



An ecosystem-based approach and management framework for the integrated evaluation of bivalve aquaculture impacts

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ABSTRACT: An ecosystem-based approach to bivalve aquaculture management is a strategy for the integration of aquaculture within the wider ecosystem, including human aspects, in such a way that it promotes sustainable development, equity, and resilience of ecosystems. Given the linkage between social and ecological systems, marine regulators require an ecosystem-based decision framework that structures and integrates the relationships between these systems and facilitates communication of aquaculture–environment interactions and policy-related developments and decisions. The Drivers-Pressures-State Change-Impact-Response (DPSIR) management framework incorporates the connectivity between human and ecological issues and would permit available performance indicators to be identified and organized in a manner that facilitates different regulatory needs. Suitable performance indicators and modeling approaches, which are used to assess DPSIR framework components, are reviewed with a focus on the key environmental issues associated with bivalve farming. Indicator selection criteria are provided to facilitate constraining the number of indicators within the management framework. It is recommended that an ecosystem-based approach for bivalve aquaculture be based on a tiered indicator monitoring system that is structured on the principle that increased environmental risk requires increased monitoring effort. More than 1 threshold for each indicator would permit implementation of predetermined impact prevention and mitigation measures prior to reaching an unacceptable ecological state. We provide an example of a tiered monitoring program that would communicate knowledge to decision-makers on ecosystem State Change and Impact components of the DPSIR framework.

KEY WORDS: Bivalve aquaculture management · Ecosystem-based approach · DPSIR framework · Indicators · Thresholds · Benthic effects · Pelagic effects · Social-ecological systems

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INTRODUCTION

Aquaculture is the fastest growing food-producing sector in the world and is expected to continue to grow and help compensate for the anticipated global shortage of supply from capture fisheries. While there is a clear need for the continued worldwide expansion of aquaculture to fill this gap, this development needs to be promoted and managed in a responsible manner that minimizes negative environmental impacts. To ensure that human activities are carried out in a sustainable manner, numerous international maritime policies have been implemented, including the European Union 'Water Framework' and 'Marine Strategy Directives,' the Canadian 'Oceans Act,' the US 'Ocean Action Plan,' and the Australian 'National Strategy for Ecological Sustainable Development.' These legislations and policies mandate that decision making and marine management should include as nested components: (1) a knowledge-based approach, (2) an ecosystem-based approach, and (3) an integrative management framework that includes economic, environmental, social, and equity considerations. The International Council for the Exploration of the Sea (ICES) Working Group on Marine Shellfish Culture was tasked with providing a recommended governance approach for the integrated evaluation of the impacts of bivalve aquaculture activities in the coastal zone. This paper summarizes our deliberations and recommendations.

The ecosystem-based management approach has been defined as 'a comprehensive integrated management of human activities based on the best available scientific knowledge about the ecosystem and its dynamics, in order to identify and take actions on influences that are critical to the health of ecosystems, thereby achieving sustainable uses of ecosystem goods and services and maintenance of ecosystem integrity' (Rice et al. 2005, p. 4). The Convention on Biological Diversity defined the ecosystem-based approach as a strategy for the integrated management of land, water, and living resources that promotes conservation and sustainable use in an equitable way (www.cbd.int/ecosystem/; see also Soto et al. 2008). Such an approach must strive to balance diverse societal objectives (e.g. GESAMP 2001, Nobre et al. 2009) by taking into account the knowledge and uncertainties of biotic, abiotic, and human components of ecosystems, including their interactions, flows, and processes (ecosystem functions) and services within ecologically and operationally meaningful boundaries. Three spatial scales/levels of an ecosystem-based approach to aquaculture manage-

ment include the farm, the water body and its watershed/aquaculture zone, and the global, market-trade scale.

Bivalve aquaculture–environment interactions within a given water body have often been examined by scientists using the concept of 'carrying capacity' (McKinsey et al. 2006, Gibbs 2007, Grant & Filgueira 2011). This approach has traditionally focused on predicting the maximum sustainable yield of the bivalve culture (i.e. production carrying capacity) and therefore primarily reflects an economic management perspective. The more recent ecocentric focus on the sustainability of an area for aquaculture development has led to some attempts to assess carrying capacity by considering potential changes in ecosystem structure and function and ecological variability over different spatial and temporal scales. This 'ecological carrying capacity' approach is defined as the level of culture that can be supported without leading to significant changes to ecological processes, species, populations, or communities in the growing environment (Gibbs 2007). Although the modeling of ecological carrying capacity is still in its infancy, it is more directly linked to the objectives of ecosystem-based management than production carrying capacity modeling. However, to be compatible with the philosophy of the ecosystem-based approach (i.e. a balance of ecological and human needs), an integration of all of the hierarchical categories of carrying capacity (physical, production, ecological, and social; McKinsey et al. 2006) is required.

Ecosystem-based aquaculture management requires many specific components and tools in addition to models and tools for assessing the carrying capacity of an area. These include methodologies, technologies, and policies for hazard identification, risk assessment and management, environmental quality assessment, environmental monitoring programs and associated sampling designs, impact assessment, impact mitigation, and decision support and communication among stakeholders. In addition, an overall decision framework is required that will permit the ecosystem-based management approach to be integrated with economic and social considerations and communicated to diverse stakeholders. Consequently, much of our science-based advice and recommendations focused on the following topics:

(1) An operational management framework for decision-makers that facilitates ecological sustainability by considering the capacity to incorporate an ecosystem perspective, societal values, and the economic viability of industry.

(2) Effective performance-based approaches and indicators for characterizing ecosystem status changes and impacts from a highly diverse bivalve aquaculture industry.

(3) Identifying the potential consequences to coastal marine ecosystems from aquaculture related to specific changes in environmental quality and impacts and identifying related thresholds of potential public concern.

While scientists have an important place in designing a framework for the management of bivalve aquaculture, it is not their responsibility to make final decisions about regulatory policies. A recurring bottleneck to the establishment of an operational framework is the need to define 'unacceptable' impacts. While natural science has an important role in advising managers and policy-makers on the ecological consequences related to available management options, the setting of impact limits needs to incorporate societal values and needs and economic realities. Although socio-economic issues were initially considered outside the scope of our activities, deliberations on many components of a bivalve aquaculture management approach required discussion of the costs of implementing our advice to a highly diverse industry and what impact level may constitute a 'potential' public concern. To help define what level of impacts are acceptable, social sciences can help in clarifying the values and expectations of different groups and contribute to the economic evaluation of environmental services known to be provided by bivalve aquaculture (e.g. provision of habitat, water clarification, shoreline stabilization; Cohen et al. 2011). International environmental conservation and protection legislations pertaining to the utilization of coastal areas generally reflect societal values, and an analysis of pertinent policy statements can provide useful insights towards identifying regulatory triggers/thresholds.

This paper is structured to present and rationalize our recommendations by starting with brief overviews of potential ecological interactions with bivalve aquaculture and the attributes of available integrative management frameworks. The potential management roles of ecological modeling and indicator-based approaches for describing ecosystem status and aquaculture sustainability are then discussed. More specific aspects of a recommended bivalve aquaculture management framework are then addressed, including the identification of performance indicators related to specific environmental, and to some extent socio-economic, effects from bivalve culture operations. This leads to a discussion on thresholds of eco-

logical and potential public concern, and some key elements of an ecological monitoring program for the highly diverse bivalve aquaculture industry.

ECOSYSTEM INTERACTIONS WITH BIVALVE AQUACULTURE

A fundamental understanding of the influence of this expanding industry on coastal ecosystems, as well as interactions with other anthropogenic stressors, is the foundation for developing strategies for sustainable aquaculture and integrated coastal zone management. The culture of bivalve mollusks and their associated rearing structures has the potential to impact the environment in numerous positive and negative ways (e.g. Dame 1996, Souchu et al. 2001, Christensen et al. 2003, Newell 2004, Cranford et al. 2006, 2007, Dumbauld et al. 2009, Forrest et al. 2009, McKinsey et al. 2011, Shumway 2011). Environmental concerns regarding bivalve culture are related primarily to how the culture interacts with, and potentially controls, fundamental ecosystem processes. Where negative effects have been reported, they are generally linked to the consumption of suspended particles and particularly the phytoplankton, effects on coastal nutrient dynamics from ammonia excretion and organic waste recycling, and effects resulting from the translocation of suspended matter from pelagic to benthic compartments (Fig. 1). Positive effects on biodiversity can result from the introduction of additional biotic and abiotic structure to the system, the increase or alteration of prey availability (cultured and fouling species), the capacity of bivalves to clarify water and extract excess phytoplankton that can have harmful effects in eutrophic areas, and/or from enhanced seabed organic enrichment (Callier et al. 2008, D'Amours et al. 2008). Given the intensity of bivalve culture in some regions and the complex nature of positive and negative aquaculture–environment interactions, an ecosystem-based perspective is mandatory for assessing the net environmental impact (Cranford et al. 2006).

