Sustainability Science in Aquaculture

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Definition

There is no one definition of "sustainability" as the concept applies to aquaculture. Most aquaculture scientists define sustainability as synonymous with "environmental sustainability". Sustainable aquaculture is however a concept broader than determinations of site-specific environmental impacts since it embodies a scientific knowledge of systematic impacts of aquaculture off-site, and impacts to combined human-environmental systems. Sustainable aquaculture incorporates the concepts of "stewardship", "design with nature," the "precautionary principle", "risk analysis", and "carrying capacity". Sustainability science in aquaculture 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 aquaculture development options.

Glossary

Stewardship: Ecosystem stewardship is an ethic practiced by aquaculture practitioners, organizations, communities, and societies who strive to sustain the qualities of healthy and resilient ecosystems and their associated human communities. Stewardship takes the long-term view and promotes activities that provide for the well being of both this and future generations.

Nested Systems of Governance: Environmental and societal issues relating to sustainable aquaculture impact, and are impacted by, conditions and actions (at both higher and lower levels) in an ecosystem governance hierarchy. Some issues can be addressed more effectively at one level, and less effectively at another. The choice of the issue or set of issues to be addressed within a given site must therefore be made in full knowledge of how responsibility and decision-making authority are distributed within a layered governance system. Planning and decision-making for aquaculture at one scale; for example, within a municipality or province, should not contradict or conflict with planning and management at another; for example, large scale aquaculture at the nation-state scale. The reality is that such contradictions and conflicts are common. A major challenge for the aquaculture practitioner is to recognize these differences and work to either change them or select goals and strategies that recognize that such contradictions must be accommodated or resolved. In practical terms this means that a central feature of ecosystem-based aquaculture is that all planning and decision-making must recognize and analyze conditions, issues, and goals in respect to the next higher level in a governance system. Thus, ecosystem-based aquaculture at the municipal scale must —at a minimum—be placed within the context of governance at the scale of the province.

Participation: One of the defining characteristics of the practice of the ecosystem approach to aquaculture is its emphasis on participation and its relevance to the people affected. The emphasis upon participation recognizes that if an aquaculture program is to be successful those whose collaboration and support is needed must be involved in the processes of defining the issues that the program will address, and in selecting the means by which goals and objectives will be achieved. Both individuals and members of communities and institutions are more likely to comply with a management program when they feel that that it is consistent with their values, and responds to their needs and to their beliefs of how human society should function. Voluntary compliance by a supportive population lies at the heart of the successful implementation of a program. A participatory approach helps stakeholders and the public to see the efforts of an aquaculture program as a whole.

Area of Focus: The area of focus (AoF) is the geographically defined area that an ecosystem-based aquaculture project or program has decided to address and that therefore is the focal point for a baseline. The term 'area of focus' is a geographic limit set to model the choices available to the aquaculture practitioner and allows for a dialogue between stakeholders as to the influence of the production. The AoF is a simplification of the far more complex concept of an “action arena” put forward by Ostrom [1] to model the choices of individuals when studying the behavior of institutions.

Adaptive Management: A central feature of the practice of any form of ecosystem-based aquaculture is that it must respond positively to changing conditions within its AoF (and to its own experience). In other words, the practice of aquaculture must be grounded in a process of learning and adaptation (the "evolution of the blue revolution" [2]). Adaptive management is not reactive management, but proactive thinking and acting. This does mean that the aquaculture practitioner simply responds to the unexpected. Adaptive management in aquaculture is a conscious process of examining the course of events as these are revealed by pre-selected indicators of changes in an aquaculture ecosystem (both its social and environmental components), and by events occurring at differing spatial scales.

Capacity Building: There is growing international recognition that the lack of human capacity to practice an ecosystem approach to aquaculture is a key factor in limiting forward progress in the conservation and sustainable use of aquatic systems [3,4]. To date, however, no accepted performance standards have been developed for assessing the effectiveness and impacts of aquaculture projects and programs that have adopted the ecosystem approach. We herein offer conceptual frameworks and methods for assessing the maturity of aquaculture development and management initiatives, and gauging their impacts upon the condition of coastal ecosystems. These are the core ingredients for an ecosystems approach to aquaculture that builds the capacity of local populations and leaders to identify forces that shape the coastal ecosystems of which they are a part, and to select the actions that can maintain and enhance qualities that are critical to a desirable future.

Carrying capacity: The carrying capacity is the number of organisms or farming operations that the environment can sustain indefinitely without environmental harm, given the food, habitat, space, water, and other requirements from the environment.

Precautionary principle: A principle states that if an action or policy has a suspected risk of causing harm to the public or to the environment that in the absence of scientific consensus the burden of proof rests on those who advocate taking the action.

Sustainable development: The management and conservation of the natural resource base and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Sustainable development conserves resources, is environmentally non-degrading, and is technically appropriate, economically viable, and socially acceptable [5].

Transdisciplinary: A modern research strategy that crosses many disciplinary boundaries to create a holistic approach. Transdisciplinary research efforts are focused on problems that cross the boundaries of two or more disciplines, and develops new or reframes old concepts, methods and findings that were originally developed by one discipline, but are now used by several others.

Introduction

> "The changes taking place [on planet Earth] are, in fact, changes in the human-nature relationship. They are recent, they are profound, and many are accelerating. They are cascading through the Earth's environment in ways that are difficult to understand and often impossible to predict. Surprises abound." [6]

There are 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. 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. 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 uses the wisdom from multiple disciplines in decision-making (e.g. it is "transdisciplinary"). In aquaculture, it 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.

