets • Ropes, Lines, Socks
Environmental Location	• Outdoor: Natural • Outdoor: Artificial • Indoor
	•
Water Salinities	• Freshwater • Brackishwater • Saltwater (also called "mariculture")
Water Flow	• Running Water (lotic) • Standing Water (lentic) • Standing Water with Flushing
Water Treatment	• Open, Flow-through • Closed, Full Recirculation • Semi-closed, Partial Recirculation
Feeding Strategies	• Continuous • Scheduled • Natural
Feed Qualities	• Complete • Supplemental • Natural
Seed/Fry Sources	• Nature • Wild Capture of Broodstock • Hatcheries

Species Natural Food Habits	• Carnivorous • Omnivorous • Herbivorous • Opportunistic
Species Stocking Strategies	• Monoculture • Polyculture • Janitorial Polyculture
Species Temperature Tolerances	• Coldwater • Warmwater • Eurythermal • Senothermal
Species Salinity Tolerances	• Marine • Freshwater • Euryhaline • Stenohaline
Social-Ecological System Types	**Kinds**
Management (Stocking, Economic) Intensities	• Intensive • Semi-Intensive • Extensive
Marketing Channels	• Human Food: Local • Human Food: Export • Recreation • Display • Tourism

Table 2 (Costa-Pierce, 2003)

A natural and social ecological classification of aquaculture ecosystems

Solar Aquaculture	Smallholder Aquaculture	Semi-Intensive Aquaculture	Intensive Aquaculture	Intensive Industrial Aquaculture
Natural foods	Low quality supplemental feeds, fertilizers	High quality supplemental feeds, fertilizers	Complete feeds	Complete, high protein feeds
Plants, shellfish, fish	Tilapia, carps, crustaceans	Crustaceans, fish	Marine fish, crustaceans	Marine fish, crustaceans
In nature, In large ponds	Ponds, Tanks	Ponds, Tanks	Tanks, Pens, Raceways	Tanks, Pens, Raceways
Families, small businesses	Families, small businesses	Families, small to medium-scale national businesses	Large, regional & national businesses	Multi-national corporations

References

Allen, TFH, Starr TB. 1982. *Hierarchy: Perspectives for Ecological Complexity.* University of Chicago Press.

Allen, TFH, Hoekstra TW. 1992. *Toward a Unified Ecology. Complexity in Ecological Systems Series.* Columbia University Press, NY.

Altieri, M. 2002. Agroecology: the science of natural resource management for poor farmers in marginal environments. Agricul. Ecosys. Environ. 93:1-24.

Bailey C, Jentoft S, Sinclair P. 1996. *Aquacultural Development: Social Dimensions of an Emerging Industry.* Westview Press, Boulder, CO.

Bunting, S.W., 2013. Principles of Sustainable Aquaculture, Promoting Social, Economic and Environmental Resilience. Routledge, Abingdon, UK.

Chopin, T., Cooper, J.A., Reid, G., Cross, S., Moore, C., 2012. Open-water integrated multitrophic aquaculture: environmental biomitigation and economic diversification of fed aquaculture by extractive aquaculture. Rev. Aquac. 4: 209–220.

Costa-Pierce, B. 2002. *Ecological Aquaculture.* Blackwell, Oxford, UK.

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

Costa-Pierce, B.A. 2010. Sustainable ecological aquaculture systems: the need for a new social contract for aquaculture development. Marine Technology Soc. Jor. 44(3): 1-25.

Costa-Pierce, B.A. and G.G. Page. 2012. Sustainability science in aquaculture, p. 564-581. In: Meyers, R. (ed.), *Encyclopedia of Sustainability Science and Technology*. Springer Reference, N.Y.

Cranford, P.J., Reid, G.K., Robinson, S.M.C., 2013. Open water integrated multi-trophic aquaculture: constraints on the effectiveness of mussels as an organic extractive component. Aquacult. Environ. Interact. 4, 163–173.

Gliessman, S. 1998. Agroecology: ecological processes in sustainable agriculture. Ann Arbor: Ann Arbor Press.

Hagen, J.B. (1992). *An Entangled Bank: The origins of ecosystem ecology*. Rutgers University Press, New Brunswick, N.J.

Jamieson, D. 1996. *Climatic Change* 33:323-336.

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

Ludvigsen S. 2002. *AquaVision Magazine* (Stavanger, Norway) 2002:20-25.

McKindsey, C.W., 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.

Navarrete-Mier, F., Sanz-Lazáro, C., Martín, A., 2010. Does bivalve mollusc polyculture reduce marine fin fish farming environmental impact? Aquaculture 306: 101–107.

Odum, H.T. (1971). *Environment, Power, and Society*. Wiley-Interscience New York, N.Y.

Odum, E.P 1969. "The strategy of ecosystem development". in: *Science* 164:262-270.

Olsen S, Page G and Ochoa E (2009) The analysis of governance responses to ecosystem change: A handbook for assembling a baseline. LOICZ Reports & Studies No. 34. GKSS Research Center, Geesthacht, Germany

O'Neill RV, DeAngelis DL, Waide JB, Allen TFH. 1986. *A Hierarchical Concept of Ecosystems.* Vol. No. 23. Monographs in Population Biology, Princeton University Press.

Reid, G.K., Chopin, T., Robinson, S.M.C., Azevedo, P., Quinton, M., Belyea, E., 2013a. Weight ratios of the kelps, *Alaria esculenta* and *Saccharina latissima*, required to sequester dissolved inorganic nutrients and supply oxygen for Atlantic salmon, *Salmon salar*, in integrated multi-trophic aquaculture systems. Aquaculture 408–409: 34–46.

Reid, G.K., Robinson, S.M.C., Chopin, T., MacDonald, B.A., 2013b. Dietary proportion of fish culture solids required by shellfish to reduce the net organic load in open-water integrated multi-trophic aquaculture: a scoping exercise with cocultured Atlantic salmon (*Salmo salar*) and blue mussel (*Mytilis edulis*). J. Shellfish Res. 32 (2): 509–517.

Ulanowicz RE. 1997. *Ecology, the Ascendent Perspective.* Columbia University Press, NY.