Research on bivalve culture impacts have primarily focused on the production and sedimentation of organic biodeposits (feces and pseudofeces) that may impact benthic biogeochemistry and the structure and composition of benthic and pelagic communities. The effects of bivalve farms on benthic environments are relatively well known (see reviews by Cranford et al. 2006, 2008, McKinsey et al. 2011, Shumway 2011). Bivalves have an exceptional capacity to filter large volumes of water to extract phytoplankton and

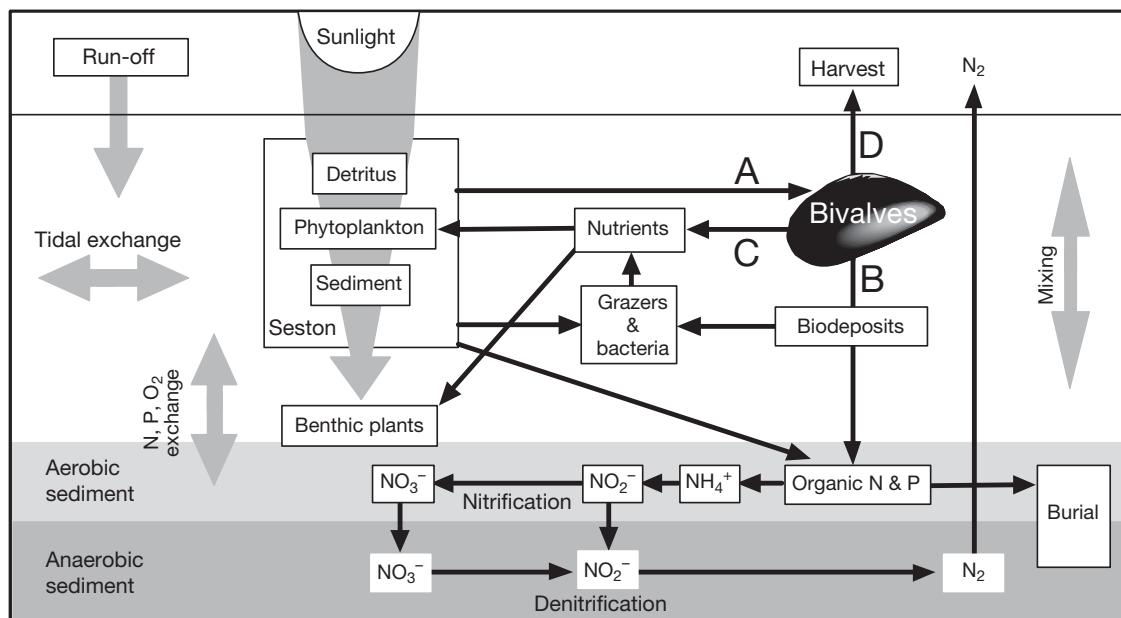


Fig. 1. Conceptual diagram of bivalve aquaculture interactions in coastal ecosystems related to: (A) the removal of suspended particulate matter (seston) during filter feeding; (B) the biodeposition of undigested organic matter in feces and pseudofeces; (C) the excretion of ammonia nitrogen; and (D) the removal of materials (nutrients) in the bivalve harvest (Cranford et al. 2006)

other suspended particulate matter and can, under some conditions, control suspended particle dynamics at the coastal ecosystem scale (e.g. Cloern 1982, Officer et al. 1982, Dame 1996, Grant et al. 2008). Bivalve filter-feeding naturally results in some local reduction (depletion) of their food supply (suspended particulate matter). If the bivalve culture is consuming the seston faster than it can be replaced by tidal flushing and phytoplankton growth, then the culture will become food limited and farm yield will become less than maximal for that site. If the spatial scale of phytoplankton depletion expands outward from the farm(s) to include a significant fraction of the coastal inlet, then this effect on the base of the marine food web generates ecological costs to other components of the ecosystem that may result in significant ecological and socio-economic consequences. Potential effects on nutrient cycling, fluxes, and retention may also be expressed at the coastal ecosystem scale (e.g. Newell 2004, Nizzoli et al. 2006, Cranford 2007) such that the boundary of the aquaculture system to be managed must include both benthic and pelagic components and extend beyond the footprint of the farm.

The spatial extent and magnitude of ecological interactions with bivalve culture are always site-specific, with vulnerability depending on factors controlling food consumption and waste production (e.g. intensity of culture and food supply) and waste dis-

persion. Waste dispersion rate is controlled by physical factors (e.g. circulation, bathymetry, and coastal morphology) and largely determines the capacity of the local environment to prevent excessive food depletion, altered nutrient dynamics, and benthic organic enrichment.

INTEGRATIVE MANAGEMENT

Decisions underlying the design of an ecosystem approach for bivalve culture should be grounded in holistic methods and a management framework that considers the complexity and interactions between ecological, social, and economic systems (e.g. GESAMP 2007). Considering the diverse nature of bivalve culture techniques and the variable risk of bivalve aquaculture impacts on marine environments, flexibility within the ecosystem approach is necessary. However, regardless of the specific details of any given aquaculture activity, it is suggested that the ecosystem approach address the following minimum requirements:

- (1) Incorporate the best available scientific knowledge of cultured ecosystems, their processes and dynamics and their resulting potential for degradation.
- (2) Address potential phytoplankton interactions with bivalve culture, including effects on suspended

particle dynamics (concentration, composition, size spectra, transport) and pelagic trophic structure.

(3) Address potential impacts on seabed geophysical properties, geochemical processes, and the structure and ecological role of benthic flora and fauna (i.e. address potential changes to benthic habitat, biodiversity, and ecosystem function).

(4) Address potential interactions between different farms within the water body and the role of fouling communities on culture structures in order to assess the net cumulative environmental effect.

(5) Consider cost versus benefit of implementing different management options.

(6) Consider the potential ecological services provided by the culture activities, including potential mitigation of eutrophication and increased biodiversity.

(7) Integrate ecosystem management with other relevant sectors within a management framework that also considers social issues and economic impacts with respect to setting standards for sustainability (i.e. finding an equitable balance that permits industry to remain economically viable).

(8) The approach should be inclusive and continuous with diverse stakeholder participation, transparency, and communication.

Additional general principles of the ecosystem approach are provided by the Convention on Biological Diversity (www.cbd.int/doc/publications/eatext-en.pdf).

A management framework that incorporates the ecosystem approach must provide the means to structure sets of measurable indicators of the ecological, social, and economic factors that are relevant to bivalve aquaculture. This needs to be accomplished in a way that can address many aspects of a problem in a manner that facilitates their interpretation and aids in the understanding of how different issues are interrelated. Indicator systems are seen as central tools for ecosystem-based fisheries management, helping to steer fisheries towards sustainability by providing timely and useful information to decision-makers (Rice 2003). An indicator is observed or estimated data describing a particular characteristic of the system. Performance indicators are descriptive indicators associated with target values (thresholds or limits). Environmental performance indicators and related standards are often presented within already established frameworks that are generally built in a given societal context (Olsen 2003). Several conceptual management frameworks are reviewed in the following sections to address their potential for adaptation to sustainable aquaculture development.

Market-driven frameworks for industry self-regulation

A global activity related to the development of an ecosystem-based approach for aquaculture is the creation of performance-based standards that are linked to certification schemes designed to manage the key social and environmental issues associated with bivalve farming. It is believed that the implementation of certification schemes helps the industry sector to work toward more sustainable aquaculture, including reduced impacts. The underlining principle of certification is that a body fully independent from the production sector should be responsible for certification while the costs are borne by industry. Certification schemes relevant in some way to aquaculture have been reviewed by Funge-Smith et al. (2007) and the World Wildlife Fund (WWF 2007). Organizations active in this field include the Food and Agriculture Organization of the United Nations (FAO), WWF, Friends of the Sea, Naturland, Global Gap, and the Aquaculture Certification Council. The Marine Stewardship Council decided to cease working on aquaculture certification, but continues to be a key participant because it does certify bivalve aquaculture activities where juveniles are collected from wild stocks. The WWF Bivalve Aquaculture Dialogue has recently completed certification criteria and standards for bivalve aquaculture based on performance-based standards. These standards have been given to a new organization (Aquaculture Stewardship Council) responsible for certifying farms that are in compliance. The FAO has produced guidelines (FAO 2007) intended for the production of improved finfish and bivalve aquaculture certification schemes that comply with the main principles of the ecosystem approach. The FAO specified certification standards named 'Hazards, Analysis, and Critical Control Point' (HACCP) that are the core of several national legislations across Europe and the United States.