The emerging fields of ecological aquaculture [2,3] and agroecology [7,8] recognize that the implementation of more sustainable food production systems require knowledge about how ecosystems are utilized and how conflicts among social groups are addressed. A baseline of response to social ecological changes is the foundation for the implementation of more sustainable food systems, and the practice of adaptive management must be included as responses to changes in the condition of ecosystems in which new 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 knowledge-based 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 [9].

This 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 engagement of governmental agencies, businesses, non-governmental groups and academics to achieve the highest form of sustainable development in any known protein production food system by using the concepts of ecological design 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.

Sustainability Strategic and Implementation Planning for Aquaculture

The concept of sustainability and the methods to measure the evolutionary progress towards more sustainable systems are limited, but have become a necessity. Wurts [10] stated that "Whether the word sustainability has become overused or not, it has catalyzed a forum for oversight of the growth and development of aquaculture on a global scale."

Sustainability is not a "black/white" phenomena; rather, it is many "shades of grey", an evolutionary process that we call the "sustainability trajectory" (**Figure 1**). To measure and evaluate progress along a trajectory requires establishment of baselines for the main issues of public concerns, then developing a diverse but targeted set of resource and social indicators. These indicators are then used to report progress on and analyze interactions between social, environmental, and economic impacts (both positive and negative ones). It is important to note that sustainability science as applied to aquaculture is driven as much by social as by environmental/ecological concerns, thus, sole involvement of technical experts in sustainability plans and assessments is insufficient.

Developing an operational framework for how the sustainability of aquaculture operations is the first step. Having such a blueprint is rare for aquaculture businesses and management entities, and is very much needed. There are numerous certification bodies that are vying for the opportunity to use their labels/logos to claim ownership of the sustainability rubric in aquaculture. We propose here an overall sustainability science approach which can step above the cacophony of approaches and assist in developing a common language and can be used by international and national, non-advocacy organizations such as the FAO, ICES, or governments and industry.

Our approach in based upon the development of a baseline that has two parts and then follows a sequence of five steps:

The first part of a baseline is an ecosystem audit of the AoF that defines the natural and social systems within which aquaculture is planned.

This involves the documentation and analysis of both natural and social systems, draws upon cases studies of other aquaculture systems in the region and how the governance system in a specific place has responded – or failed to respond – to the trajectories of ecosystem change. It examines the long-term trends in both human well-being and the environmental conditions in the AoF and examines responses to the issues raised by past and current expressions of food production systems.

The second part of the baseline is an outline of the strategic approach to designing a new aquaculture program, or adapting an on-going program, to address the ecosystem management issues of the place in terms of economic, environmental, and societal benefits. Together, these parts form the reference points against which future changes in the aquaculture ecosystem will be gauged. Our methods encourage a long-term perspective, an appreciation of the roles played by civil society, markets and government, and offer a holistic, ecosystem-based, approach to stewardship.

Baselines are not formulaic but are designed planning exercises with buy-in from key stakeholders such as the client, community, regulatory community or identified group of people involved in the project. While not formulaic, baselines do include a set of common metrics to include:

- Ecological aquaculture design (or redesign) of production practices (see Ecological Aquaculture chapter in this Encyclopedia)
- Health and quality control standards
- Social goals at both the individual and community levels for local food, job and regional development (e.g., "green jobs", "local foods")
- Governance goals.

The following five steps encompass some essential parts of any baselining process:

(1) Define the sustainability issues. Aquaculture systems can use environmentally derived feeds, water, and energy, occupy land and water space, and generate wastes. There are at least eight issues of wide public and regulatory concerns regarding aquaculture development:

- Destruction of habitats
- No net gain to global seafood supplies
- Environmental impacts of discharged wastes
- Impacts of escapees
- Diseases in farmed fish
- Chemical use and discharge
- Impacts of coastal marine mammals
- Siting causes visual pollution

Once issues are defined, a baseline can be further developed which can measure progress over time by:

(2) Completing a sustainability assessment of these issues by evaluating the status of current aquaculture practices that affect natural and social resource systems (**Table 1**), which also includes an assessment of governance systems (**Tables 2,3**) [11-13].

(3) Completing a detailed risk analysis for all components of this comprehensive assessment [14];

(4) Completing a plan for ameliorating identified impacts by incorporation of better (or best) practices [15-17], and/or enhancing reuse or recycling pathways, and

(5) Completing a plan for communicating the evolution of operations towards greater stewardship and sustainability [14].

To be effective, sustainable aquaculture initiatives must: (a) be "profitable" over long periods of time – ideally many decades; (b) be capable of being adapted to changing conditions; and (c) provide the mechanisms to encourage both wise resource use and collaborative behaviors. Much of the challenge lies in achieving changes in the behavior of those who may be unaware of the benefits of sustainable aquaculture.

Sustainable aquaculture integrates the best available science with a transparent, equitable, and democratic approach to planning and decision making. This ecosystem approach to management needs to be carried out in a strategic manner that tailors principles of good practice to the culture and the needs of a specific place. Successful, sustainable aquaculture operations advance through linked cycles of planning, implementation, and re-assessment. These features of ecosystem management signal the transition from traditional sector-by-sector planning and decision-making to a more holistic approach based on the interactions between sectors and within and among ecosystems.

