Carrying capacity tools for use in the implementation of an ecosystems approach to aquaculture

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Abstract

The development of carrying capacity indicators and models is progressing rapidly. A framework for defining four different types of carrying capacities has been developed, and a review of available shellfish and cage finfish models has been completed indicating new examples of potential decision-making tools for the spatial planning and the ecosystem-based management of aquaculture. The ability to estimate different types of carrying capacities is a valuable tool for decision-makers and the public when assessing the impact of development and expansion of aquaculture operations, and can be of good use to help develop more sophisticated spatial plans and multiple uses of aquatic space that include aquaculture. Development of more refined-and inclusive-carrying capacity frameworks and models will help organize the many available indicators and metrics, plus allow improved tracking of communications about, and sectoral progress towards, an ecosystems approach to aquaculture.

Introduction

Aquaculture is growing rapidly in inland and coastal regions throughout the world, most notably in Asia (People's Republic of China, the Kingdom of Thailand, the Socialist Republic of the Socialist Republic of Viet Nam, the People's Republic of Bangladesh, the Republic of India) and Latin America (the Federative Republic of Brazil, the Republic of Chile) (Costa-Pierce, 2010; FAO, 2009). Rapid growth has fuelled concerns over the ecological and social impacts of aquaculture in crowded inland and coastal areas rife with user conflicts where "new" uses such as aquaculture compete for space and resources with traditional users of land, water, and coasts. FAO has estimated an increased growth of aquaculture to 2030 of at least 50 million metric tons, raising further concerns over resource use in aquaculture (Costa-Pierce *et al.* 2012).

It is now widely recognized that further aquaculture developments need to be planned and designed in a more responsible manner that minimize as much as possible negative social and environmental impacts. The European Union Water Framework, Marine Strategy Directives, the Canadian Oceans Act, and the US National Policy for the Stewardship of the Ocean, Coasts, and Great Lakes all call for spatial planning for human activities such as aquaculture to be carried out in a more sustainable fashion, including the essential components of: (i) knowledge-based approaches for decision-making, and (ii) ecosystem-based approaches for integrated management.

In 2006 the Fisheries and Aquaculture Department of the Food and Agriculture Organization (FAO) of the United Nations recognized the need to develop an ecosystem-based management approach to aquaculture similar to the Code of Conduct for Responsible Fisheries. FAO (Soto *et al.*, 2008) suggested that an ecological approach to aquaculture (EAA) would have three main objectives: human well-being, ecological well-being, and the ability to achieve both via more effective governance within a hierarchical framework that was scalable at the farm, regional, and global levels. In 2008, FAO defined an EAA as a ***strategy for the integration of aquaculture within the wider ecosystem such that it promotes sustainable development, equity, and resilience of interlinked social-ecological systems***. Three principals were adopted, and key issues developed at the different scales of society; with principle #1 being a key driver, that ***aquaculture should be developed in the context of ecosystem functions and services (including biodiversity) with no degradation of these beyond their resilience capacity*** (Soto *et al.*, 2008). Defining, developing, and adapting existing methods to estimate resilience capacity, or the limits to “acceptable environmental change” are essential tasks to moving forward with an EAA.

Determinations of “acceptable change” have both natural and social science components. Many terms has been used to estimate these, including “environmental carrying capacity”, “environmental capacity”, “limits to ecosystem function”, “ecosystem health”, “ecosystem integrity”, “fully functioning ecosystems”, etc., all of which are subject to an intimate knowledge of not only natural ecosystem science, but also social-cultural and political factors (Hambrey and Senior, 2007). Environmental impact assessments bracket only some of these issues.

Concepts of carrying capacity

A goal of aquaculture management is to have tools available that can predict and measure the capacity of an area to support a cultured species. Carrying capacity is an important concept for ecosystem-based management which helps define the upper limits of aquaculture production and ecological limits, and the social acceptability of aquaculture without causing “unacceptable change” to both natural ecosystem and social functions and structures. Kaiser and Beadman (2002) defined carrying capacity as the potential maximum production a species or population can maintain in relation to available resources. Assessment of carrying capacity is one of the most important tools for technical assessment of not only the environmental sustainability of aquaculture since it is not limited to farm or population sizes issues but also can be applied to ecosystem, watershed, and global scales.

