Ecosystem Based Aquaculture and Environmental Sustainability

Shelton Padua

ICAR-Central Marine Fisheries Research Institute, Kochi
shelton_padua@yahoo.com

The ecosystem approach to aquaculture (EAA) is the fruit of the discussions between the Food and Agriculture Organization (FAO) of the United Nations and aquaculture experts around the world held in the 90s and 00s. The aim of the discussions were to device the ways to move the planning and management of aquaculture towards greater sustainability. The EAA was devised as a tool to support the implementation of the FAO Code of Conduct for Responsible Fisheries (CCRF) and has helped to promote the sustainable exploitation of capture fisheries worldwide. The rapid growth of the aquaculture sector worldwide, and the interaction of aquaculture activities with other economic sectors and natural resource users, require a responsible and integrated approach to aquaculture development (FAO 2003; Garcia *et al*. 2003).

The ecosystem approach to aquaculture (EAA) is a strategy for the integration of the activities within the wider ecosystem such that it promotes sustainable development, equity, and resilience of interlinked social-ecological systems.

The EAA is guided by three strategic principles:

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.
2. Aquaculture should improve human well-being and equity for all relevant stakeholders.
3. Aquaculture should be developed in the context of other sectors, policies and goals, as appropriate.

The EAA builds on these principles to provide a planning and management framework for effectively integrating the aquaculture sector into local planning. The EAA tries to provide mechanisms for producers and government authorities to engage with one another for the effective and sustainable management of aquaculture operations and requires them to simultaneously embrace the environmental, socio-economic and governance objectives of the sector.

Evidence from field projects on the EAA in different countries indicates that institutional and human capacity issues stand out as the most salient constraints towards its implementation. In more general terms, the type of constraints facing the implementation of the EAA are legislative and regulatory issues; ineffective interagency integration and coordination; financial constraints; lack of human resources; and ambiguity in the perceived benefits of these approaches by administrators and producers alike (Miao *et al*. 2013).

Threats and challenges to the implementation of the EAA:

1. Competing development objectives
2. Difficulties with interagency cooperation
3. Ecosystem and administrative boundaries
4. Equity issues
5. Insufficient awareness
6. Insufficient knowledge
7. Lack of or limited technical and human capacity and resources (including monetary)
8. Limited stakeholder participation
9. Poor governance and regulation
10. Unregistered or illegal farms

The EAA has been instrumental in raising awareness of the importance of sustainable development and placing them at the heart of aquaculture planning and the work of those supporting and acting for the development of this sector. EAA pitches for a holistic approach to aquaculture development and that makes it unique compared to other food production sectors. For example, the EAA touches on inseparable planning and management issues and uniquely captures interactions between aquaculture and capture fisheries at multiple scales (Soto *et al*. 2012).

Spatial planning and EAA

The promotion and implementation of the EAA have taken a range of forms and led to a range of positive outcomes. The ecosystem approach to aquaculture provides the conceptual guideline for spatial planning and management (Aguilar-Manjarrez *et al*., 2017). Inappropriate spatial arrangement and site selection of aquaculture is a major constraint to sustainable development and expansion of the industry. To create a successful aquaculture business, it is necessary to have farm sites based in locations that are suitable for sustainable production. All aquaculture species have specific biological needs such as oxygen, temperature and good water quality that have to be fulfilled to secure high production and to minimize stress and disease. The location of aquaculture farms requires access to land and water, where use must also co-exist with other human activities. Access to roads and electricity (infrastructure) is also necessary. A poor location of an aquaculture farm will not only create environmental problems such as localized eutrophication, but it may also have a broader impact on environmental, social and economic aspects, such as conflicts with other human activities over the use of inland and coastal zone resources, that can detract from the benefits of a sustainable aquaculture industry.