Aquaculture that is constructed upon principles that encourages high-energy consumption and the profligate use of natural resources must give way to new locally derived values and new forms of practice. As suggested by Daly [18], qualitative development rather than quantitative growth is the path of future progress. If such ideas are to be made operational at the scale of an aquaculture operation, a trajectory can be established based on goals for profit as well as social and environmental benefit. Once the goals of an aquaculture program or project have been defined as expressions of the ecosystem approach much of the day-to-day work is concerned with the well known best practices of aquaculture management.

For example, there has been much debate about the impacts of shrimp pond mariculture on mangrove forests through the Topics. Mangrove ecosystems provide essential goods and services to humanity, harboring an extraordinarily large biodiversity for the small areas of the planet that these systems occupy, and provide a sustainable source of timber and charcoal to coastal communities while protecting fragile coastlines from erosion and storms. Establishment of proper scientific baselines to measure the true impacts of mariculture on coastal ecosystems is essential. Pullin [19] cautions that, "Analysis on depletion of mangrove cover in Asia point towards the fact that shrimp ponds have recently been and/or now being constructed either on former mangrove areas that were cleared long ago and considered degraded), or on more recently cleared areas for which the primary purpose of clearance was timber abstraction (logging, wood chip industries or charcoal production) or by adopting traditional trapping ponds…Aquaculturists in Asia are therefore more often than not the end users of already degraded or destroyed mangroves rather an the primary culprits of mangrove destruction".

Good examples globally of an ecosystem approach to aquaculture at the watershed/aquaculture zone scale are found in both 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 [20,21], as well as highly productive, land-based aquaculture ecosystems for marine species [22]. These aquaculture ecosystems are productive, semi-intensive enterprises that are water and land efficient, highly, and are net energy and material gains to society which follow principles similar to the fields of agroecology and agroecosystems [23].

In Australia, an Ecologically Sustainable Development (ESD) framework approach to aquaculture development was used [24]. This 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 of all other marine users, and users' management plans for operations and administration as well as environmental administrative attributes, then proposed development and monitoring plans.

As a result of this ESD approach, nine marine aquaculture zones of 2400 ha in Port Phillip Bay and Westernport, Victoria, Australia were permitted. The Australian ESD approach combined analytical and participatory methods and developed sustainability plans that considered both ecosystem and human well-being, then developed implementation strategies by designing and enhancing effective governance systems for the expansion of aquaculture.

The development of a sustainability baseline should be the responsibility of a lead aquaculture agency. Its full implementation may require alternative methods of governance and employ innovative management approaches. There may be a need to facilitate an operational definition of aquaculture ecosystem boundaries for assessment, or area of focus, to set geographical limits to assess parameters such as carrying capacity or water management needs, and to understand the governance regime within which the area of focus is nested in order to understand and clarify such things as administrative and legal jurisdictions.

Using such guidance and sustainability science frameworks, the possibilities for designing productive aquaculture ecosystems that better fit into the local social and ecological context are many, since aquaculture can encompass the wide availability of species, environments and cultures.

Improved Governance of Aquaculture Ecosystems

To be effective, ecosystem based aquaculture initiatives must (1) be sustainable over long periods of time – ideally over many decades, (2) be capable of being adaptable to changing conditions and (3) provide the mechanisms to encourage or require specified forms of resource use and collaborative behaviors among institutions and user groups that are stakeholders of the aquaculture system. Much of the challenge lies in both understand and achieving changes in the behavior of the stakeholder groups and institutions associated with the aquaculture production systems. Ecosystem-based aquaculture integrates the best available science with a transparent, equitable and democratic approach to planning and decision-making. Management needs to be carried out in a strategic manner that tailors principles of good aquaculture practice to the culture and the needs of a specific place. Successful aquaculture programs advance and change through linked cycles of planning, implementation and re-assessment. These features of ecosystem management signal the transition from traditional food production sector planning and decision-making to a holistic approach based on the interactions between sectors and within and among ecosystems.

FAO Fisheries and Aquaculture Department [25] found that one of the key trends towards more sustainable forms of aquaculture development and management is enhanced regulation and better governance. We define governance as the formal and informal arrangements, institutions, and mores that structure and influence how resources or an environment are utilized, how problems and opportunities are evaluated and analyzed, what behavior is deemed acceptable or forbidden, and what rules and sanctions are applied to affect how natural resources are distributed and used.

As shown in **Table 2,** there are three mechanisms by which the processes of governance are expressed: the marketplace, the government, and the institutions and arrangements of civil society [11]. These mechanisms interact with one another through complex and dynamic interrelationships that are examined and contrasted and documented in a baseline. Each of the three governance mechanisms influence and can alter patterns of behavior through measures such as those identified in **Figure 2.** For sustainable, ecosystems-based aquaculture, it is important to distinguish between management and governance. Management is the process by which human and material resources are harnessed to achieve a known goal within a known institutional structure. We therefore speak of aquaculture business management, park management, personnel management or disaster management. In these instances the goals and the mechanisms of administration are well known and widely accepted. Governance, in contrast, addresses the values, policies, laws and institutions by which a set of issues are addressed. It probes the fundamental goals and the institutional processes and structures that are the basis for planning and decision-making. Governance sets the stage within which management occurs [12].

The future of sustainable aquaculture is highly dependent on understanding the response by all three expressions of governance; markets, civil society, and government. For example, Kenya has fostered a participatory policy formulation for aquaculture, providing a legal and investment framework through government, establishing public–private partnerships to engage markets, providing basic infrastructure support, promoting self-regulation, providing a research platform for civil society to be engaged, undertaking zoning for aquaculture and providing monitoring and evaluation support [25].