Inglis, Hayden and Ross (2002) and McKindsey *et al.* (2006) defined four different types of carrying capacities (physical, production, ecological and social), and found that, with few exceptions, carrying capacity work has focused on determinations of production carrying capacity, which is the maximum sustainable yield of cultured organisms that can be produced within an area. Although these accepted definitions were originally described for bivalve aquaculture, they have also been applied to finfish cage culture (Gaĉek and Legović, 2010).

Physical carrying capacity assumes the entire waterbody is leased for aquaculture, being little more than the total area suitable for aquaculture. Inglis, Hayden and Ross (2002) and McKindsey *et al.* (2006) note that the notion of physical carrying capacity does not inform about at what density cultured organisms are stocked, or their production biomass. Physical carrying capacity is useful to quantify potential area available for aquaculture in the ecosystem, but it offers little information towards determinations of aquaculture's limits at the waterbody or watershed level in the EAA.

Production carrying capacity estimates maximum aquaculture production and is typically considered at the farm scale. However, production biomass calculated at production carrying capacity could be restricted to smaller areas within a water basin so that the total production biomass of the water basin does exceed that of the ecological carrying capacity.

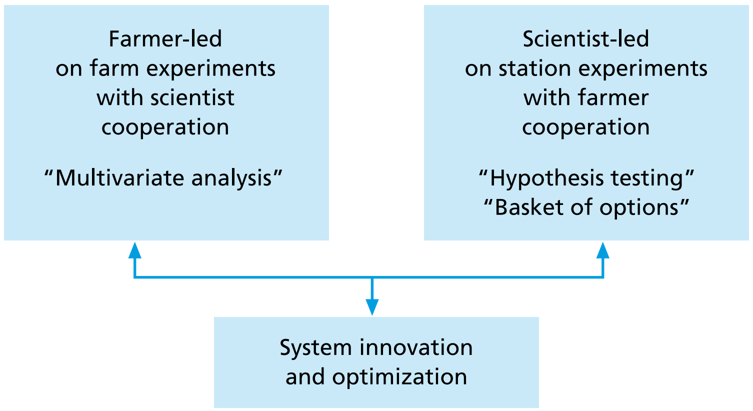
Ecological carrying capacity is defined as the magnitude of aquaculture production that can be supported without leading to significant changes to ecological processes, species, populations, or communities in the environment. Gibbs (2007) discussed a number of issues pertaining to the definition and calculation of ecological carrying capacity and highlighted the fact that shellfish aquaculture can have an impact on the system by being both consumers (of phytoplankton) and producers (by recycling nutrients and detritus) with the concomitant ecosystem impacts of both. In determining ecological carrying capacity he has urged caution when attributing cause of change (and partitioning impacts) between shellfish farm activities and other activities in the ecosystem.

When modelling is combined with stakeholder input, the resulting ecological carrying capacity calculations are exceptionally powerful in the management arena (Byron *et al.*, 2011c). Science is much more likely to be accepted if there are agreed upon, cooperative, aquaculture research frameworks that combine efforts of scientists and farmers (Figure 1), and are well integrated into outreach and extension services so that model results are adopted into management, and stakeholders have had direct input into and obtain an intimate knowledge of the science (Costa-Pierce, 2002). Efforts to improve methodologies for determining social carrying capacity may be well served to consider approaches that integrate rigorous science into participatory extension processes that include and measure the quality of participation and stakeholder inputs (Dalton, 2005, 2006).

