Theme Session H
Ecological Carrying Capacity in Shellfish Culture

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Introduction

Aquaculture is the fastest growing food-producing sector in the world and is the only means of filling the growing gap between consumer demand and seafood production from traditional 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, maritime policies (e.g. Canadian *Oceans Act* and EU *Water Framework* and *Marine Strategy Directives*) all include as essential components; 1) a knowledge-based approach for decision making, and 2) an ecosystem-based approach for integrative management. Environmental concerns regarding shellfish culture are related primarily to how the culture interacts with, and potentially controls, fundamental ecosystem processes. Many cultured bivalve species have an exceptional capacity to filter large volumes of water to extract phytoplankton and other suspended particulate matter. While ecosystem-scale changes may result from their considerable role as biofilters, bivalves also excrete large quantities of ammonia and biodeposit undigested organic matter on the seabed. Observations of culture impacts have generally focused on small-scale benthic impacts. Given the intensity of culture in some regions, a more ecosystem-based perspective is required based on the development of prognostic site assessment tools and practical ecosystem performance indicators. Owing to the number of ecosystem processes potentially influenced by mussel aquaculture, ecosystem modelling is an essential tool for understanding and predicting ecosystem interactions.

A fundamental difference between the management of wild fisheries and aquaculture is that the former aims to maximize the catch of the target species without impacting the population or the ecosystem, while the latter strives to maximize stock addition within a given area without causing similar types of impacts. A goal of aquaculture management is to have tools available that can predict and measure the capacity of an area to support the cultured species. This "carrying capacity" concept is rapidly evolving from an anthropocentric focus on maximizing aquaculture production to an ecosystem-based management approach that focuses on ecological sustainability. Carrying capacity research has largely focused on identification of production carrying capacity, which is the maximum sustainable yield of culture that can be produced within a region. Ecological carrying capacity is the level of culture that can be supported without leading to significant changes to ecological processes, species, populations or communities in the growing environment. The development of ecological carrying capacity indicators and models is still in its infancy but has the potential to feed into ecosystem-based management systems for marine areas. In addition, this work reflects the ideals and goals of the ecosystem approach to aquaculture and fisheries management. The ability to predict ecological carrying capacity is crucial to expanding large-scale bivalve aquaculture operations and has the potential to feed into ecosystem-based management systems.

A range of topics and gaps in knowledge need to be addressed to progress the science of ecological carrying capacity in shellfish including, *inter alia*, the following;

- development of guidelines towards defining an "unacceptable" ecological impact, based on theoretical and socio-economic considerations, and identification of critical limits (i.e. operational standards or thresholds) at which the levels of shellfish aquaculture stress indicate a disruption of the system warranting management actions,

- research on the development, value and application of predictive ecological models of shellfish aquaculture systems,
- time-series observations of ecological responses to shellfish aquaculture development and validation of model predictions,
- site-specific factors affecting ecological carrying capacity,
- direction for scientists from stakeholders (e.g. habitat and farm managers and non-governmental organizations) on potential ecosystem components that need to be evaluated in unbiased ecological carrying capacity assessments, and
- discussion on how models of aquaculture systems complement the ecosystem approach to marine management.

Overview

Within the theme session there were 14 oral presentations and 5 poster presentations. The presentations broadly discussed issues surrounding the estimation of carrying capacity ranging from production estimates (Smaal and Silvert; Gubbins *et al.*) to full ecological models with subsequent estimates of shellfish production and ecological carrying capacity (Jiang and Gibbs). The simple model approaches described by Smaal and Silvert and Gubbins *et al.* for estimating carrying capacity are based on determining the risk of bay-scale phytoplankton depletion from excessive bivalve grazing. Although these approaches are directed primarily at ranking the relative risk of culture activities in different settings (Gubbins *et al.*) and for optimizing shellfish yields in a given area (Smaal and Silvert), they provide information on the potential effect on the base of the marine food chain (phytoplankton), which is obviously relevant to ecological stability.

Jiang and Gibbs demonstrated that by running a full ecological model of a system that the production capacity of a system in New Zealand was 350T/km^2/yr. Whereas, when the ecological carrying capacity was factored in the actual bivalve production was reduced to 65T/km^2/yr. They defined this ecological carrying capacity limit based on significant predicted changes in major energy fluxes or the structure of the food web. Model predictions based on large-scale mussel culture included a decrease in the mean trophic level of the ecosystem, an increase in total yield, throughput and efficiency and a replacement of zooplankton by the cultured mussels. These capacity estimates and predictions have not yet been validated as the production levels have so far remained below the lower ecological estimate.