Adaptation of sustainability frameworks used to evaluate the needs and progress of governance on coastal management plans are essential to evaluate progress towards an ecosystem approach to aquaculture and build in adaptive learning and action into the strategic planning process. Governance frameworks recognize not only the importance of changes in practices such as changes over time in aquaculture farming ecosystems, but also recognize that for each change, there are correlated changes in the behavior of key partners and stakeholders within the sphere of influence of the management activity, and that these changes can be measured at local, regional and national levels (**Figure 3, Table 3**).

Sectoral agencies responsible for managing activities impacting aquatic ecosystems (e.g. capture fisheries, coastal zone development, watershed management organizations, agriculture, forestry, industrial developments) will have to develop new ways of interacting to regularly communicate, cooperate, and collaborate. The need for innovative governance to implement an ecosystem based approach to aquaculture can be seen as an obstacle but can also be seen as an opportunity to increase the social benefits that are likely to develop through synergies among food production sectors.

Social Ecology of Aquaculture

While 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. [26] have developed a "Human Ecosystem Framework" that could contribute to a baseline approach and assist in organizing multidisciplinary, social ecological approaches to aquaculture development (**Figure 3**). The most sustainable growth trajectories for aquaculture are to move towards more sustainable, social-ecological approaches to development; to shift patterns of production and consumption patterns from global to bioregional and local foods production and job creation; and to develop the indigenous human and institutional capacities that clearly demonstrate to society that "aquaculture is culture".

Future Directions: Sustainability Science Opportunities for Aquaculture

There are at least four major opportunities for sustainability science in the field of aquaculture in the:

(1) determination of "sustainable aquaculture" for retail seafood companies,
(2) growing fields of marine ecosystem and habitat restoration, conservation biology and ecology,
(3) accelerated use of agricultural meals and oils, and
(4) development of sustainable aquaculture for the poor.

Determination of Sustainable Aquaculture for Retailers

Sustainability science approaches to aquaculture can be used to better plan and develop aquaculture production networks for multiple species. Such planning approaches can be used to plan for the creation of highly diversified, segmented aquaculture networks, for maximal job creation at every unit step from "farm to plate" (e.g. seafood value chain planning), by creating numerous interconnections supplying inputs and outputs using local resources and recycled wastes and materials and expertise, and to close "leaky" loops of energy and materials that can potentially degrade natural ecosystems.

Behavioral changes will be required by industry. Social investments, strategic incentives/subsidies, and innovative market mechanisms can help facilitate change in behaviors. Self-regulation by the aquaculture industry has led to codes of practice and better management practices.

Sustainability assessments are predicated upon the fact that the modern aquaculture industry desires to be seen as a responsible steward. This means going beyond "meeting the regulations." There are a cacophony of certification bodies and seafood watch cards—there are an estimated 200 sustainable seafood guides available internationally—which has created a far too complex complex and sometimes conflicting recommendations to both consumers and retailers on what is "sustainable seafood" [27,28]. Roheim [27] states that "Shrimp, in some form, appears as a green, yellow, red, and non-consensus list item" in the seafood "watch cards".

The logic behind consumer approaches is that informed consumers who care about sustainable seafood will demand aquaculture products that carry a label or fit into the "green" (buy) area of a watch card, as opposed to those products which don't have the label, sending a market signal back to aquaculture industries that only products from sustainable aquaculture farms are preferred. Many of the independent certification programs that have developed ecolabels and "seafood watch cards" to provide consumers with additional information come from non-governmental organizations (NGOs) with specific advocacy agendas and not from neutral, scientific sources, or from regulatory bodies charged with protecting the environment and society. For example, many fisheries and aquaculture scientists are deeply concerned that consumer recommendations of NGOs are moving demand (and use) from farmed stocks to already overburdened wild fisheries. The Monterey Bay Aquarium's (MBA) Seafood Watch Program has produced millions of folding wallet cards featuring a "stop light" system of green (sustainable), yellow (chose with caution), and red (don't choose) recommendations. Farmed shrimp and salmon two of the world's largest aquaculture industries are on the MBA red list. Roheim [27] mentions that the Compass Group a major food service company has used the MBA cards to decrease purchases of farmed shrimp and salmon; which, in effect has created additional fishing pressure on wild shrimp and salmon stocks.

Most organizations believe that consumers increasing awareness of environmental and food safety issues will lead them to accept a wide variety of standards and labels, most of which are specifically intended to allay consumers' concerns about negative environmental consequences.
However, Roheim [27-29] points out concerns over ecolabeling, especially the lack of transparency and opportunity for participation in the development of standards, and concerns of developing countries that ecolabeling schemes are an attempt at disguised protection of domestic industries to restrict market access and erode competitiveness. In addition, Wessels et al. [30] found that successful ecolabeling programs must accelerate consumer education programs so that consumers become more aware of differences in species, geographic regions, and certifying agencies.

Roheim [29] states that ecolabels require traceability. Traceability is the ability to follow the movement of a food through specified stages of production, processing and distribution. Essentially, it is a record-keeping system that identifies and tracks products, transportation of products, and ingredients of products from origin to consumption, while providing the ability to quickly trace back products at any point along the supply chain. It is necessary for food safety purposes, in order to track backwards in the food chain the source of food which made consumers ill, so products could be removed from store shelves.