Social carrying capacity has been defined as the amount of aquaculture that can be developed without adverse social impacts. Byron *et al.* (2011c) has stated that the ultimate goal of determinations of social carrying capacity is to quantify the value of stakeholder involvement in a science-based effort to determine the proper limits to aquaculture in their local waters. Ecological degradation or adverse changes to ecosystems due to aquaculture may inhibit social uses. The point at which alternative social uses become prohibitive due to level, density, or placement of aquaculture farms is the social carrying capacity of aquaculture (Byron *et al.*, 2011c). Social carrying capacity was been

FIGURE 1

Aquaculture cooperative research and extension for innovation



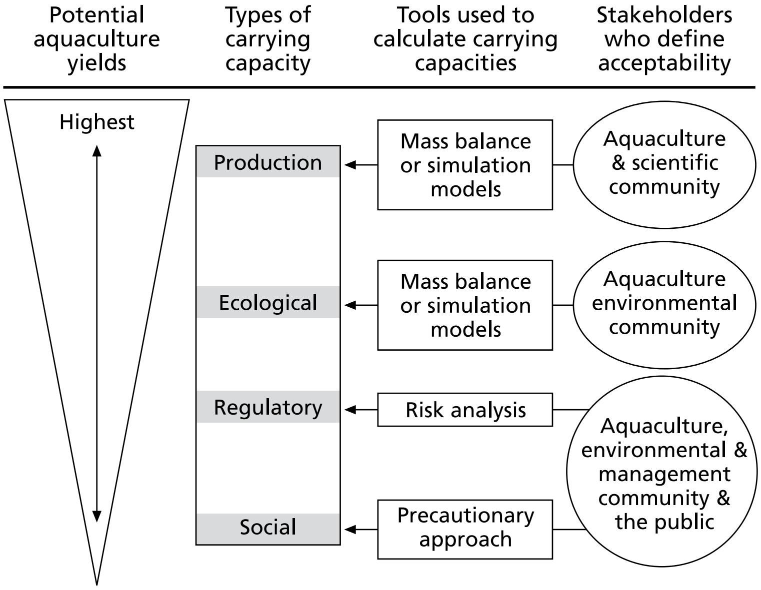
Source: Costa-Pierce (2010).

determined for Rhode Island (United States of America) waters through a stakeholder process (Byron *et al.*, 2011c) that included commercial fishing, recreational fishing, environmental groups, academia, riparian land owners, policy-makers, and other groups who agreed upon a level of shellfish aquaculture that would not restrict or inhibit use to any group.

Analytical methods for calculating social carrying capacity are still in development. Gibbs (2007) recognized the importance of economics in carrying capacity determinations and defined an "economic carrying capacity" as the "the amount of money investors are willing to invest, and the monetary value associated with sellable products and ecosystem services". Kite-Powell (2009) placed a monetary value on various ecosystem uses and calculated the social carrying capacity at which relative value for all uses were maximized. This included assigning value not only to commercial products but also to ecosystem services and other intrinsic and tacit values associated with the system or use of the system.

FIGURE 2

A framework of different types of carrying capacities for aquaculture, tools being used, and stakeholder groups involved



Source: Costa-Pierce (2010).

Note: Highest aquaculture yields occur when models predict maximum farm production for given input variables, and ecological, regulatory and social concerns are less. Potential aquaculture yields decrease as ecological, regulatory and social concerns are equal to or exceed the importance of aquatic food production. In North America and Europe, social carrying capacity drives determinations of production carrying capacity in aquaculture, and there is a strong interaction between all types of carrying capacities; elsewhere in the world such limits on production carrying capacity are much less, but are also increasing.

Every definition has a purpose for a specific situation. Ecological and social carrying capacities are unique in that they depend on social values (McKindsey *et al.*, 2006). It is up to the stakeholders to define how much change in ecosystems they are willing to accept (Byron *et al.*, 2011c). Interactions of some differing types of carrying capacities discussed here with the scientific tools being used, and the interest groups who define "acceptability" of aquaculture are described in the framework presented (Figure 2). Regulatory carrying capacity is added as a new type and defined by rigorous risk analysis and communication protocols (GESAMP, 2008).