A shortcoming in addressing bivalve aquaculture sustainability through a market-driven certification approach is that consumer awareness and values related to environmental impacts vary towards both extremes across and within geographic markets. Local perceptions on the acceptability of aquaculture impacts may not match more broadly established environmental quality criteria enforced by responsible regulatory agencies. Another potential limitation of certification schemes is that they currently do not fully encompass the complexities of interactions between bivalve culture and the ecosystem and therefore do not meet criteria outlined in legislations

that mandate an ecosystem-based approach. For example, the HACCP standards do not consider social and environmental impacts and are not strictly pertinent to the implementation of an ecosystem-based management framework as discussed herein. Third-party certification schemes do not, and are not meant to, displace an effective governance approach for ensuring the sustainable use of coastal ecosystems. A key benefit to the underlying work that has gone into the establishment of certification schemes is the compilation of information on societal expectations on the ecological performance of aquaculture operations. For example, the WWF bivalve certification standards were developed based on wide stakeholder participation in multiple dialogue workshops and through open calls for comments on the draft performance-based standards. This participatory multi-stakeholder approach, which included science input at all stages, was an iterative process designed to both reveal and balance opposing views.

Governance-driven regulatory frameworks

The development and management of aquaculture falls within the scope of numerous legislations in many countries, including many that promote an ecosystem-based approach to aquaculture management. Over the past decades, scientists and policy-makers have become increasingly aware of the complex and manifold linkages between ecological and human systems, which generated a strong research effort into social-ecological systems analysis. Social-ecological systems are understood to be complex adaptive systems where social and biophysical agents are interacting at multiple temporal and spatial scales (Janssen & Ostrom 2006). This has stimulated researchers across multiple disciplines to look for new ways of understanding and responding to changes and drivers in both systems and their interactions (Zurek & Henrichs 2007). Integrated coastal zone management can be viewed as being part of this social-ecological system paradigm, in which special emphasis is placed on the complexities of coastal settings and the various links and drivers in ecological and human systems. Using a topic-focused approach to social-ecological systems strengthens this type of analysis framework.

Several different types of regulatory frameworks have evolved within the indicator approach to sustainable development and have been applied at the international, national, regional, and/or local levels. One management framework that identifies environ-

mental problems, their causes, and solutions, and which recognizes important linkages between ecological and socio-economic systems is known as Drivers-Pressures-State Change-Impact-Response (DPSIR). The DPSIR framework organizes multiple systems of indicators and is the latest framework developed by the Organisation for Economic Co-operation and Development (OECD 2000). An early version of the DPSIR framework, called the Pressure-State-Response (PSR) framework, states that human influences and activities exert pressures on the environment, which can cause changes in the state (e.g. environmental quality) of the system. Regulators then respond with environmental and economic policies and programs intended to prevent, reduce, or mitigate pressures and/or environmental impact. The second variation added a category of impact indicators, transforming it into a Pressure-State-Impact-Response (PSIR) framework. The latest version, which has become widely employed, is the DPSIR framework (Fig. 2A). In this framework, an additional category of indicators describing human influences and activities that positively or negatively impact the environment (driving forces) was added. Each category within DPSIR is described by a set of indicators, and the framework assumes that all indicators are inter-related. A full description is given in publications by the OECD.

DPSIR is a well developed, science-based framework that reveals aspects of environmental problems, their causes, and remedies (Fig. 2B). It allows coverage of a large spectrum of particular situations concerning the environment, including aquaculture, and has been applied globally, including use by the European Environmental Agency to manage the EU 'Water Framework Directive.' DPSIR is often recommended for coastal zone management to identify the key factors and processes at different stages. Aquaculture management based on this framework would provide an analysis of aquaculture ecosystem interactions in many different types of systems and would recognize critical linkages between ecological and socioeconomic systems. DPSIR has been criticized for lacking some statistical rigor and for simplifying complex ecological linkages. However, this approach helps to focus attention on the development of regulatory-relevant research on each component of the framework and on understanding the linkages. For example, numerical models may be developed that incorporate knowledge of system interactions to explore the level of complexity needed to describe system interactions within acceptable confidence limits (also see below). We therefore recommend the

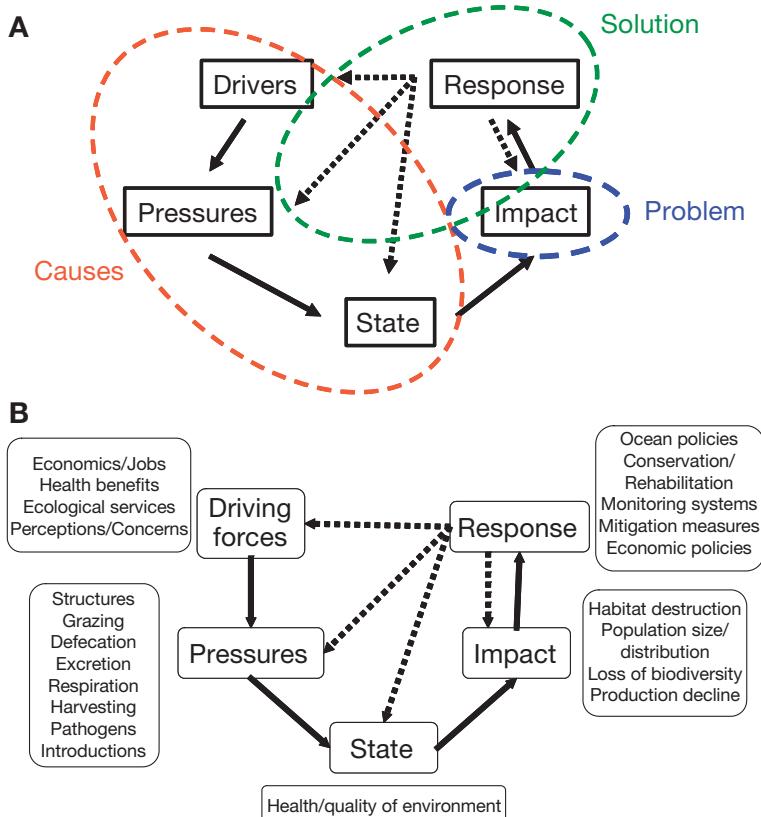


Fig. 2. The Drivers-Pressures-State Change-Impact-Response (DPSIR) framework for integrating aquaculture, socio-economic, and ecological interactions. (A) Components and functions of the DPSIR framework. (B) Example factors and processes relevant to each component of a DPSIR framework applied towards the management of shellfish aquaculture

DPSIR framework as a basis for the assessment, evaluation, and operational management of bivalve aquaculture activities in the coastal zone.

ROLE OF MODELING IN BIVALVE AQUACULTURE MANAGEMENT

Aquaculture impact assessment generally takes place at the scale of individual farms. Extrapolating these effects up to any larger scale is considerably more complex and includes considering impacts of multiple farms and ecological interactions that are a function of bathymetry, farm proximity, and circulation. Modeling permits an understanding of how all farms interact over a relevant scale and provides a means to demonstrate our state-of-knowledge of aquaculture–environment interactions, particularly when model output is tested and confirmed. Models are essentially a set of mathematical equations that represent particular features of the behavior of bivalve culture systems and coastal ecosystems. Bivalve

aquaculture models have focused on the concept of carrying capacity (see above), and types of models vary greatly in complexity (Grant & Filgueira 2011). A relatively undemanding approach is to estimate and compare those critical aquaculture processes that may cause ecological effects against oceanographic processes that may prevent the impact from being expressed. For example, a food depletion index is in widespread use that scales the estimated time it takes for a given bivalve population to filter a known water body with the flushing (residence) time of that water body (e.g. Smaal & Prins 1993). This index is included within the 2010 WWF Bivalve Aquaculture Dialogue Certification Standards as a practical (e.g. simplest available method) means of assessing the cumulative effects of all bivalve farms on the capacity of a water body to support the regional intensity of culture. This single-box ‘depletion index’ carrying capacity approach is utilized with the knowledge that it does not provide information on spatial variability in water flushing and food depletion within a water body.