Byron *et al.* introduced the various definitions of carrying capacity (Physical, production, ecological and social) and outlined a proposed approach towards the development of shellfish aquaculture in Rhode Island, USA by applying the following Soto (2007) principles;

- aquaculture should be developed in the context of ecosystem functions and services with no degradation of these beyond their resilience capacity,
- aquaculture should improve human-well being and equity for all stakeholders,
- aquaculture should be developed in the context of other sectors, policies and goals.

However, the development of a sustainable long-term management plan is a difficult course to navigate. Recent advances in the measurement and application of carrying capacity provide some guidance. Modeling ecological carrying capacity with feedback from stakeholders in the system holds the most promise for meeting Soto's (2007) three principles of aquaculture, but due to its newness, is also the least understood and practiced. Rhode Island is an excellent venue for testing this approach so that it might be made available to those in other areas who see the value of stakeholder involvement in a science-based effort to find the proper limits to aquaculture in their local waters.

A number of studies described the influence that filter feeding organisms (including culture organisms, e.g. oysters and mussels) have on specific species, populations, communities, habitat or ecological processes. These include the influence of shellfish production on nutrient dynamics (Andersen *et al*., Brigolin *et al.),* phytoplankton abundance, size structure and/or production (Andersen *et al*., Cranford *et al*., Cugier *et al*., Grangere *et al*.), zooplankton (Andersen *et al*.), secondary production (Archambault *et al*.), and the effects of shellfish biodeposition on the benthos (Andersen *et al*., Weise *et al*., and McKindsey *et al*.). Andersen *et al*. examined the effects of mussel culture in Newfoundland (Canada) on a range of system components and processes and concluded that there was potential for significant effects on planktonic processes, but that these effects are controlled by bathymetry and stratification.

Grangeré *et al*. developed an ecosystem box model of the nitrogen cycle in the Baie des Veys, France and concluded that the main variables influenced by the presence of oysters were phytoplankton and wild suspension feeders. The higher grazing pressure on phytoplankton induced by the addition of cultivated oysters as well as the trophic competition existing between wild filter-feeders and cultivated oysters explained the strong decrease in phytoplankton biomass and production and wild filter-feeder stocks. This approach suggested that the shellfish stocking in that system was beyond the ecological carrying capacity. The analysis of the year-to-year variability in river inputs indicated that the main fluxes of this ecosystem tended to increase with the increase of external inputs. However, the influence of cultivated oysters seemed to be more important than that of the environment beyond a threshold value of river inputs around 3000 T N y^{-1}. In the Baie des Veys, river inputs were seldom lower than 3000 T N y^{-1}, so, the nitrogen cycle in the Baie des Veys was influenced more by the cultivated oysters than by the environment. Finally, the comparison of fluxes between different ecosystems improved knowledge on the influence of cultivated species on their respective environment and the effect of different modelling approaches (phytoplankton vs. seston as mussel food). However, the comparison was difficult due to the numerous differences existing in the structure and the functioning of these cultivated areas.

Trophic interactions were also examined in Baie Mont-Saint-Michel (France) by Cugier *et al*. who employed coupled biological and hydro-sedimentary models to examine the relative ecological roles of wild, cultured and invasive filter-feeders. They concluded that filter-feeders strongly control chlorophyll levels in this bay. If all the filter feeders were removed from the bay, maximum chlorophyll should be 2 to 3 times higher in most part 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 native filter-feeders have their main effect in the east. Filtration pressure appears to be partially compensated by the production and deposition of organic matter (faeces and pseudofaeces) by cultivated and invader species. Remineralization of this matter seems able to sustain chlorophyll levels. Cugier *et al*. highlighted the relative pressure exerted by each category of benthic filter-feeders on the pelagic ecosystem but not on each other through trophic relationships. Future research activities by this group will address this shortcoming by developing eco-physiological models for oysters, mussels and *Crepidula*, which will also be used to explore a number of farm management scenarios.