Common problems arising from the lack of spatial planning and management of aquaculture can be categorized as: (i) fish disease; (ii) environmental issues; (iii) production issues; (iv) social conflict; (v) post-harvest and marketing issues; (vi) risk financing; and (vii) lack of resilience to climatic variability, climate change and other external threats and disasters. Spatial planning and management of aquaculture can be done at several geographical scales to address problems in aquaculture and provide opportunities to enhance development. Spatial planning could also be a means to improve negative public perception about potential environmental impacts, especially those associated with marine fish farming, and on access to and use of coastal resources (Aguilar-Manjarrez *et al*., 2017).

Impacts on the environment

One of the major challenges to the sustainable development of aquaculture is the sharing of water, land and other resources with alternative uses, such as fisheries, agriculture and tourism. Spatial planning for aquaculture, including zoning, site selection and the design of aquaculture management areas, should consider the balance between the social, economic, environmental and governance objectives of local communities and sustainable development. It is now widely recognized that further aquaculture development should be a planned activity that is designed in a more responsible manner so as to minimize negative social and environmental impacts as much as possible. One essential step is appropriate spatial planning at the local, regional and national levels, and accounting for transboundary issues where these are relevant. Although many of the social and environmental concerns surrounding impacts derived from aquaculture may be addressed at the individual farm level, most impacts are cumulative. Impacts may be insignificant when an individual farm is considered, but potentially highly significant when multiple farms are located in the same area or when the entire sector is taken as a whole.

In recent years, society has become increasingly concerned about the effects that anthropogenic activities have on the environment. Aquaculture activities also make significant contribution to these effects. The assessment of impacts from aquaculture farm activities has not been examined extensively enough to cope with the growth of this industry. These assessments are mostly based on physico-chemical measures and/or sediment characteristics with a limited focus on environmental carrying capacity studies, required for aquaculture sustainability. Environmental characteristics of the receiving environment define the Environmental Carrying Capacity (ECC) of the selected site, which will determine the discharge load (i.e., dissolved and particulate organic matter, chemicals) that might be assimilated by the affected ecosystem. These environmental characteristics include bathymetry conditions, physico-chemical characteristics of water and substrate, trophic status, and colonizing capacity (fouling) etc. (Carballeira *et al*., 2021)

Carrying capacity (CC) is an important concept in ecosystem based management. Earlier, while estimating the CC, only the resource which was farmed was taken into consideration and accordingly CC was defined as the maximum standing stock that may be kept within a particular ecosystem to maximise production without negatively affecting growth rate (Carver and Mallet 1990). Later considering the negative impacts aquaculture can have on the ecosystem services, CC was redefined as “the amount of change that a process or variable may suffer within a particular ecosystem, without driving the structure and function of the ecosystem beyond certain acceptable limits" (Duarte *et al*. 2003). In most aquaculture management programmes, the concept put forth by McKindsey *et al*. (2006) is considered. Here four different types of CC are considered i) physical ii) production iii) ecological and iv) social. These can be described as given below.

- *Physical carrying capacity* is the total area of marine or brackish water farms that can be accommodated in the available physical space.
- *Production carrying capacity* is the stocking density of the animals at which harvests are maximized.
- *Ecological carrying capacity* is the stocking or farm density which causes unacceptable ecological impacts.
- *Social carrying capacity* is the level of farm development that causes unacceptable social impacts.

Environmental Sustainability

The concept of sustainability has been the topic of much debate, both in terms of how to achieve it as well as how to define it. The United Nations Conference on Environment and Development held in 1992 define sustainable development as: "meeting the needs of the present without compromising the ability of future generations to meet their own needs". The principles of sustainability include three dimensions: (1) the economy (ability to be maintained without an outside influx of money; (2) the society [equity and cultural capital that can be passed to succeeding generations], and (3) the environment [maintenance of an ecosystem's characteristic diversity, productivity and biogeochemical cycling] (Carballeira *et al*., 2021).

Environmental aspects of sustainability in aquaculture may not be achieved until several problems are solved: eutrophication of receiving ecosystems, destruction of natural habitats, dependence on fishmeal and fish oil, introduction of exotic species and inadequate medication practices.