To implement an ecosystem approach to sustainable aquaculture, carrying capacity methods are only one of several tools needed. A review of available tools for assessment of sustainability in aquaculture is presented (Table 1), but is not exhaustive as metrics such as Ecological Footprinting (Wackernagel, 1994; Wackernagel and Rees, 1996), Primary Productivity Required (Talberth *et al.*, 2006), Energy Flow (Sangwon, 2005), and Virtual Water Flow (Hoekstra *et al.*, 2009) analyses have increasingly been used to judge the overall sustainability of aquaculture versus other primary food production practices (Welch *et al.*, 2010).

TABLE 1
Sustainability science toolkit appropriate to an ecosystems approach to aquaculture (Costa-Pierce and Page, forthcoming).

Social sustainability	Environmental sustainability	Economic sustainability
Stakeholder analysis: analysis of attitudes of stakeholders at the initiation of and throughout a project. Allows tracking of how stakeholders change attitudes over time with educational processes (Fletcher *et al.*, 2003; Savage *et al.*, 1991; Hemmati *et al.*, 2002; Dalton, 2005, 2006) **ISO 26000 guidelines** for corporate social responsibility (ISSD, 2004) **ICLEI** (International Council for Local Environmental Initiatives) provides software and tools to help local governments achieve sustainability goals (www.iclei.org)	**Life cycle analysis:** complete assessment of products from raw material production, manufacture, distribution, use and disposal, including all transportation; used to optimize environmental performance of a single product or a company. A similar analysis called a MET (Materials, Energy, and Toxicity) Matrix is also used (American Center for Life Cycle Assessment www.lcacenter.org; Bartley *et al.*, 2007; Ayer and Tyedmers, 2009) **ISO 14000 certification:** norms to promote more effective and efficient environmental management and provide tools for gathering, interpreting and communicating environmental information (Interrnational Organization for Standardization (ISO), www.iso.org/iso/iso_14000_essentials) **Environmental impact assessment:** the process of identifying, predicting, evaluating, mitigating biophysical, social, and other effects of development proposals prior to policy decisions (Environmental Impact Assessment Review, www.elsevier.com/wps/find/journaldescription.cws_home/505718/description#description; IAIA, 1999) **Environmental indicators:** the use of quantitative indicators of resource use, efficiency and waste production in aquaculture (Boyd *et al.*, 2007)	**Cost-benefit analysis:** analysis of cost effectiveness of different uses to determine if benefits can outweigh costs (US Federal Highway Administration) www.fhwa.dot.gov/planning/toolbox/costbenefit_forecasting.htm **Triple bottom line or "full cost" accounting:** costs considered for all environmental, economic, and social impacts; costs measured in terms of opportunity costs (the value of their best alternative use); guiding principle is to list all parties affected and place a monetary value on effects on welfare as valued by them (Savitz and Weber, 2006; McCandless *et al.*, 2008)

Models to determine shellfish carrying capacity

Environmental concerns regarding shellfish aquaculture are related primarily to how aquaculture interacts with, and potentially controls, fundamental ecosystem processes at the base of the aquatic food web. Shellfish also excrete large quantities of ammonia, and biodeposit organic matter on the seabed causing impacts on benthic habitats, which, depending on the intensity of culture, can cause adverse impacts in some regions. McKindsey *et al.* (2006, 2009) and Weise *et al.* (2009) attempted to model impacts of mussel biodeposition on the benthos. Such models provide useful information in determinations of the carrying capacity of a site. McKindsey *et al.* (2006) and Callier *et al.* (2009) provided quantifiable evidence that benthic species richness will decrease with increasing biodeposition, and found that some organisms can be good indicators of environmental stress, both by their presence (tolerance) and extirpation (sensitivity). Results of this manipulative experiment are an important step towards evaluating the environmental carrying capacity of sites for bivalve aquaculture.

Many models have been generated to assess carrying capacity relating to shellfish aquaculture, ranging from simple model approaches developed to determine the risk of bay-scale phytoplankton depletion from excessive bivalve grazing (production carrying capacity) to full ecological models with subsequent estimates of shellfish production and ecological carrying capacity (Table 2). Most models are estimates of single species capacity within an ecosystem, assessments of the relative risk of culture activities in different settings, or models developed to optimize shellfish yields in a leased area.