The ecosystem management domain (spatial and temporal boundary scales) and the need for information on variability at different scales within this domain are important considerations in the design of a management framework. The possible need to predict system status and impact variability at different scales may be explored by increasing the level of model complexity. Dynamic models are the most complex modeling approach and include 2D box models to 3D finite element models coupled with hydrodynamic models. An advantage of dynamics models is that they are able to simulate events, such as changes in an ecological effect over a year. For example, the zone of potential benthic community effects from bivalve biodeposits may be predicted using particle tracking models, such as DEPOMOD (Cromej et al. 2002, Weise et al. 2009), that predict organic matter flux to the seabed. The ECASA project has identified a virtual toolbox containing, among other ‘tools,’ a list of models such as ShellSIM, EcoWin, FARM, Longlines, DEB, DEPOMOD, and DDP that can be used by environmental managers to guide actions that minimize the environmental impact from bivalve aquaculture operations (www.ecasatoolbox.org.uk). These models are intended to help maintain environmental quality and ensure the sustainability of sites and water bodies for aquaculture.

Ecosystem models that include bivalve aquaculture scenarios can provide a holistic perspective required within an ecosystem-based management framework. Models can provide information on potentially critical ecological effects that may be hard to measure but are suspected to cascade through all trophic levels and alter ecosystem structure and function. Suspended mussel culture husbandry practices (raft and long-line) can permit the holding of a relatively high biomass per unit area and direct access to food supplies in the water column. Consequently, modeling activities have focused, to a large extent, on this form of culture. Grant et al. (2008) used a fully-coupled biological–physical–chemical model to demonstrate that suspended mussel culture may, under certain conditions, exert a controlling effect on the concentration and distribution of phytoplankton and other suspended particles. Similarly, Cranford et al. (2007) utilized a nitrogen budget and box model to demonstrate how a suspended mussel culture activity controlled nutrient dynamics at the coastal ecosystem scale.

Ecosystem models have been used as an integral part of the DPSIR framework to test scenarios of aquaculture pressures on water quality (Nobre et al. 2005) and ecosystem productivity (Marinov et al. 2007). Models are useful to address several components of the DPSIR framework, and perhaps most practically can help to identify performance indicators of ecosystem status and aquaculture impacts and their associated operational management thresholds. Modeling is also among the few tools capable of assessing aquaculture sustainability while also considering the cumulative effects of additional human activities (e.g. eutrophication, climate change) and resident and invasive suspension-feeding species (Cranford et al. 2007, Ferreira et al. 2008). In summary, it is possible to utilize models to:

- (1) assess the potential impact of bivalves on the ecosystem state;
- (2) define indicators based on predicted ecological fluxes that summarize ecosystem functions (e.g. nutrient throughput, recycling, and time scales; Prins et al. 1998);
- (3) define ecological thresholds linked to the density-dependant effects of bivalve aquaculture;
- (4) compare ecosystems using the selected set of prognostic indicators;
- (5) simulate bivalve culture interactions before and/or after the commencement of husbandry, or as a result of a proposed increase in bivalve standing stock;
- (6) optimize the spatial layout of individual farms in a manner that best promotes ecosystem sustainability;

(7) assess interactions between aquaculture and other human activities in the coastal zone; and

(8) assess ecosystem functioning in the long term and determine whether aquaculture ecosystem interactions interfere with other services provided by the ecosystem.

A number of countries have well-developed policies and procedures in place that utilize modeling tools for planning and monitoring as well as regulation of impacts from nutrient enhancement and organic waste deposition and dispersion (reviewed by Henderson et al. 2001). However, the direct use of models for the regulation and monitoring of aquaculture has been restricted to fish aquaculture in a relatively small number of countries (Henderson et al. 2001). With respect to bivalves, the models that are in current use to predict production carrying capacity, food depletion, and ecological interactions have only been indirectly utilized through inclusion of scientists in national and regional advisory activities. Practicality issues related to technical complexity in model implementation and interpretation and the need for site-specific parameterization and forcing data have generally limited the routine use of dynamic ecosystem modeling for bivalve aquaculture governance. However, applications of these models have contributed substantially to the state-of-knowledge that will be instrumental when developing an operational ecosystem-based management approach. Model applications have greatly advanced our understanding of interactions between many components of the DPSIR framework.

INDICATORS FOR BIVALVE CULTURE— GENERAL CONSIDERATIONS

Ecological indicators can help to describe ecosystem status, ecosystem health, environmental performance, and functional sustainability performance (Rice 2003, Gibbs 2007). Indicator selection depends on the activity addressed and the spatial or economic scale considered (Spangenberg 2002, Rochet & Trenkel 2003). Indicators therefore need to be identified and developed specifically for bivalve aquaculture as a way to assess and quantify changes, progress, and improvements towards sustainable industry development. Ideally, the indicator framework for integrative bivalve cultivation assessment should transparently encompass the full spectrum of components of the DPSIR framework such that hypotheses about the links between all components and management outcomes on the local to national

level may be tested. For instance, if management responses to observed aquaculture impacts were effective, it may result in improved public perceptions and further aquaculture growth. Failing to incorporate such an auditing component within the framework may promote ineffective policies and prolong the transition to sustainability (Rudd 2004).

No one universal set of indicators is applicable in all cases (Segnestam 2002), and no single indicator can account for the whole system; economic, social, and ecological dimensions need to be integrated. However, a small set of well-chosen and highly relevant indicators tends to be the favorite choice of most users, including the stakeholders for aquaculture. The selection criterion can be applied when there is a need to constrain the number of indicators. Gilbert & Feenstra (1994) identified 4 desired features of sustainability indicators: (1) they must be representative of the system chosen and must have a scientific basis; (2) they must be quantifiable; (3) a part of the cause-effect chain should be clearly represented; and (4) they should offer implications for policy. These features intersect with the principles of the DPSIR framework. Notwithstanding the need to adapt all components of the DPSIR framework towards aquaculture application, our focus here is on summarizing and recommending ecological indicators specific to bivalve culture that are related to the 'state' and 'impact' components. Although they specifically address ecosystem components and processes from the farm footprint to far-field effects (coastal ecosystem scale), these indicators are also of high societal relevance.

The interactions and feedbacks between the economic, social, and environmental components of DPSIR play out over time and space. These are referred to as 'cross-scale' or 'multi-scale' processes. Indicators for bivalve cultivation commonly focus on processes at the geographic scale that influence bivalve aquaculture development, which can include local to national decision-making requirements. The application of certain indicators and their respective decision thresholds for bivalve cultivation may need to differ between countries and between regions due to these scale issues and to differences in demands, traditions, cultures, or management systems. To take account of this array of complexity in the context of decision-making, a number of research-supported approaches to indicator and monitoring systems have been developed and advanced to better understand the current and future interaction of various driving forces (Carpenter & Brock 2006). Recently, indicator systems have also been used to address multi-scale processes or to link social-ecological systems devel-

oped at various geographical scales in order to better understand the interaction of processes, objectives, and institutional arrangements across scales (Carpenter et al. 2008). Such an indicator set would capture environmental status and impacts while also tracking the state and trends in social satisfaction and economic revenues at different geographic scales.

Indicators need to be relevant to the scale of the issue they address and must address political realities if they are to gain acceptance and to achieve practical application. Processes at different geographic scales commonly unfold over different time and space scales. For example, a system's social-ecological dynamics will unfold more slowly as the spatial scale expands from local to regional to national, and more quickly as aquaculture grows over time from concept to carrying capacity. Indicator approaches may be used to address multi-scale processes and to link repercussions at various geographical scales to understand more fully the social-ecological dynamics of bivalve cultivation. Indicators that provide information that is not scale-dependent will obviously have wide application. However, not all indicators are relevant to multiple geographical and temporal scales but are needed to provide specialized knowledge on a particular focal issue. It is important that local to regional aquaculture managers understand the context in which a selected indicator works.

Several recent papers have proposed a list of performance criteria for selecting ecological indicators (Kurtz et al. 2001, Rice et al. 2005) and specifically for fishery indicators (Garcia & Staples 2000) and bivalve aquaculture (Cranford et al. 2006, Gibbs 2007). The following criteria were used as a guide by the authors for assessing the potential application of various indicators for use in the management of bivalve culture:

(1) Relevance: The meaning of an indicator represents the first essential phase in the process of indicator selection. The indicator selection must be closely linked to potential negative environmental effects that should be addressed.