Optimal environmental monitoring plans help to understand the impacts of waste management, their utilization and possibilities of how it can be reduced. The exploitation of farming wastes implies a double benefit; less environmental contamination and higher economic profits. Thus, polycultures and technological advances should help the aquaculture industry and are necessary towards aquaculture sustainability. From an ecological point of view, intensive fish farming represents the highest environmental risk when compared to other aquaculture sectors due to the feeding needs and the chemicals used associated with the production process (Tornero and Hanke, 2016).

Environmental Effects of Aquaculture

As the aquaculture sector is developing and expanding, it has an increasing effect on the surrounding environment. These effects include nutrient pollution from uneaten feed and metabolic waste, chemical pollution from various substances used in the production process (such as medical treatments, including antibiotics and antiparasitics) as well as the spread of farmed fish genes, parasites, and diseases to wild populations. An important indirect effect of the production process is the high impact on aquatic ecosystems through the need to use wild fish to feed carnivorous species of farmed fish. There are also other direct effects, such as landscape visual impact, noise, odour, and marine litter from intensively farmed areas (Radford and Slater, 2019).

Nutrient Pollution

During the production process, uneaten feed and the metabolic waste of fish release nitrogen and phosphorus into the water. This process causes problems in intensive farming areas. Waste originated from aquaculture farms may create a significant source of excess nutrients within the coastal areas. These excess nutrients are mainly related to the proliferation of primary producers that may trigger micro- and macroalgal blooms that may be toxic (Carballeira *et al*., 2021).

Chemical Pollution

Numerous chemicals are being used in aquaculture production to prevent and treat disease outbreaks, ranging from medicines such as antiparasitics and antibiotics to disinfectants. Antifouling chemicals are also being used at aquaculture facilities to avoid the clogging of meshes. Chemicals used in aquaculture enter surrounding aquatic environments and may be toxic to non-target organisms in proximity of the farming sites because they are not highly selective, e.g., benzoylurea pesticides affect naupliar development of copepod *Tisbe battagliai* . Moreover, the effectiveness of most chemical treatments is low within high fish densities because of increased host availability. This is especially the case in open cage systems where chemical inputs are directly released to the marine environment (Carballeira *et al*., 2021).

Disease Outbreak and Biological Pollution

Outbreaks of fish diseases are a result of the interaction between the pathogen, the host, and the environment. Several drivers may cause a disease outbreak: high fish density, compressed rearing cycle and a limited genetic diversity. Considering the high stocking densities within aquaculture farms, bacterial, viral, and fungal diseases as well as the spread of parasites is taking place at an increasing rate. For example, in marine aquaculture such spread of diseases occurred during Infectious Salmon Anemia outbreaks. Another recently growing problem is dealing with parasites (e.g., salmon lice *Leopephtheirus salmonis*).

Another issue concerning aquaculture-based negative effects on the environment is the risk of biological pollution. Biological pollution can be caused by the farming of exotic species, which also act as vectors for new parasites and diseases, and of native but cultured individuals with a reduced genetic diversity that may also pose a threat to wild populations. After shipping, aquaculture is the second largest sector causing the introduction of exotic species worldwide and likely to increase because of the spread of farms into more pristine areas. Biological pollution can take place as the accidental release of fish during operation, damage to cages (e.g., caused by harsh weather conditions), or attacks by wild predators. It may also occur during spawning when farmed fish are kept in open cages to a size in which they can become sexually mature (e.g., Atlantic cod (*Gadus morhua*)), allowing drifting of fertilized eggs into the surrounding environment (Carballeira *et al*., 2021).

Pollution Assessment

Environmental Monitoring Plans (EMPs) are usually based on the assessment of water and sediment changes. The following sections describe the current type of assessment, monitoring plans and methods, and how to improve and adapt it to different types of facilities.