TABLE 2

Carrying capacity models for use in the implementation of an ecosystems approach to shellfish aquaculture.

System	Carrying Capacity type	Model framework	Management application	Reference
Oosterschelde estuary, Netherlands	production	empirical study: correlate current velocity and shellfish biomass with seston depletion	none	Smaal *et al.*, 1986
Nova Scotia, Canada	production	empirical study: divided food filtered by food available	none	Carver and Mallet, 1990
Marennes-Oléron Bay, France	production	coupled physical and biological submodels into an ecological model	none	Raillard and Ménesguen 1994
Carlingford Lough, Ireland	ecological and production	coupled circulation, primary production, and oyster growth model	none	Ferreira, Duarte and Ball, 1997
Marennes-Oléron Bay, France	production	model based on physical transport and deposited matter	none	Bacher *et al.*, 1998
Carlingford Lough, Ireland	production	population dynamics model	none	Bacher *et al.*, 1998
Carlingford Lough, Ireland	production	one-dimensional ecosystem box model including physical and biological processes	none	Ferreira, Duarte and Ball, 1998
na	ecological and production	Conceptual	none	Smaal *et al.*, 1998
Takapoto Atoll, French Polynesia	ecological	inverse analysis of carbon flow in lower trophic levels	none	Niquil *et al.*, 2001
Oosterschelde estuary, Netherlands	production	empirical study	none	Smaal, van Stralen and Schuiling, 2001
Sungo Bay, Shandong Province of China	ecological	coupled two-dimensional circulation-biogeochemical model	potential	Duarte *et al.*, 2003
Thau lagoon	ecological	population model for oysters and mussels	none	Gangnery *et al.*, 2003
Sanggou Bay, Northern China	ecological and production	individual-based species models and multi-cohort population models	potential	Nunes *et al.*, 2003
Tasman and Golden Bays, New Zealand	ecological and production	EcoPath: linear food web	none	Jiang and Gibbs, 2005
Northern Irish Lough System	ecological, production, and social	circulation, biogeochemical, bivalve growth, production, and eutrophication	potential	Ferreira *et al.*, 2007
Lagune de la Grande-Entrée, Iles-de-la-Madeleine, Québec. Magdalen Islands in the central Gulf of St. Lawrence in eastern Canada	ecological and production	coupled biological-circulation-chemical model	none	Grant *et al.*, 2007
Mont Saint Michel Bay, Normand-Breton Gulf (English Channel), France	ecological	two-dimensional coupled circulation-sediment model, lower trophic-level model, and bivalve-filtration model	potential	Cugier *et al.*, 2008
Carlingford, Strangford, and Belfast loughs in Northern Ireland	ecological, production, and social	coupled circulation, lower trophic level, individual-based bivalve growth, and population models	potential	Ferreira *et al.*, 2008a