(2) Effectiveness: This determines the ability of managers to respond to variations in aquaculture forces and pressures. While some indicators may respond to dramatic changes in the system, a suitable indicator displays high sensitivity to particular and, perhaps, subtle stress, thereby serving as an 'early-warning' indicator of reduced system integrity.

(3) Precision and accuracy: An indicator is considered to be robust if the natural variability of the indicator in the environment is low and if the inherent variability in results from available methodologies

and technologies for collecting indicator measurements is low. If variability is too high, the sampling design (monitoring program) needed to detect an unacceptable effect size may be extensive and impractical. This is related to the next indicator criteria.

(4) Feasibility: Theoretical indicator constructions are useless on an operational basis if adequate data are not available, either due to the fact that the data are technically very difficult to obtain or if collecting the necessary information is too expensive. Thus, indicators must be practical and realistic, and their cost of collection and development therefore needs to be considered. This may lead to trade-offs between the information content of various indicators and the cost of collection. Such pragmatic considerations are paramount for identifying monitoring requirements for an industry that includes many small-scale operations. Low-cost measures are obviously preferable if they are able to contribute to management objectives as effectively as more costly approaches.

(5) Sensitivity: A good indicator must be sensitive, with a known substantial response to disturbances over time.

(6) Clarity: The ease of data interpretation is an important consideration for managers and non-scientists involved in the decision-making process. Indicators act as information communication tools and changes in an indicator should easily be understood by stakeholders.

(7) Responsiveness: For management to be effective, the time frame between data collection and the decision-making process needs to be as short as possible. Responsive and adaptive management approaches strive to implement mitigation measures quickly so that the impact does not continue to increase. Near real-time indicators therefore have a distinct advantage in such programs, whereas indicators that require considerable work to process samples and interpret data are less desirable. Time lags greater than approximately 6 mo for managers to receive final results for an indicator can be considered detrimental to management.

In the following sections, we assess different indicator sets and their feasibility according to the performance criteria outlined above. The indicators described provide information on ecological system status and, more specifically, the impact of bivalve aquaculture in the coastal zone and were compiled from a number of sources. Several European research contracts were aimed at producing indicators related to the interaction of aquaculture (and bivalve culture) with the marine environment. Examples of attempts to compile indicators related with the sustainable

development of marine aquaculture include the MARAQUA (Read et al. 2000), Consensus (www.euraquaculture.info/), and ECASA (www.ecasa.org.uk) research programs. A Canadian national science advisory review was conducted to identify and recommend an indicator-based approach and environmental monitoring framework for managing bivalve aquaculture impacts on marine habitat (DFO 2006, Chamberlain et al. 2006, Cranford et al. 2006). In addition, Gibbs (2007) identified sustainability performance indicators based on bivalve aquaculture interactions in the water column. Potential indicators are presented according to a scheme that includes benthic, pelagic, and socio-economic aspects of marine coastal ecosystems. Additional indicators on site morphology, hydrography, and husbandry practices (e.g. standing stock) are needed to increase the reliability of impact assessments (Borja et al. 2009) and to aid in the interpretation of ecosystem 'State' and 'Impact' indicators.

Benthic habitat indicators

The primary source of bivalve aquaculture effects on seabed habitat (i.e. the properties of sediments required by a particular organism or population) is the deposition of excess organic matter in bivalve feces and pseudofeces and other fall-off from suspended culture structures (bivalve and fouling organisms and their biodeposits). Potential sediment habitat state indicators are summarized in Table 1. Some indicators are intended to address the flux of organic matter to the sediment, some characterize the change in the sediment properties, while others describe the state of biogeochemical processes associated with the ecological recycling of deposited organic matter.

There is a close relationship between observed changes in all of the indicators presented in Table 1 across the full range of the sediment organic enrichment gradient (Hargrave et al. 2008, Hargrave 2010). Those studies showed that changes in benthic habitat state can be classified based on 'sulfide regimes.' The concentration of total dissolved (free) sulfide (S^{2-}) in surficial (0–2 cm) sediments is a sensitive, cost-effective, and proven indicator of the organic enrichment effects of bivalve aquaculture on benthic habitat and communities (e.g. Cranford et al. 2006, 2009, Hargrave et al. 2008, Hargrave 2010). Aquaculture management regimes in Canada, as well as the global certification scheme developed by the WWF, focus on total 'free' S^{2-} measurements using electro-

Table 1. Potential indicators of the state of benthic habitat relevant to assessing the effects of increased organic matter deposition by bivalve aquaculture

Indicator	Description
Sedimentation rate	Sediment trap measurements of the amount (flux of sediment and organic matter) and composition (total organic, carbon, nitrogen, etc.) of particulate matter falling from bivalve culture
Biodeposition rate	Quantitative collections of the biodeposits produced by bivalves
Sediment texture	Sediment grain size and indices of the increase in the fine fraction (e.g. percent sand-silt-clay)
Organic enrichment	Total organic matter and/or organic carbon concentration in surficial sediments
N and P enrichment	Total nitrogen, organic nitrogen, and phosphorus concentrations in surficial sediments
Sediment quality	Percentage organic carbon, C:N ratio, and refractive proportion (R_p) index (Kristensen 2000)
Redox potential	The oxidation-reduction potential (Eh) in surficial sediment is related to the energy-yielding reactions of bacterial cells (e.g. low Eh values are linked with the anaerobic degradation of biodeposited organic matter). A related indicator is the depth of the redox potential discontinuity, which represents the depth where Eh potentials change rapidly from positive to negative values
Total free sulfides	Sediment pore water sulfide measurements made using various electrode and spectrophotometric methods. Total S^{2-} in pore water creates toxic biological effects for benthic fauna by interference with aerobic respiration
Water content	The percentage of surficial sediment dry weight is related to grain size, which can be altered by addition of bivalve biodeposits
Dissolved oxygen	Sediment oxygen concentration measurements. Chemical and biological oxygen uptake increases when organic matter sedimentation increases. Hypoxic and anoxic sediment conditions impact benthic fauna
Benthic/pelagic flux	Measurements of the uptake/release of sulfate, oxygen, and nutrients at the sediment/water interface
Pigments	Chlorophyll and phaeopigment concentrations measured in surface sediment. A fraction of the phytoplankton ingested by bivalves is not digested and can accumulate beneath the facilities
Visual observations	Photography and video imaging of the seabed surface and sediment vertical profiles can reveal changes in sediment color and texture linked to enhanced sediment and organic biodeposition. The presence of sulfur-reducing bacterial mats also indicates reducing conditions at the sediment water interface
Benthic Enrichment Index (BEI)	Derived from measurements of surface sediment organic and water content and Eh (Hargrave 1994)
Benthic Habitat Quality Index (BHQ)	Calculated based on vertical profile imaging of sedimentary structures from undisturbed sediment (Nilsson & Rosenberg 2000). Vertical profile images of sediment beneath aquaculture operations show changes in sediment color and organism distributions indicative of organic enrichment effects

chemical methods. The collection of data on other geochemical organic enrichment indicators is also encouraged to provide additional habitat protection (confirmation of total dissolved S^{2-} results) and to permit the calculation of composite habitat indices (e.g. Benthic Enrichment Index; Hargrave 1994). The sediment profile imaging technique offers some practical benefits, including high sensitivity (e.g. Grant 2010), but after the redox discontinuity layer reaches the sediment surface, visual indicator cues can appear constant while geochemical conditions

and community impacts continue to degrade with increasing organic enrichment. Sediment profile imaging has been shown to underestimate seabed organic enrichment effects (Mulsow et al. 2006) and be less effective than direct physical and biochemical quantitative measurements of sediment cores (Keegan et al. 2001). Advances in sediment dissolved oxygen measurement based on optical methods appear to have overcome past methodological problems that have limited the practical application of this indicator. Benthic biological effects from organic enrich-

ment are largely linked to a combination of the toxic effects of H₂S and oxygen deficiency, both of which can be measured cheaply, accurately, and rapidly. We therefore suggest a focus on these 2 indicators for characterizing the DPSIR benthic 'State' parameter.