Nutrient Pollution Assessment

Nutrient release may affect water quality (e.g., water turbidity, dissolved oxygen), increase trophic resources, and modify the geochemical properties of sediment. Nevertheless, most times the effect of a fish farm on the water column is negligible due to the high dilution and recycling of nutrients at sites where farms are established. For this reason, environmental impact assessments are mainly based on the study of sediment, but this is not possible in hard-bottom sites. To reach sustainable alternatives, effective assessment methods must be used without being sediment dependent. Traditional water monitoring measures physico-chemical parameters mainly related with organic contamination (dissolved oxygen, nitrogen forms, phosphorus, salinity, turbidity, pH, chlorophyll, temperature, sulfides, and redox potential). When a parameter represents a certain pollution threshold, the water sample is sent to a laboratory for further analysis. Every step is performed manually, which is time- and cost-consuming, and contamination episodes might be missed. The technology driven, sensor based methods may offer a solution to this problem.

Chemical Pollution Assessment

Chemical treatments used in aquaculture depend on several factors - disease, the location of the facility, system parameters, treatment type, and legislation. There are specific regulations concerning the use and quantities of specific substances in aquaculture but this highly differs between countries. These include mandatory risk evaluation and authorization processes before a particular substance can be used. There are also various modelling tools, based on the assessment of dilution and dispersion of both chemical treatments and particles (from medicated feed), that calculate chemical exposure and ecotoxicological risks close to cages. Regulations are being setup concerning allowed substances, routes of delivery, dosage by fish species and other limitations. Fish do not metabolize antibiotics efficiently; releasing a large part of the substance to the marine environment that should be posteriorly monitored or reused within polycultures (Burridge *et al*., 2010). Producers in the largest farming countries are required to report particular diseases and the chemicals prescribed to avoid their outbreaks and minimize chemical treatments, e.g., allowable number of salmon lice (*L. salmonis*) per fish in Atlantic salmon (S. salar) farming which is monitored regularly during the production process.

Biological Pollution Assessment

Fish from open net cages may escape and enter directly into the surrounding environment. The ability to assess the escape rate depends on factors determined by species behavior, including the time escaped fish are spending close to the aquaculture facilities after the escape and their mortality rates. These behaviors are important for calculating the efficiency of potential recapture methods Recapture is said to be mostly ineffective (around 50% of escaped fish) although required in many jurisdictions. According to that, a contingency plan consisting of notification of the escape to responsible authorities, recapture actions and a final report must be carried out. Farmed fish can be tagged and there by identified in case of escape using acoustic telemetry or mark and recapture techniques. Methods to detect escaped fish can also be based on genetic differences and external characteristics, as a consequence of high crop densities and handling (fin erosion, opercular deformities and body lesions). The location of the farm (to avoid harsh weather conditions) is important as a preventive measure for escapes.

Environmental Monitoring Plans

The effects of marine aquaculture on the surrounding environments (especially in open production systems) may be limited to a minimum. To establish these limits, monitoring data are needed at different levels of organization, so that, ecological changes can be detected and Ecological Quality Standards can be defined and included within an Environmental Impact Assessment (EIA). Monitoring techniques must be effective, scientifically rigorous, cost-effective, dynamic, and regionally/site adapted to facilitate their usage and avoid unwanted damage to the ecosystem. Research is still needed to improve the monitoring programs, in particular those related to eutrophication at different scales and the ecosystem approach at larger scales. Only few countries apply the ECC approach (e.g., Norway) and regulations. But the majority are aimed at favouring farmers' production (e.g., feed efficiency and absence of anoxic sediments) and regulate food standards (FAO, 2009; Weitzman and Filgueira, 2019).

Monitoring Methods

Unfortunately, EMPs do not usually consider ECC measures and there are issues associated with current monitoring methods regarding sampling, selection of indicator species, use of biotic indices and the absence of sediment (hard-bottom sites). Most of the time methods lack standardization and effectiveness at different aquaculture scenarios. The main monitoring methods are discussed here.