System	Carrying Capacity type	Model framework	Management application	Reference
Xiangshan Gang, China	production	integrated systems analysis using dynamic coupling of economic drivers with ecological models with emphasis on polyculture	potential	Ferreira *et al.*, 2008b
Sanggou Bay, Northern China	production	integrated systems analysis using dynamic coupling of economic drivers with ecological models with emphasis on polyculture	potential	Ferreira *et al.*, 2008b
Huangdun Bay, China	production	integrated systems analysis using dynamic coupling of economic drivers with ecological models with emphasis on polyculture	potential	Ferreira *et al.*, 2008b
Scottish Lochs	ecological	coupled circulation, lower trophic level, and bivalve-growth models	used to determining license-level activity	Gubbins *et al.*, 2008
Sanggou Bay, Northern China	ecological and production	coupled ecosystem-physiology-circulation and bivalve-growth models	potential	Sequeira *et al.*, 2008
Xiangshan Gang, China	ecological and production	coupled ecosystem-physiology-circulation and bivalve-growth models	potential	Sequeira *et al.*, 2008
Carlingford Lough, Ireland	ecological and production	coupled ecosystem-physiology-circulation and bivalve-growth models	potential	Sequeira *et al.*, 2008
Loch Creran, Scotland	ecological and production	coupled ecosystem-physiology-circulation and bivalve-growth models	potential	Sequeira *et al.*, 2008
Tracadie Bay, Prince Edward Island, Canada	ecological and production	dynamic ecosystem box-model	potential	Cranford, Hargrave and Doucette, 2009; Filgueira and Grant, 2009
Loch Creran, Scotland	ecological, production, and social	coupled circulation, lower trophic-level, bivalve-growth, population, and financial an profit models	potential	Ferreira *et al.*, 2009
Pertuis Brenton, France	ecological, production, and social	coupled circulation, lower trophic-level, bivalve-growth, population, and financial an profit models	potential	Ferreira *et al.*, 2009
Bay of Piran, Slovenia	ecological, production, and social	coupled circulation, lower trophic-level, bivalve-growth, population, and financial an profit models	potential	Ferreira *et al.*, 2009
Chioggia, Italy (Adriatic coast)	ecological, production, and social	coupled circulation, lower trophic-level, bivalve-growth, population, and financial an profit models	potential	Ferreira *et al.*, 2009
Ria Formosa, southern Portugal	ecological, production, and social	coupled circulation, lower trophic-level, bivalve-growth, population, and financial an profit models	potential	Ferreira *et al.*, 2009
Great-Entry and House Harbor lagoons on Magdalen Islands and Cascapedia Bay, Quebec, Canada	ecological and production	coupled circulation and sediment models (DEPOMOD; Cromey, Nickell and Black, 2002)	potential	Weise *et al.*, 2009
Narragansett Bay, Rhode Island, United States of America	ecological and production	EcoPath: linear food web	potential	Byron *et al.*, submitted
Coastal Ponds, Rhode Island, United States of America	ecological and production	EcoPath: linear food web	potential	Byron *et al.*, submitted

Most models have assumed shellfish to be the equivalent of "aquatic cows", grazing almost exclusively on standing stocks of phytoplankton and algae. However, cultured bivalve species have an exceptional capacity to filter large volumes of water containing not only phytoplankton, but also, zooplankton, detritus and other suspended particulate matter (Ferriera *et al.*, 2008a). In Ireland it has been estimated that shellfish remove 4 X more detritus than phytoplankton (Ferriera *et al.*, 2007). Byron *et al.* (2011b) found that in a highly productive temperate bay (Narragansett Bay, R.I., United States of America) that 71 percent of the total energy flow of the ecosystem originated from detritus, and that large quantities of shellfish aquaculture could be supported sustainably with incremental decreases in the large detrital pool. A review of some of the more important models is warranted:

- Cranford *et al.* (2007), Cranford, Hargrave and Doucette (2009) and Grant *et al.* (2008) presented new methodologies for mapping the "depletion plume" from shellfish aquaculture and showed that significant phytoplankton depletion from extensive mussel culture activities in Tracadie Bay (Canada) occurred. Studies showed that mussel aquaculture embayments in Prince Edward Island (Canada) were at a high risk of significant bay-wide particle depletion from mussel culture and that succession had occurred to the point where these bays were dominated by picophytoplankton (0.2–2.0 µm cell diameter). Large-scale removal of larger phytoplankton by mussels occurred, causing significant ecological destabilization that would be expected to alter predator-prey and competition interactions between resident species.
- Jiang and Gibbs (2005) developed an Ecopath model for a marine ecosystem where large-scale expansion of mussel aquaculture was proposed. They defined ecological carrying capacity as significant changes in modelled energy fluxes or the structure of the food web. The model estimated the mussel production capacity in New Zealand at 350 tonnes/km^2/year; however, ecological carrying capacity models reduced bivalve production to 65 tonnes/km^2/year.
- Ferreira, Hawkins and Bricker (2007) developed the Farm Aquaculture Resource Management (FARM) model to be used by both the farmer and regulator to analyze culture location and species selection, and to assess farm-related eutrophication effects. FARM allows ecological and economic optimization of culture practice including timing and sizes for seeding and harvesting, densities, and spatial distributions. This modelling framework combines physical and biogeochemical components as well as bivalve growth models for determining shellfish production. It can be applied to multiple bivalves species and polyculture. FARM is a useful valuation methodology for integrated nutrient management in coastal regions.
- Grangeré *et al.* (2008) developed an ecosystem box model of the nitrogen cycle in the Baie des Veys, the French Republic and concluded that oyster aquaculture had the most impact on phytoplankton and suspension feeders. Higher grazing pressure on phytoplankton by cultured oysters as well as the trophic competition occurred, indicating shellfish biomass was beyond the ecological carrying capacity. Analysis of annual variability indicated that ecosystem fluxes varied with external river inputs. The influence of cultivated oysters seemed to be more important than other environmental factors beyond a threshold value of river inputs around 3 000 tonnes N/year. In the Baie des Veys, river inputs were seldom lower than 3 000 tonnes N/year, so, the nitrogen cycle in the Baie des Veys was influenced more by the cultivated oysters than by the environment.
- Cugier *et al.* (2008) examined trophic interactions in Baie Mont-Saint-Michel (the French Republic) by developing coupled biological and hydro-sedimentary models to examine the relative ecological roles of wild, cultured, and invasive filter-feeders. They concluded that filter-feeders controlled chlorophyll levels.

If all filter feeders were removed from the bay, maximum chlorophyll would be 2–3X higher in most parts of the bay. The invasive gastropod, *Crepidula fornicata* was deemed to have a dominant effect in the western bay, where this species is concentrated, while wild filter-feeders had their main effect in the east. Filtration pressure appears to be partially compensated by the production and deposition of organic matter (feces and pseudo feces) by cultivated and invader species. Demineralization of this matter was able to sustain chlorophyll levels.

- Weise *et al.* (2009) applied numerical models to the distribution of biodeposits around mussel lines (shellfish-DEPOMOD) and predicted near-field effects at a high resolution (meter-scale). Since shellfish culture sites are typically located in shallow coastal areas, this type of resolution is important to model dispersion of biodeposits over fairly short distances. This model, in conjunction with other models/indices that focus on far-field effects (e.g. nutrient cycling, pelagic carrying capacity), provide industry and ocean managers with the tools to efficiently and comprehensively assess effects associated with shellfish culture activities within an ecosystem-based management framework.

Byron *et al.* (2011a, b and c) developed Ecopath models for decision-makers considering the carrying capacity of oyster aquaculture in Narragansett Bay (United States of America). Current biomass was found to be 0.47 tonnes/km^2/year. The ecological carrying capacity was found to be 297 tonnes/km^2/year (625 X current harvests). Approximately 38 950 tonnes of shellfish or 13X the current total could be harvested without exceeding the ecological carrying capacity (Byron *et al.*, 2011a). At production carrying capacity, 3 481 tonnes/km^2/year are possible or 1 235 897 tonnes/year for Narragansett Bay. If farming was limited to 3 481 tonnes/km^2/year across only 9 percent of the area of the Bay, this would still be below the ecological carrying capacity.

Models to determine cage fish carrying capacity

In the 1990's determinations of carrying capacity for cage aquaculture were made using statistical models based upon empirical data (Beveridge, 1993). The driver for determinations of carrying capacity was the increasing concern about the environmental impacts of cage aquaculture in smaller, enclosed, poorly flushed waterbodies due to impacts of nutrients and waste feeds on not only pelagic and benthic ecosystems, but also due to increased user and other social conflicts. Such dramatic environmental-social concerns over the poorly planned and regulated expansion cage culture occurred in dramatic fashion as evidenced by the major "boom and bust" cycles of cage aquaculture in the Republic of the Philippines (Laguna be Bay and the 7 lakes of San Pablo; Beveridge, 1993), in Indonesian reservoirs (Costa-Pierce, 1998), and trash-fish-fed cage culture in many Asian countries (Pullin, Rosenthal and MacLean, 1993).