Benthic community impact indicators

The impacts on benthic communities of increased organic matter input to sediments are well known (Pearson & Rosenberg 1978, Hargrave et al. 2008). Hypoxic to anoxic and sulfidic conditions are created in surface sediments if oxygen consumption rates exceed the supply, which is limited by physical and biological factors that control sediment–water exchange. The macrobenthic community can be expected to exhibit the following responses to an increase in organic loading:

(1) a decrease in species richness and an increase in the total number of individuals as a result of the high densities of a few opportunistic species;

(2) a general reduction in most species biomass, although there may be an increase in total biomass corresponding to the presence of a few opportunistic species;

(3) a decrease in body size of the average species or individual;

(4) a shallowing of that portion of the sediment column occupied by infauna; and

(5) a shift in the relative dominance of trophic groups.

The choice of community indicators is related to the specific needs of regulators. Using the DPSIR framework as an example, benthic community indica-

tors have often been used as a general indicator of changes in ecosystem quality or health (State), but are conceptually suited to monitoring the impact that results from changes in benthic habitat. The most commonly employed benthic community indicators are summarized in Table 2.

Many criteria have been used to select indices of benthic community effects, and the range of indicators employed has led to difficulties comparing results across studies. The number and abundance of benthic species at a site can be examined in a wide variety of ways to provide an index of biodiversity. H' , j , and c (Table 2) are routinely used to help describe the diversity of macrofaunal communities. However, values obtained with community diversity and biomass indicators should be interpreted cautiously and with a full understanding of what these indicator results actually reveal about community changes. Consequently, community impact programs typically require the use of several indicators to interpret changes in the fauna and the probable cause of biodiversity change in assessing farm impacts (e.g. Borja et al. 2009). Multivariate analysis is a powerful tool for identifying patterns in the large amount of data on species and abundance produced from a site survey. It can also incorporate other data on environmental conditions at the site to provide an understanding of the ecology and environmental degradation of the area under study.

Information on opportunistic and scavenger species (i.e. indicator species), which tend to increase in number under some bivalve farms, is relatively easily interpreted compared to results based on diversity indices. Deposit-feeding polychaete taxa and large carnivorous nematode worms have been observed to

Table 2. Indicators of the intensity of benthic community impacts from organic matter deposition by bivalve aquaculture

Indicator group	Indicators and methods
Biodiversity metrics	Including the Shannon-Wiener diversity index (H'), Pielou's evenness index (j), Simpson's dominance index (c), and Margalef's species richness (d). Generally used for macrofauna, but can be applied to assess meiofauna diversity
Indicator species	Highly enriched marine sediments are generally dominated by a few opportunistic macrofaunal species, such as <i>Capitella</i> sp., that are tolerant of high organic enrichment and low oxygen conditions. The AZTI Marine Biotic Index is calculated based on the relative proportion of 5 species groups (previously classed as being sensitive to opportunistic)
Trophic indices	In highly organically enriched areas, benthic communities are dominated by deposit feeders and scavengers, at the expense of filter feeders. The Infaunal Trophic Index provides a categorization of overall species abundance within different trophic groups in soft bottom communities
Benthic similarity	Comparison of community structure with multivariate statistics
Size structure	Most species that are tolerant to organic enrichment belong to families such as the Spi-onidae, and have a small size. Differential sieving of sediment for macrofauna studies, on 1 mm and 0.5 mm sieves, allows quantification of the relative contribution of the smaller individuals to the whole community

dominate in organically enriched sites where Mollusca and Echinodermata are completely excluded. The reduction/absence of suspension feeders and increase in deposit feeders are also good indicators of organic matter perturbation. The loss of bio-irrigating species (deep-burrowing infauna) is ecologically important because this could further enhance anoxic conditions caused by organic enrichment. The AZTI Marine Biotic Index (AMBI; Muxika et al. 2005) incorporates these indicator species concepts and provides a pollution classification for a given site that represents benthic community 'health.' The application of AMBI to a given site requires the availability or development of an impact tolerance list and produces a number in a range from 0 to 7. While this indicator is not specific to an aquaculture impact, it reacts predictably to the presence of organic enrichment (Muxika et al. 2005, Callier et al. 2008). Studies on the effects of bivalve farming confirm the predicted transition in AMBI benthic status with increasing organic biodeposition under mussel lines in Canada (Weise et al. 2009) and also suggest a decrease in benthic impacts with distance from farms in Europe (Borja et al. 2009).

The Infaunal Trophic Index (ITI) takes a functional approach to impact assessment and is based on the feeding types of the fauna encountered at the survey sites. Benthic similarity analysis can determine differences between sites even at low organic enrichment and provides a reliable indication of impacts between control and farm sites, and along transects leading

away from farms. ITI and AMBI are proven approaches for indicating impacts and are highly recommended for monitoring benthic community impacts. All approaches that require taxonomic identification are expensive to conduct, and analysis/interpretation times can be extensive. It has been suggested that the strong correlations that exist between observations of the degree of benthic community impacts and surficial sediment geochemical changes permit geochemical indicators to serve as low-cost proxies of community effects (Hargrave et al. 2008).

Pelagic indicators

Farm structures may affect water flow both within farms (Strohmeier et al. 2005) and over the scale of coastal ecosystems (Plew 2011) by causing drag. These structures also generate turbulence, which can mix the water column or distort stratification (Stevens & Petersen 2011). Bivalve aquaculture may also alter a number of chemical and biological properties in the water column. Owing to the movement of the water, these effects can be transported far-field with the potential for a measurable impact at the coastal ecosystem scale (Cranford et al. 2006, 2008, Gibbs 2007). Several pelagic indicators have been proposed to monitor potential changes in environmental quality (State) and lower trophic levels (Impact) related to bivalve culture (Table 3).

Table 3. Indicators of the intensity of pelagic alterations and impacts from the activities of cultured bivalves

Indicator	Description and methods
Nutrient concentration	There is ample evidence to link bivalve aquaculture as a major control on coastal nutrient dynamics
Dissolved oxygen concentration	The biological oxygen demand within the water body is increased by the respiration of the culture, the fouling community, and the remineralization of organic wastes
Bacterial abundance	A greater abundance of naturally occurring bacteria may occur due to availability of organic matter in bivalve biodeposits and the consumption of some fraction of the natural microplanktonic grazer community by the cultured bivalves
Phytoplankton biomass, seston concentration, and particle depletion	The natural high variability in phytoplankton and seston biomass (chlorophyll <i>a</i> and/or suspended particulate matter concentration) requires extensive, high-resolution synoptic surveys to detect the magnitude and scale of food depletion at the farm to bay scale
Depletion index	This bay-scale indicator is not directly measured, but is computed using site-appropriate data on the bivalve culture, their feeding rates, and the flushing characteristics of the water body (e.g. Prins et al. 1998)
Phytoplankton size	The picoplankton contribution index (proportion of total phytoplankton) indicates any large-scale changes in the size structure of the microbial plankton community that can result from removal of larger phytoplankton by culture bivalves. Analysis is based on size-fractionated chlorophyll <i>a</i> analysis (Cranford et al. 2006)
Trophic heterogeneity	Spatial and temporal scales of variability in the availability of suspended food sources may be generated by bivalve-mediated food depletion. This heterogeneity may be detected through trophic studies using stable isotopes of C and N in bivalve tissues (Lefebvre et al. 2009)

Although there is ample evidence to show that bivalve aquaculture can be a major control on coastal nutrient dynamics and phytoplankton biomass, the use of nutrient and chlorophyll *a* (chl *a*) concentrations as impact indicators is challenging. This is attributed to the high natural short- to long-term variability in these indicators in coastal systems. In many cases, a single chemical measurement or abundance does not prove to be an effective indicator, whereas a statistic computed from data in an exposed site will better reflect the phenomenon. For example, changes in different nutrient ratios may be more informative than concentration measurements and may act as suitable proxies for detecting impacts on nutrient dynamics. Similarly, a few isolated measurements of chl *a* are not relevant for indicating the magnitude and extent of food reduction resulting from bivalve feeding. However, synoptic surveys with towed sensor vehicles have provided intensive information on aquaculture-related changes in suspended particle distributions (phytoplankton biomass and total suspended particle concentrations) around suspended bivalve farms (Cranford et al. 2006, Gibbs 2007). These results provide details on the extent (horizontal and vertical) and magnitude of phytoplankton depletion by the bivalve culture, which contribute to direct and model-based assessments of bivalve carrying capacity (e.g. Grant et al. 2008). Concomitant with any significant phytoplankton depletion will be a similar reduction in the zooplankton via direct consumption and possibly from reduced food availability. Although high-resolution environmental sensor surveys are rapid and the data are valued, the high capital and technical costs related to using associated indicators presently limits their application for routine monitoring.