Sampling

Before and After Control Impact (BACI) is a common design proposed to evaluate anthropogenic perturbations on ecological variables. However, the BACI method depends on the preoperational study (which is only done once just before starting the activity) and requires choosing control sites arbitrarily and assumes the control and impact sites to be similar before the impact. When a contaminant disperses with distance from a point source, it is suggested that a gradient design will be more sensitive to change than BACI sampling designs. Gradient designs avoid the problem of arbitrarily selecting a control site, enable chemical, physical, and biological changes to be assessed as a function of distance, and results are easier to interpret and to use in public policy decisions.

Indicator Species and Biotic Indices

Geochemical changes of the sediment due to organic enrichment alter the composition and structure of the infauna, favouring the dominance of the tolerant-generalist versus the sensitive specialized species. The effects of the farms on the benthic communities are widely studied, especially on the communities of macro and meio invertebrates from the infauna, and occasionally on the benthic microbial communities. It is usual to determine the degradation of the sediment by using the formation and coverage of *Beggiatoa spp.*, a chemotrophic filamentous bacterium common in sulfur-rich environment. Benthic communities (e.g., bacterial mats, polychaetes, amphipods) are the most studied group as they are those that manifest the greatest changes when environmental conditions are altered. It is very common to use them as bioindicators of the state of the benthic ecosystem.

Stable Isotope Analysis

Deducing the fate of nutrients in an aquaculture or natural system can be done based on balance calculations of the nutrient content in plants or animals. However, there are shortcomings to this technique when trying to account for all nutrient transformation in the system. A more detailed view can be obtained through stable isotope analysis (SIA), a widely accepted tool to reconstruct diets and trophic relationships of organisms and their food. The analysis of stable isotopes is often applied in marine or estuarine sciences and can be used to examine fluxes of carbon and nitrogen from ecosystems and pollution from coastal aquaculture. Compared to the natural aquatic ecosystem, aquaculture derived nutrients are usually enriched in their δ15N and depleted in their δ13C values, allowing this source to be traced along gradients and into sinks . In case larger isotopic differences are needed, isotope labeling (the introduction of compounds high in the heavy isotope) can be applied to trace the fate of the labeled matter over time, through specific metabolic pathways or along trophic chains.

Site Selection

One of the main challenges for the sustainable development of aquaculture is the distribution of water, land, and other resources with alternative uses, such as fishing, agriculture, and tourism. Marine Spatial Planning must consider the zoning of aquaculture (to define suitable areas for fish farming or mixed activities) and identifying the most appropriate places for the specific location of farms (site selection). Environmental impacts of a single farm may not be significant when considered individually but may be relevant if other farms, fishing grounds, or activities are located in the same area. Environmentally sound selections of the site, away from habitats of ecological interest, together with adequate management, are the best tools to prevent or minimize the negative environmental effects of farming. Therefore, aquaculture operators must act as environmental managers to ensure a pollution-free environment in which to culture healthy organisms. Impacts on the benthos and water column may happen because of an improper site selection, administrative issues, and/or overproduction (Aguilar-Manjarrez *et al*., 2017).

Development of Sustainable Methods

Integrated Multi-Trophic Aquaculture (IMTA)

An important step towards sustainable aquaculture is to consider excess food and fecal matter not as a waste product, but as a resource that contains high amounts of nutrients and essential fatty acids that should be recycled and not discarded (Bischoff *et al*., 2009). Based on this idea the concept of IMTA was created, which applies a simplified food web structure to a farming system of fed-species, such as fish and shrimp, together with extractive organisms, such as molluscs and seaweed that take up particles and nutrients from the environment. Integrated aquaculture also produces higher yields than mono-species systems in addition to satisfying rising consumer demands for environmental standards. The practice of IMTA aims to perfect this principle by combining species at different trophic levels for a balanced-ecosystem approach. Reducing the load of nutrients and organic matter released by IMTA systems, preserves the quality of the receiving ecosystem, a secondary economic benefit is obtained and the social image of aquaculture is improved. Macroalgae are a popular component of IMTA setups and have a number of advantages over conventional mechanical or microbial filtration systems. Common nitrifications filters use up dissolved oxygen and require additional equipment and monitoring. Contrary to this, integrating algae into an aquaculture system counterbalances nutrients, CO2 levels, acidity, and increases dissolved oxygen while producing valuable biomass (Barrington *et al*., 2009).