For consumers Roheim [27] argues the need for ecolabels determined at the larger international levels, such as the Marine Stewardship Council (MSC), so that consumers "do not need to inquire about catch area or gear types, but only need to look for the label". The plethora of efforts has also confused and perplexed retailers who are the main "drivers" of certification at present, not consumers [27-29]. However, even though many buyers wish to purchase sustainable seafood, most seafood products are not certified, and they are very confused by the many NGO efforts. A purchasing policy determined by assessing which seafoods are "sustainable" by making an assessment of the plethora of NGOs "opinions" seems to us confusing, risky, and costly. Rather, we recommend a simple, buying protocol **(Figure 5)** that incorporates a sustainability assessment (where needed) as discussed here.

Aquaculture and the Restoration of Ecosystems

Aquaculture science can be viewed as 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 lack of appreciation for the positive environmental attributes of non-food 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 [31].

Aquaculture technologies (hatchery, nursery, grow-out) for marine plants are used for the restoration of mangroves, seagrasses, and coastal wetland plants such as *Spartina sp*. In addition, live rock and coral aquaculture facilities are active for not only the aquarium trade, but also for the environmental restoration of coral reefs (liveaquaria.com). In this regard, there is little difference between sustainable aquaculture and the emerging fields of ecological engineering and industrial ecology. Indeed, tidal wetland, mangrove forest, coral, and seagrass restoration aquaculture—in addition to establishment and maintenance of oyster reefs—are important examples of aquaculture creating, enhancing, and maintaining productive marine ecosystems and habitats, and improving water quality.

Aquaculture and Agriculture Science

There science questions as to whether aquaculture contributes to the depletion of world fisheries. Fed aquaculture depends on both wild and farmed fish stocks and on intact aquatic habitats and excellent water quality, plus a growing quantity of agricultural resources. 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 much less planning and research regarding the future impacts of fed aquaculture on agriculture.

Agricultural meals and oils as alternatives to marine sources are developing rapidly. Current projections forecast that fed aquaculture may use 50% or less of the world's fish meal [32] which would mean a large expansion of use of agricultural and other terrestrial sources of feed proteins and oils. Terrestrial proteins and oils from soybeans, sunflowers, and lupins are available at volumes larger than the available global quantities of fishmeal. Soybeans have high protein content of ~28%, peas have ~22%, and these have good amino acid profiles. Other abundant agricultural cereals have lower protein contents of ~12-15%. Processing can create protein concentrates with protein levels of >50% [33]. Vegetable oils have very low EPA (eicosapentaenoic acid) and DHA (docosahexaenoic acid) levels. However, substitution of plant oils upwards of 50% of added dietary oil has not resulted in growth reductions or increased mortalities in fish such as salmon and trout.

If agricultural sources of meals and oils are the future of fed aquaculture there will be a need for a new sustainability planning and science on the impacts of fed aquaculture as a driver of agriculture production, especially so for soybeans. Increased aquaculture consumption of the world's grains and oils raises the concern over the spread of unsustainable agriculture practices. Brazil has been targeted as one of the world's major soybean suppliers. Costa et al. [34] have 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 a 16% less rainfall compared to a 4% decrease in rainfall in land areas cleared for pasture.

Aquaculture for the Poor

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 [4]. 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 [4].

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, 216 million live on US$2/day, 88 million are undernourished, and 16 million children under 5 are malnourished [35].

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 [35].

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 foods) for a protein-hungry planet [36-38]. Greater than 75% of global fisheries are traded. In 2000, more than 60% of fishmeal was traded. Only 7% of meat is traded, 17% of wheat, and 5% of rice. To tackle this huge challenge, the FAO ecosystems approach to aquaculture [39] has created a new code for responsible global aquaculture development, and has combined this into one common development framework for 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 develop and alternative model of aquaculture development but also interact closely with capture fisheries and agriculture but help deliver to the world's poor its needs for nutrient dense, protein rich seafoods. Components of a global strategy could be to:

(1) 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 to: (a) increase the ecosystem resilience of the Humboldt ecosystem, and (b) relieve the increasing overdependence of aquaculture countries such as Thailand (shrimp) and Norway (salmon) on this southeastern Pacific Ocean marine ecosystem.

Alder et al. [37] estimated that about 36% of the world's fisheries catch (30 million tons) are processed into fishmeal and oil, mostly to feed farmed fish, chickens, and pigs. 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. [28] reported that Peru exports about half of the world's fishmeal from its catch of 5–10 MMT/y of anchovies while half of its population of 15 million live in poverty and 25% of its infants are malnourished. A campaign launched in 2006 combining scientists, chefs, and politicians to demonstrate that anchovies are more valuable to the Peruvian people and its economy as direct foods has resulted in a 46% increase in demand fresh and 85% increase in canned anchovies. One ton of fillets has sold for five times the price of 1 ton of meal and requires half the fish (3 tons for 1 ton fillets vs. 6 tons for 1 ton meal). Peru has decided to dedicate 30% of its annual food security budget (approx. US$ 80 million) for programs to supply anchovies to its people. Higher prices for fish used as direct human foods for food security will limit processing of fish to meals for terrestrial animal and aquaculture feeds, thereby decreasing the supply of fishmeals and oils for global aquaculture trade and development, but meeting the Millennium Development Goals of eliminating everywhere extreme hunger and starvation.