Isotopic signatures in consumers of pelagic food resources can reflect changes in the quality and quantity of suspended organic matter, predator/prey interactions, and biogeochemical cycles. To our knowledge, no studies have measured trophic state responses to bivalve aquaculture, but sessile organisms such as bivalves are promising indicator species for this type of analysis (Lefebvre et al. 2009). A potential consequence of large-scale phytoplankton depletion by large bivalve populations is an increase in the proportion of small phytoplankton. Bivalves do not effectively retain picophytoplankton during feeding, and this selective feeding behavior may result in bay-scale shifts in size distribution at the base of the food web, particularly in poorly flushed aquaculture embayments (Cranford et al. 2006, 2008). This shift

towards smaller phytoplankton is also aided by bivalves consuming predators that naturally control picophytoplankton abundance. Significant changes in phytoplankton size structure and abundance have the potential to cause cascading effects through all trophic levels owing to changes in predator/prey interactions. Consequently, indicators of phytoplankton size (e.g. relative concentrations of chl *a* retained on 0.2 and 3 μm pore size filters) are perceived as being highly beneficial for use in ecosystem-based monitoring programs in extensively farmed bivalve aquaculture inlets. This recommendation is also linked to the relatively low cost of performing size-fractionated chl *a* analysis and the fact that site-specific measurements of plankton community alterations generally reflect conditions over large spatial and temporal scales of impact.

Bivalve performance indicators

Potential bivalve performance indicators include growth rate, condition index, and meat yield per husbandry effort. These measures do not reveal information on specific changes in the structure and functioning of ecosystems, but provide an indication as to whether bivalve aquaculture is affecting the system to a greater extent than can be absorbed by natural processes (i.e. environmental status indicators). In this respect, particle depletion and bivalve performance measurements are highly complementary. The former indicator provides information on changes in pelagic food supplies that likely control the latter (see Rosland et al. 2011). Monitoring bivalve condition is a way to assess how the physiological status of the bivalve is affected by food limitation. Bivalve performance indicators may be measured using cultured and separately caged animals. The strength of caging bivalves for this purpose is that standardization of performance measures is simplified. However, in the typical case of large spatial (horizontal and vertical) and temporal variability in natural environmental conditions that control bivalve performance in the farmed region (e.g. temperature, currents, food abundance and nutritional quality, and salinity), caged bivalve indicator results are highly site-specific. This leads to difficulties in extrapolating monitoring data to the scale of aquaculture operations.

Long-term trends in total bivalve production of a water body have been used to assess the effects of increasing stocking density on bay-wide aquaculture production, presumably due to depletion of natural

food supplies (Héral et al. 1989, Cranford et al. 2010). Time-series measurements of aquaculture production are therefore useful indicators of impacts on particulate food supplies, including the phytoplankton. These data are generally collected by aquaculture operations for purposes other than use as a general indicator of bay-scale ecological status. A major problem with all types of bivalve performance indicators is that setting of a maximum bivalve performance threshold for a specific site requires production carrying capacity to be exceeded (point where a reduction in the performance indicator values is observed). This is not a desirable trait for any sustainability indicator. A more important application of farm stocking and production data is that they are required in the interpretation of farm impacts observed using other indicators.

SOCIO-ECONOMIC CONSIDERATIONS AND INDICATORS

An integrated ecosystem-based bivalve aquaculture management approach requires assessing socio-economic dynamics (current status and impacts) as well as the environmental dimensions of sustainability. Indicators of socio-economic issues not only need to measure the financial operating performance of commercial bivalve farms but also the wider impacts of aquaculture on society at large. Indeed, it is precisely these impacts which, within the DPSIR framework, can be expected to invoke a governance response intended to alter the way in which aquaculture is regulated and managed. Among the many different indicators proposed in the literature, some are of direct relevance for bivalve culture operations. They are related to 4 different overarching social dimensions, namely (1) the social acceptability of the bivalve culture, (2) the supply availability to the market, (3) the livelihood security for the local communities, and (4) the economic efficiency of bivalve culture operations.

Bivalve culture may cause visual intrusion, which may impact tourism, or it may compete for space with other coastal activities in a spatially constrained environment. These can be evaluated by means of observations and regular interviews with local stakeholders and government bodies. The social acceptability of the bivalve culture operations may be evaluated by means of regular enquiries, using statistical treatments of the public attitude towards aquaculture (Whitmarsh & Wattage 2006) and/or assessment of emerging and existing conflicts. However, emotional

ownership of the sea/coastal area by the local residents/stakeholders and the social values that drive these ownerships are difficult to capture. 'Contracting costs' of getting a group of people to agree on an issue (not necessarily in money) are difficult to assess given that bivalve aquaculture is developed in diverse coastal settings and may be contested and negotiated by individuals and communities according to local social practices, economic conditions, and environmental perceptions.

Indicators of cultured bivalve availability to the market (supply) correspond, to some extent, with consumption statistics that are usually computed at national levels. Indicators of livelihood security for the local communities, such as the tax revenues from leasing plots, correspond to the well-being of the bivalve producer on the local level. Indicators that address this issue pertain to income per capita and employment rate. The importance of aquaculture in supporting local livelihoods is most directly measured by per capita income in this sector. A proxy measure may be derived based on the ratio of gross value added to employment. Total employment is a measure of the scale or 'importance' of the aquaculture industry in absolute terms. This is an indicator of the number of people who are dependent on aquaculture directly (and indirectly) for their livelihood. It has a political as well as an economic significance.

Indeed, one of the most important groups of indicators relates to the direct economic efficiency of a particular bivalve aquaculture operation. These can be gauged from productivity ratios, protection costs, and profits. Productivity is a measure of output per unit of input. For instance, trends in labor productivity are an important indicator of technical progress in aquaculture, and productivity differences between farms may indicate which farms are most vulnerable to falling prices and profits. Protection costs may be incurred in dealing with the environmental impacts of aquaculture. These likely consist of compliance costs incurred by bivalve farms arising from the obligation of farms to undertake impact assessments and regulation, surveillance, and enforcement costs by the respective institutions. Environmental protection costs are the counterpart of environmental damage costs. Thus, an inverse relationship between these can be expected. Profitability is a basic indicator of financial viability. In the absence of published data, the profitability of a bivalve operation can be addressed and calculated from its component elements (i.e. input costs, pricing of products, etc.).

OPERATIONAL THRESHOLDS OF POTENTIAL CONCERN

Operational thresholds define the targets that need to be addressed by managers and regulators in any aquaculture monitoring program. 'Threshold' is a general term of value that can be determined by administrative and advisory scientific processes. For example, if a strict policy was mandated, a threshold may be 'no change in benthic habitat from organic enrichment.' That is a threshold derived from policy implementation of a sense of what is socially acceptable. The operational expression might be 'no more than 1500 µM of total free sulfide.' The threshold in this case is set by a policy statement. In contrast, if the desire is to prevent mortality of a specific benthic organism, one might set a threshold defined by scientific knowledge of the organisms' response to a predicted environmental change. There are other less well-defined thresholds which describe the point at which ecosystems show a sudden regime shift from one state to another (e.g. benthic assimilative capacity). In identifying a threshold, it is important to be clear on whether the threshold is determined by policy decisions or by changes in ecosystems.

In the case of large areas of bivalve cultivation, it is difficult to set scientific thresholds as there is considerable spatial and temporal variability in the natural distribution of water and sediment quality parameters. The use of thresholds is often based on mean values or another measure of central tendency. However, the ecosystem's response to a disturbance may be an increase in variability and it may be possible to observe no change in the mean values of the indices even though the variability may increase (e.g. Warwick & Clarke 1993). This is important because it is often the occasional extreme in environmental variability that shifts ecological status. Consequently, it is difficult to set a threshold, and sometimes the criterion is simply a 'no net loss' or 'no change.' To set an adequate threshold, scientists, managers, and all stakeholders must together identify the value of acceptable change from reference conditions. To address these difficulties, ecosystem managers increasingly use a monitoring endpoint, known as thresholds of potential concern (TPC), to decide when management intervention is needed (Biggs & Rogers 2003). TPCs are a set of operational goals along a continuum of change in selected environmental indicators (Gillson & Duffin 2007). TPCs are being continually adjusted in response to the emergence of new ecological information or changing management goals. They provide a conceptual tool that enables ecosys-

tem managers to apply variability concepts in their management plans, by distinguishing normal 'background' variability from an important change or degradation (Gillson & Duffin 2007).