Lagooning/Artificial Wetlands

Wastewater lagooning is a highly effective, low-cost solution (initial installation and maintenance) for purifying wastewater from land-based farms (Porrello *et al*., 2003). The treatment of wastewater consists of a series of physical, chemical, and biological processes to remove contaminants and separate clean or at least reusable water and solid waste, which can be used for a number of industrial or agricultural purposes. Such types of artificial wetlands are already widely used for the treatment of municipal waste and are especially effective at removing excess nitrogen and storing excess phosphorus in the soil. This type of phytotreatment has already been tested with wastewater from fish ponds as means of algal ponds and wetlands and has shown to be an efficient system by reducing nutrient contents and modifying physico-chemical parameters of water (Omitoyin *et al*., 2017). However, lagooning systems require large surface areas, thus, competing for land space with other sectors.

Sustainable Feed Management

Sourcing of aquaculture feed is one of the sustainability core challenges of marine finfish aquaculture. Intensified production and the cultivation of high value carnivorous fish largely depends upon the use of fish meal and fish oil as the main feed ingredients, making it a consumer of capture fisheries products, especially of nontargeted fisheries and small forage fish. This has caused environmental as well as economic concerns, with feed costs being a large part of total production expenses, and important progress has been made towards sustainability by improving feed efficiency, turning fish offal into useful silage or designing plant-based, polychaetebased, and insect-based protein feeds. The challenge has been to replace fish oil with other alternatives and ensure the high content of highly unsaturated fatty acids within the feed to maintain the nutritional quality of the fish for human consumption. While the use of land-based feed may reduce the pressure on fisheries, it can significantly increase the pressure on freshwater resources (water footprint), due to water consumption and pollution in crop production.

However, recently new approaches have been developed to reduce excess feed used and loss of food. In intensive fish farming where feeding is taking place by an automatic system, it is important to monitor the feeding activity of the fish and adjust the amount of feed to the feeding behavior. Such monitoring can be done by using, for example, an underwater camera technology or other similar methods that detect uneaten feed and stopping the feeding process (Carballeira *et al*., 2021).

Sustainable Use of Chemicals

There is an increasing tendency to develop methods with the aim of reducing extensive chemical substance use, and, therefore, minimizing environmental pollution. Such alternative methods can have other positive effects on production such as cost minimization for the producer and increased consumer acceptance.

Precision Fish Farming (PFF)

There is a recent sustainable framework of fish farming called Precision Fish Farming (PFF), which developed from the concept of Precision Livestock Farming (PLF) (Norton and Berckmans, 2018) to pisciculture. PLF and PFF use hardware (e.g., sensors), observers, and intelligent software to improve animal health and welfare while increasing productivity, yield and environmental sustainability (Føre *et al*., 2018).

References

FAO (2003) Fisheries Management. 2. The Ecosystem Approach to Fisheries. FAO Technical Guidelines for Responsible Fisheries. No. 4, Suppl. 2. FAO, Rome. URL: http://www.fao.org/docrep/005/Y4470E/Y4470E00.HTM

Garcia SM, Zerbi A, Aliaume C, Do Chi T, Lasserre G (2003) The ecosystem approach to fisheries. Issues, terminology, principles, institutional foundations, implementation and outlook. FAO Fisheries Technical Paper No. 443. FAO Rome. [Cited 24 January 2018.] Available from URL: http://www.fao.org/docrep/006/Y4773E/Y4773E00.HTM

Aguilar-Manjarrez, J., Soto, D. & Brummett, R. 2017. Aquaculture zoning, site selection and area management under the ecosystem approach to aquaculture. Full document. Report ACS113536. Rome, FAO, and World Bank Group, Washington, DC. 395 pp.