(2) 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 [40] 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 fishmeal contents in diets to 25%. Additional research with phospholipids in meals, triglycerides in fish oil, and antioxidants in 2008 have resulted in excellent fish performances from feeds with almost no marine fishmeal and oil. Current research is exploring the extraction of functional ingredients from other non-marine by-products.

(3) Develop alternative ecological aquaculture models that accelerate the movement towards 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 [32] 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. As stated previously, 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 [41,42]. Turchini et al. [43] 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. [44] found that palm oil could replace fish oil in rainbow trout diets, and reduce the dioxin contents in fish.

(5) Develop new governance systems that integrate aquaculture, agriculture and fisheries using ecosystem-based management approaches which 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 [45] 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 be need to be further developed and well utilized or serious consequences for the Earth's living systems will result.

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Table 1. Important sustainability science tools used to assess and communicate the sustainability of aquaculture[1]

Social Sustainability	Environmental Sustainability	Economic Sustainability
Stakeholder analysis: analysis of attitudes of stakeholders at the initiation of and throughout a project. Allows tracking of how stakeholders change attitudes over time with educational processes [46-50] **ISO 26000 guidelines** for corporate social responsibility [51] **ICLEI** (International Council for Local Environmental Initiatives) provides software and tools to help local governments achieve sustainability goals [52]	**Life cycle analysis**: complete assessment of products from raw material production, manufacture, distribution, use and disposal, including all transportation; used to optimize environmental performance of a single product or a company. A similar analysis called a MET (Materials, Energy, and Toxicity) Matrix is also used [53-55] **ISO 14000 certification:** norms to promote more effective and efficient environmental management and provide tools for gathering, interpreting and communicating environmental information [56] **Environmental impact assessment**: the process of identifying, predicting, evaluating, mitigating biophysical, social, and other effects of development proposals prior to policy decisions [57,58] **Environmental indicators:** the use of quantitative indicators of resource use, efficiency and waste production in aquaculture [17]	**Cost-benefit analysis**: analysis of cost effectiveness of different uses to determine if benefits can outweigh costs [59] **Triple bottom line or "full cost" accounting:** costs considered for all environmental, economic, and social impacts; costs measured in terms of opportunity costs (the value of their best alternative use); guiding principle is to list all parties affected and place a monetary value on effects on welfare as valued by them [60,61]

[1]This table does not contain a comprehensive list of all available tools; rather, tools selected here were chosen since they appear regularly in the modern sustainable aquaculture research, industry, and management literature. Gibson et al. [62] gives a most complete analysis of all of the available tools for sustainability assessments.

Table 2. Sustainability science assessments of aquaculture includes an assessment of governance systems, which examine the three processes of governance: government, the marketplace, the government, and civil society.

Major Expressions of Governance
Government
Laws and regulations
Taxation and spending policies
Education and outreach
Marketplace
Profit seeking
Ecosystem service valuation
Cost-benefit analysis
Eco-labeling and Green Products
Civil Society: Organizations and Institutions
Product choices
Advocacy and lobbying
Vote casting
Co-management
Stewardship activities

Table 3. Orders of governance outcomes [12,13] applied to an ecosystem approach to aquaculture [2,3]

Orders	**Explanations**	**Indicators**
First Order	Government at the national level commits to a plan of action designed to adopt an ecosystem approach to aquaculture (EAA) by issuing a formalized commitment to an EAA, thereby putting in place the ''enabling conditions''	New laws, programs, and procedures are initiated that provide the legal, administrative, and management mechanisms to achieve the desired changes in behavior by: (i) building constituencies that actively support EAA with the user groups that will be most affected; with government institutions involved; and with the general public; (ii) developing a formal government mandate for an EAA with the authority necessary to implement actions in the form of laws, decrees, or other high level administrative decisions that create an EAA as a permanent feature of the governance structure of aquaculture; creation of commissions, working groups, user organizations and non-governmental organizations (NGOs) dedicated to the advancement of an EAA agenda; designating EAA zones; (iii) devoting resources, especially sustained annual funding, adequate to implement an EAA; (iv) developing an implementation plan of action for an EAA that is constructed around unambiguous goals; (v) creating the institutional capacity necessary to implement the new EAA plan of action.
Second Order	Evidence of successful implementation of an EAA	(1) Changes in the behavior of institutions and interest groups have occurred such as collaborative planning and decision-making through creation of task forces, commissions, civic associations, etc.; (2) Successful application of conflict mediation activities; (3) Evidence of functional changes such as establishment of new public-private partnerships, new collaborative actions undertaken by user groups, implementation of new school curricula that incorporates an EAA; (4) Changes in behaviors directly affecting ecosystem goods and services, such as the elimination of socially and environmentally destructive aquaculture practices; (5) Investments in infrastructure supportive of EAA policies and plans.
Third Order	Evidence of sustained achievements in institutional and behavioral change due to an EAA as seen in the environment and indicators for the quality of life, incomes, or engagement in alternative livelihoods that have improved target communities	(1) Improvements in ecosystem qualities, such as sustained conservation of desired ecosystems and habitats, halting or slowing undesired trends such as nutrient releases, feed wastage, diseases, damaged benthic ecosystems, etc.; (2) Improvements in society as evidenced by monitoring of social indicators such as increases in indices of quality of life, reduced poverty, greater life expectancy, better employment opportunities, greater equity in access to coastal resources and the distribution of benefits from their use, greater order, transparency and accountability in how planning and aquaculture development decision-making processes occur, greater food security, or greater confidence in the future.