Some presentations coupled physical models with production estimates. In particular, the interaction between shellfish culture and physical attributes of systems was examined to determine how shellfish production is influenced. Filguera and Grant indicated that artificial upwelling of nutrient-rich deeper water stimulated phytoplankton growth in a Norwegian fjord, with a potential increase in production carrying capacity for mussel cultivation. With the aim of evaluating aquaculture effects and assisting in the development of sustainable mussel culture, a model was developed which represented regions of the fjord. Subsequent manipulations of the model maximized mussel production in the upper fjord based on projected nutrient phytoplankton enhancement by the upweller with a view to efficiently managing mussel production in the fjord. Grant *et al*. compared the results of this model to those of a fully spatial model of the entire fjord. The range of regeneration times in stratified waters bodies will also have a bearing on the capacity of the system to produce shellfish and the degree of interaction between cultured shellfish and other filter feeding organisms in a system. For example, Strand *et al*. demonstrated that nutrients in a Norwegian fjord tend to be limiting due partially to the fact that the regeneration times of deposits into deeper waters is protracted. Strand *et al*. also highlight that fjords and coastal waters in Norway are considered to be low-seston environments with implications for estimates of ecological carrying capacity. Suspended culture of mussels in fjords may change the ecological energy flow in the ecosystem because the littoral zone is short and natural stocks of benthic suspension feeders are relatively low.

McKindsey *et al*. and Weise *et al*. focused their presentation on the influence mussel biodeposition has on the benthos and on attempts to model these effects. Information relating to biodeposition effects will go some way towards determining the environmenatal carrying capacity of a site in particular as it relates to the benthos. The dose-response study conducted by McKindsey *et al*. provided quantifiable evidence that species richness will decrease with increasing biodeposition and reiterates the fact that some organisms can be good indicators of environmental stress, both by the presence (tolerance) and extirpation (sensitivity). The results of this manipulative experiment are an important step towards evaluating the environmental carrying capacity of sites for bivalve aquaculture. Further research is needed to extend the generality of the findings beyond site-specific effects, to determine the range of biodeposition increase, as well as to reduce potential experimental artefacts.

Weise *et al*. applied numerical models, developed originally for modelling the distribution of biodeposits around salmon cages, to the distribution of biodeposits around mussel lines. The study demonstrated that the model can be adapted for shellfish culture sites and may be a good tool to investigate the spatial extent of biodeposition. Shellfish-DEPOMOD can predict near-field effects at a high resolution (metre-scale). Since shellfish culture sites are typically located in shallow coastal areas, this type of resolution is important to adequately model the dispersion of waste material as dispersal of biodeposits may occur over fairly short distances. Although there is an acknowledged need to more fully understand shellfish farm waste production and resuspension processes, the model presented can be used to estimate the spatial extent of effects. This model, in conjunction with other models/indices that focus on far-field effects (e.g. nutrient cycling, pelagic carrying capacity), can provide industry and ocean management with the tools to efficiently and comprehensively assess effects associated with shellfish culture activities within an ecosystem-based management framework.

Cranford *et al*. presented results from studies at mussel farms in Canada and Norway on the spatial scales of phytoplankton depletion. This study presented new methodologies for mapping the depletion plume and showed that significant phytoplankton depletion from extensive mussel culture activities in Tracadie Bay (Canada) occurs at the coastal ecosystem scale, which confirms model predictions. This study also showed that mussel aquaculture embayments in Prince Edward Island (Canada) that are at the highest risk of significant bay-wide particle depletion from mussel culture were dominated by picophytoplankton (0.2 – 2.0 µm cell diameter). This highly novel observation is likely the result of the large-scale removal of larger phytoplankton by mussels and represents a significant ecological destabilization that can be expected to alter competition and predator-prey interactions between resident species.

Conclusions

Ecosystem-based management has become an important concept in coastal zone management, which includes aquaculture. Assessment of aquaculture has occurred mostly at the local scale by measuring the 'footprint' of shellfish farms. Extrapolating these effects up to any larger scale has been limited by identification of a signal attributable solely to aquaculture, and the ability to make meaningful measurements over larger areas. When many local farm units are considered, the scenario is even more complex because their impacts interact as a function of bathymetry, proximity, circulation, and coastal morphology. Several presentations highlight the identification of practical indicators of benthic and pelagic effects of shellfish aquaculture that can be applied at ecologically relevant scales. Modelling can also addresses the problem of understanding multiple farm interactions and cumulative effects of other coastal zone activities (e.g. eutrophication and invasive species) at a scale relevant to coastal ecosystems. The presentations highlight the importance of having good information pertaining to the hydrological conditions to drive physical models and understand better the interactions within systems.

An important outcome of the session was the acknowledgment that investigators are designing research projects to consider multiple factors influencing the form and function of marine ecosystems. The combination of subjects into single research projects has and will continue to contribute greatly to the understanding of the interaction of human activities in marine systems. These projects will subsequently provide scientifically robust and important information towards the development and management of activities in the marine environment. Carrying capacity research continues to provide information on a system-wide level; however, models are being refined to provide important information on the capacity relating to partitioning on differing spatial and temporal scales.