Over the past decade numerous simulation models have been developed to predict environmental changes with different nutrient loadings from dissolved and particulate inputs from fish cage aquaculture (Table 3). With one exception (CADS_TOOL, which makes economic predictions from site specific data), all of these modelling tools remain focused on providing information and predictions on how the environment would respond to various siting and production levels for fish culture aquaculture. Important input variables from physical oceanography and limnology are used to weigh morphometric, stratification, water flow and current data along with biological factors such as aquaculture feed inputs, consumption, and waste production that help predict changes in ecosystem trophic state and functioning of the pelagic and benthic environment due to fish cage aquaculture. In summary, most scientific work to develop tools to provide information to measure the carrying capacity of fish cage aquaculture appears to have only informed discussions of production and ecological carrying capacities.

TABLE 3
Selection of important models for use in determinations of carrying capacity in the implementation of an ecosystem approach to cage culture of finfish

Models/Tools	Objectives	Carrying capacities	Sources
Statistical models	Assimilation capacity of the environment is calculated based upon discharges; Assessments of aquaculture carrying capacities are made on levels of unacceptable water quality and/or benthic environmental impacts	Ecological carrying capacity	Beveridge (1993); Huiwen and Yinglan (2007)
Site selection framework	Aggregates, weights and ranks criteria for determinations of siting cages in offshore waters	Regulatory and Social carrying capacities	Benetti *et al.* (2010)
3D Tidal Model	Calculates site placement, spatial distribution of cages, and number of cages	Ecological carrying capacity	Gaĉek and Legović (2010)
CADS_TOOL (Cage Aquaculture Decision Support Tool)	Site selection, site classification, site economic appraisal	Production and Regulatory carrying capacities	Halide (2009; http://data.aims.gov.au/cads)
DEPOMOD and AUTODEPOMOD	Site selection from current velocity and direction, depth, feed input and cage plans. Predictions of waste fecal and feed deposition and benthic impact.	Production and Regulatory carrying capacities	Cromey, Nickell and Black (2002); SEPA (2005); www.sepa.org.uk/aquaculture/modelling
MERAMOD and TROPOMOD	DEPOMOD for Mediterranean and tropical species	Production carrying capacity	www.philminaq.eu
MOM (Modelling-Ongrowing fish farms-Monitoring)	Stocking capacities determined by modelling preservation of water quality and benthic ecosystem integrity	Production carrying capacity	Erivk *et al.* (1997); Hansen *et al.* (2001); Stigebrandt *et al.* (2004)
AquaModel	Models determine fish cage biomass impacts on pelagic and benthic ecosystems	Ecological carrying capacity	Rensel *et al.* (2007); www.aquamodel.org

Recommendations

McKindsey *et al.* (2006) in their review found that the vast majority of modelling efforts undertaken to assist managers with information on aquaculture's impact on the environment considered only one or a limited number of ecosystem components. McKindsey *et al.* (2006) and the International Council for the Exploration of the Sea (ICES, 2008) identified gaps in knowledge that need to be addressed in order to advance progress in the scientific basis of carrying capacity for aquaculture, including:

- Development of specific guidance to better define "unacceptable" ecological impacts that include stakeholder identification of important ecological attributes and ecosystem components.
- Identification of critical limits (i.e. performance standards or thresholds) at which the levels of aquaculture developments disrupt and ecosystem, thus requiring management actions.
- Development of spatially explicit time-series of ecological responses to aquaculture development and validation of model predictions.

- Identification of site-specific factors affecting ecological carrying capacity.
- Development of models that consider temporally variable activities (e.g. seasonal harvesting).
- Validation of models be conducted across a range of habitat and culture conditions in order to assess their general applicability.

A great opportunity for the future is to use aquaculture carrying capacity models to complement aquatic spatial planning and management. In addition, the better use of carrying capacity models for management will help better refine the roles of use of aquaculture risk assessment and communications protocols for aquaculture (GESAMP, 2008), and a more rational application of the precautionary approach.

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