PERFORMANCE-BASED MANAGEMENT APPROACH FOR BIVALVE AQUACULTURE

Evaluation of impacts specific to bivalve aquaculture presents a particular challenge owing to the wide range of culture species, husbandry practices, environmental settings, and variable spatial scale. Bivalve aquaculture farms may range from less than 0.5 ha to operations in some regions that include a large fraction of total coastal embayment volume. Given the highly diverse nature of the bivalve aquaculture industry, it is not sufficient to simply provide a toolbox of potential indicators of environmental status specific to bivalve aquaculture, it is equally important to make recommendations, based on sound science, as to which tools are most appropriate under different conditions.

Aquaculture monitoring has generally focused on the benthic marine habitat in the immediate vicinity of a farm. This stems from the fact that the seabed habitat and species composition reflect the synergistic effects of past and present activities as well as natural processes that assimilate or disperse particulate wastes. There is also a relatively high level of understanding of benthic organic enrichment effects and the interconnectedness between the various indicators. Fortunately, this knowledge has already resulted in identification of scientifically defensible indicator/threshold classification schemes. Examples include the total 'free' sulfides classification (Hargrave et al. 2008) and the AMBI index. Effective measures are also available for mitigating benthic organic enrichment impacts, and prescribed responses to environmental degradation could be linked to operational thresholds defined within a responsive ecosystem-based management framework.

It is not sufficient to rely completely on local benthic geochemical and community parameters, as they do not necessarily encompass effects at the ecosystem level. Some combination of modeling and incorporation of additional indicators that target potential pelagic effects and higher trophic levels are needed over relatively large (inlet-scale) areas to adequately assess bivalve aquaculture effects. Furthermore, these should be accompanied by socio-economic indicators. The inability to adequately define quantitative operational thresholds for many highly rele-

vant indicators of ecosystem status (particularly those describing the structure and dynamics of the water column), owing to present gaps in our knowledge of ecosystems, should not preclude their potential use. Surveillance sampling programs based on selected water column parameters are recommended under conditions where environmental impact assessments and ongoing monitoring data indicate a relatively high risk of bay-scale impacts. Of particular concern are potential impacts on suspended particle concentrations and the resulting alterations in pelagic microflora and fauna communities and cascading effects through the pelagic food web. Surveillance monitoring of a suite of ecosystem traits that are thought to affect productivity, community structure, and habitat (i.e. contextual indicators; Gavaris et al. 2005), is highly warranted when and where significant particle depletion by bivalve aquaculture is predicted. Seston depletion modeling capabilities have rapidly progressed in recent years and include some relatively simple quantitative assessment approaches and decision support systems. Surveillance of pelagic indicators would complement benthic operational monitoring and would support the basic monitoring principle of delineating cause–effect relationships.

Bivalve aquaculture management needs to incorporate a high degree of flexibility owing to the high diversity of this industry. It is therefore recommended that environmental assessments be based on a tiered indicator monitoring approach that is structured on the principle that increased environmental risk requires an increase in monitoring effort. This principle is employed in the Norwegian and Canadian management of finfish aquaculture impact on the benthic environment (Hansen et al. 2001, Stigebrandt 2011). Various levels of monitoring could be triggered based on:

- (1) the nature of the operation (e.g. species, bottom versus suspended culture, proximity to other farms, and stocking density per area or volume);
- (2) the environmental risk predicted during aquaculture site assessments (e.g. ecological risk assessments and model-based predictions);
- (3) the ongoing measurement of environmental indicators towards verification of operational thresholds; and
- (4) other environmental sensitivity indices (e.g. presence of valued ecosystem components and sensitivity designations).

In addition, instead of partitioning the range of variation of each indicator into 2 classes (acceptable versus unacceptable), a few more threshold classes may be more pertinent as these can be linked to

management responses/mitigations that allow actions to be taken that prevent more critical thresholds being exceeded in the future. A tiered responsive management framework, based on sediment geochemical classification, is currently employed in parts of eastern Canada to manage benthic effects from aquaculture and has been adapted to some extent in the 2010 WWF Bivalve Aquaculture Dialogue standards (WWF 2010). Progressively more rigorous monitoring and regulatory responses are automatically implemented in response to degrading site classification.

Under the recommended responsive management framework, decision-makers would have the ability to increase or decrease the level of monitoring required for any site during subsequent sampling cycles, based, at least in part, on the review of all monitoring program results. Prior to implementing any monitoring program, it is important that baseline data on environmental status be collected so that decisions on the appropriate level of monitoring can be made.

TIERED MONITORING APPROACH

For bivalve aquaculture farms that have been assessed as having a relatively low risk, only a minimal level of monitoring appears to be warranted. This monitoring level is intended to be a rapid screening method for periodic evaluations of bivalve aquaculture impacts at a given site. Low cost, rapid screening indicators that may be appropriate for this level of site assessment include the collection of benthic images (still photographs and/or video) and simple model estimations (depletion index approach) of the potential for bivalves on this site to contribute to large-scale phytoplankton depletion within the water body (Table 2). The primary operational threshold that could be addressed in this level of monitoring is the appearance of *Beggiatoa* mats (bacteria that oxidize H₂S as an energy source) on the seabed, that are indicative of a relatively high degree of organic enrichment and a hypoxic to anoxic sediment classification. As with all types of monitoring, the choice of reference sites for comparison with farm data would include consideration of general bathymetric, hydrographic, and seabed type conditions in both areas.

A second monitoring tier is recommended to provide more frequent information on environmental status and impacts at sites where there are indications (predictions) or previous measurements of

organically enriched seabed conditions known to be deleterious to marine organisms. Possible indicator recommendations for this secondary monitoring tier would include a quantitative assessment of surface sediment (e.g. upper 2 cm) geochemical conditions (redox potential, total 'free' sulfides, organic content, and water content). Sampling would be best conducted annually in late summer/early fall when the biological oxygen demand of surface sediments is greatest. Discrete water sampling could target bay-scale changes in the size structure of the phytoplankton (picophytoplankton proportion). An annual bivalve inventory report for the farm would aid in interpreting indicator results, as it would for all monitoring tiers.

The most intensive monitoring tier is recommended for assessing sites that are predicted to present a relatively high environmental risk and/or the results of previous monitoring at the site show degrading habitat status. In addition to conducting all components of the above programs, the annual collection of data could be expanded to include benthic community analysis (AMBI, ITI, etc.). Benthic sampling effort should also be increased to give greater spatial delineation of the impacted area. As with the other monitoring tiers, it is recommended that regulators have the capacity to alter the level of monitoring required for any site during subsequent sampling cycles.

The recommended bivalve aquaculture management approach attempts to provide sufficient flexibility to be adapted to a diverse array of bivalve husbandry methods, cultured species, and farming intensities. The tiered indicator toolbox and multiple decision threshold approach for assessing environmental changes and degradation (DPSIR State changes and Impacts) is intended to permit regulators the capacity to adapt the approach depending on site-specific differences in environmental risks, degree of impact, and regional social values on sustainability issues. It also provides a means of implementing set impact mitigation measures at an early stage of observed environmental degradation. Economic considerations have also been addressed to some extent by describing environmental monitoring tiers that progress from the use of low-cost, semi-quantitative indicators, to more intensive monitoring and surveillance programs that can be selected based on the level of environmental risk. Inherent within recommending a management approach is adherence to the basic principle that monitoring and management programs be continually adaptive to changes in our state of knowledge concerning poten-

tial environmental impacts, indicators, and related methodological approaches.

The basic purpose of the DPSIR framework is to ensure that any significant adverse effects of bivalve aquaculture pressures on environmental quality and related societal benefits (State change and Impacts) will trigger an appropriate response to ensure that the economic and societal benefits of aquaculture can be delivered in a sustainable manner. It is critical to maintain broad stakeholder communication at all steps in the development and utilization of this framework. Societal perceptions of aquaculture impacts and sustainability, and regulatory competence often represent a critical negative driver for aquaculture. Closing the DPSIR loop between regulatory responses and aquaculture drivers (Fig. 1) is critical for the future expansion of this industry. This linkage can best be maintained through the establishment of a transparent and well-communicated management framework that includes stakeholder participation at all stages and which promotes a broad awareness of the consequences and effectiveness of regulatory decisions.

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