Miao W, Mohan CV, Ellis W, Brian D, eds (2013) Adoption of Aquaculture Assessment Tools for Improving the Planning and Management of Aquaculture in Asia and the Pacific. RAP Publication 2013/11. FAO Regional Office for Asia and the Pacific, Bangkok.

Soto D, Bianchi G, Aguilar-Manjarrez J (2012a) Implementing the ecosystem approach to fisheries and aquaculture: a case study in the Estero Real, Nicaragua. FAO Aquaculture Newsletter 49, pp. 10–11. FAO, Rome.

Soto D, White P, Dempster T, De Silva S, Flores A, Karakassis Y *et al*. (2012b) Addressing aquaculture-fisheries interactions through the implementation of the ecosystem approach to aquaculture (EAA). In: Subasinghe RP, Arthur JR, Bartley DM, De Silva SS, Halwart M, Hishamunda N, Mohan CV, Sorgeloos, P . (eds.) Farming the Waters for People and Food. Proceedings of the Global Conference on Aquaculture 2010, Phuket, Thailand. 22–25 September 2010. pp. 385–436. FAO, Rome and NACA, Bangkok.

Carballeira Braña CB, Cerbule K, Senff P and Stolz IK (2021) Towards Environmental Sustainability in Marine Finfish Aquaculture. Front. Mar. Sci. 8:666662. doi: 10.3389/fmars.2021.666662

Carver C.E. A and Mallet A. L.,1990. Estimating carrying capacity of a coastal inlet for mussel culture Aquaculture, 88: 39-53.

Duarte P Hawkins A Meneses R Fang J Zhu M 2003 Mathematical modelling to access the carrying capacity for multi-species culture within coastal waters. Ecol. Model., 168: 109-143.

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. Aq

V., and Hanke, G. (2016). Chemical contaminants entering the marine environment from sea-based sources: a review with a focus on European seas. Mar. Pollut. Bull. 112, 17–38.

Radford, C., and Slater, M. (2019). Soundscapes in aquaculture systems. Aquacult. Environ. Int. 11, 53–62.

Bischoff, A. A., Fink, P., and Waller, U. (2009). The fatty acid composition of *Nereis diversicolor* cultured in an integrated recirculated system: possible implications for aquaculture. Aquaculture 296, 271–276. doi: 10.1016/j.aquaculture.2009.09.002

FAO (2009). Environmental Impact Assessment and Monitoring in Aquaculture: Requirements, Practices, Effectiveness and Improvements No. 527. Rome: FAO Fisheries and Aquaculture Department.

Weitzman, J., and Filgueira, R. (2019). The Evolution and Application of Carrying Capacity in Aquaculture: Towards a Research Agenda. Hoboken, NJ: Wiley. doi: 10.1111/raq.12383.

Barrington, K., Chopin, T., and Robinson, S. (2009). "Integrated multi-trophic aquaculture (IMTA) in marine temperate waters", in Integrated Mariculture: A Global Review, ed. D. Soto (Rome: FAO) FAO Fisheries and Aquaculture Technical Paper. No. 529.

Porrello, S., Lenzi, M., Persia, E., Tomassetti, P., and Finoia, M. G. (2003). Reduction of aquaculture wastewater eutrophication by phytotreatment ponds system I. Dissolved and particulate nitrogen and phosphorus. Aquaculture 219, 515–529.

Omitoyin, B. O., Ajani, E. K., Okeleye, O. L., Akpoilih, B. U., and Ogunjobi, A. A. (2017). Biological treatments of fish farm effluent and its reuse in the culture of nile tilapia (Oreochromis niloticus). J. Aquac. Res. Dev. 8:1000469.

Norton, T., and Berckmans, D. (2018). Engineering advances in precision livestock farming. Biosyst. Eng. 173, 1–3. doi: 10.1016/j.biosystemseng.2018.09.008

Føre, M., Frank, K., Norton, T., Svendsen, E., Alfredsen, J. A., and Dempster, T., *et al*. (2018). Precision fish farming: a new framework to improve production in aquaculture. Biosyst. Eng. 173, 176–193.

****