Figure 1. Sustainability is not a "black or white", nor an "either or" concept. It is the evolution of practices and principles over time towards ameliorating environmental and social impacts, with plateaus along the way in changed states. In many cases, these "pauses" are done to insure economic viability. In this diagram, we plot one example indicator (water use, other important indicators have been proposed [17]) along such a "sustainability trajectory".

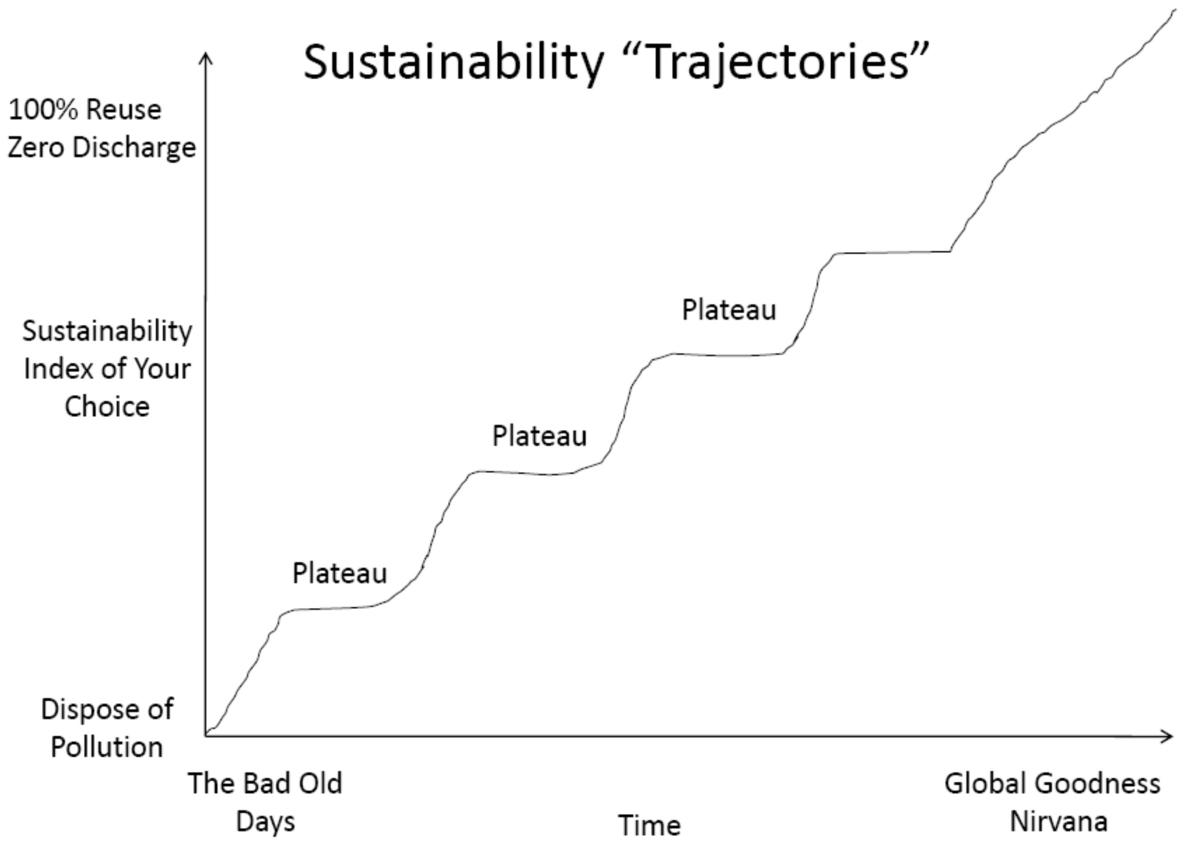

Figure 2. The three mechanisms by which the processes of governance are expressed interact with one another through complex and dynamic interrelationships that are vital parts of sustainability science assessments of aquaculture as each alter behaviors and decision-making that determine human uses of ecosystems [11-13].

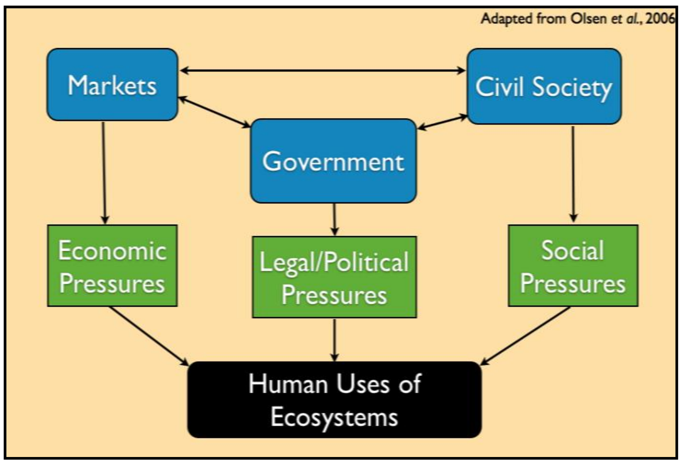

Figure 3. The four orders of coastal governance outcomes. This framework is used to develop governance baselines in environmental programs [12,13]. An example of how progress towards better governance for sustainable aquaculture is shown in Table 3.

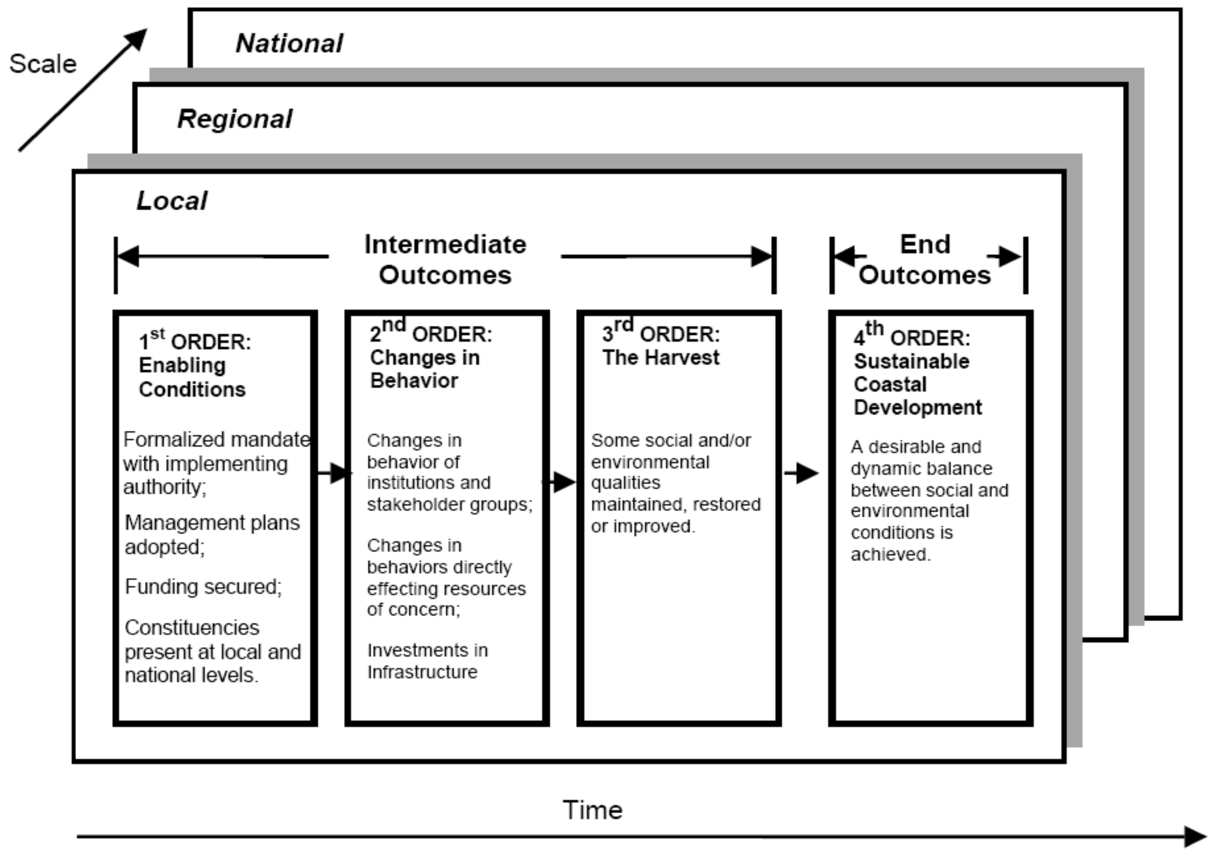

Figure 4. The Human Ecosystem Framework [26]. Assessment of new interventions such as aquaculture into societies requires knowledge of not only biophysical and natural resource systems but also social resources and human social systems.

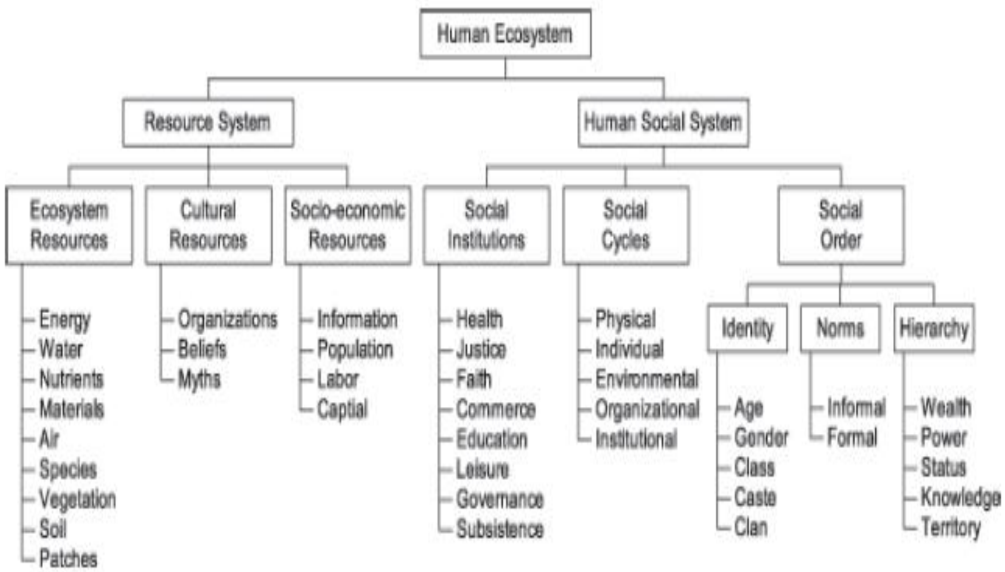

Figure 5. A simple decision-tree for determinations of the sustainability of aquaculture products by retailers.