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Theme H: Ecological Carrying Capacity in Shellfish Aquaculture

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Phytoplankton depletion by mussel aquaculture: high resolution mapping, ecosystem modeling and potential indicators of ecological carrying capacity

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Abstract
Mussels held in suspended culture have an exceptional capacity to filter the water column and reduce suspended particle concentrations. However, seston depletion is only of concern if the phytoplankton are cleared faster than they can be replaced by tidal exchange and primary production. The occurrence of significant phytoplankton depletions over extended periods and different spatial scales is directly linked to concepts of production and ecological carrying capacity owing to food limitation and alterations in ecosystem structure, material fluxes and pathways and nutrient cycling. Knowledge on ecosystem interactions with shellfish aquaculture supports the growth of a sustainable industry and the development of an ecosystem-based management approach. The scale and magnitude of phytoplankton depletion was documented at mussel aquaculture farms in Canada and Norway using a computer controlled, towed undulating vehicle (BIO-Acrobat) that collects geo-referenced CTD and chlorophyll *a* data. Rapid synoptic surveys with intensive horizontal and vertical sampling permitted high resolution 3-D mapping of phytoplankton variations over farm to coastal ecosystem scales. Phytoplankton depletion by mussels is size-specific and it is expected that in areas where mussels control phytoplankton biomass, that picophytoplankton (0.2 to 3.0 µm) will dominate. This hypothesis was tested, and confirmed, by measuring total and picophytoplankton biomass in Prince Edward Island embayments, where the risk of phytoplankton depletion varies greatly owing to regional differences in water flushing, bay volume and culture biomass.

Key words: mussel culture; phytoplankton depletion; picophytoplankton; carrying capacity; ecosystem models; indicators

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 need for the continued worldwide expansion of aquaculture to fill this gap, industry development needs to be promoted and managed in a manner that minimizes negative environmental impacts (FAO, 2008). Unlike finfish culture, which requires the addition of feed and chemical additives, mussel farming relies entirely on natural food supplies. Environmental concerns are related primarily to how the cultured mussels interact within the ecosystem. Mussels live in dense colonies and have an exceptional capacity to filter large volumes of water to extract food (phytoplankton and other suspended particulate matter). Filter-feeding by mussels naturally results in some local reduction (depletion) of their phytoplankton food supply. However, if the mussel culture is consuming phytoplankton faster than they can be replaced by tidal flushing and phytoplankton growth, then the mussels will become food limited and production will be less than maximal for that site. This is referred to as exceeding “production carrying capacity”. If the spatial scale of phytoplankton depletion includes a significant fraction of the coastal inlet, then this effect on the base of the marine food web raises

concerns about the ecological costs to other components of the ecosystem. These costs can be used to define the "ecological carrying capacity" of the site.

It is difficult to make generalizations about the environmental effects of shellfish aquaculture and to extrapolate results from one site to another without employing sound ecosystem-based science. There is a need to continue to improve and test methods for predicting and measuring environmental interactions at a wide range of shellfish aquaculture sites, with a focus on providing practical tools for assessing the production and ecological carrying capacity for shellfish aquaculture. Research was conducted through close international partnerships to improve and integrate knowledge on farm- to bay-scale ecological interactions with cultivated mussels and to aid in the development of effective strategies that will promote the sustainability of the aquaculture industry. This study focused on determining the scale and magnitude of phytoplankton depletion from mussel filter-feeding at aquaculture sites in Canada and Norway to assess the capacity of the culture to control the phytoplankton: an effect that has relevance to assessing ecological carrying capacity. In addition, this study examined the effect of the mussel biofilter on the size-structure of the phytoplankton. Mussels effectively retain particles larger than 3 µm and it was hypothesized that under conditions where mussels control the phytoplankton at the scale of coastal ecosystems, the phytoplankton will be dominated by picophytoplankton species (0.2 to 2.0 µm diameter) that are not effectively retained by the mussels.

Methods

Detection of the zone of phytoplankton depletion in and around aquaculture sites is not trivial due to the large degree of natural variation in coastal waters. This study utilized the rapid, high-resolution 3-D *in situ* mapping approach that has been shown to be a reliable means of quantifying food depletion at farm to bay-wide scales (Cranford et al, 2006; Grant et al., 2008). A computer controlled tow vehicle (BIO-Acrobat) carrying a CTD and chlorophyll fluorometer was set to undulate between set water depths while being pulled behind a small boat. All measurements were sampled at 2 Hz and the data stream was geo-referenced during data acquisition. The depth range surveyed included water above, within and below the farmed depth range. The spatial area sampled varied been farm-scale (Hogsfjord, Norway) to bay-scale (Tracadie Bay, Canada) surveys. Data provided by the Seapoint chlorophyll fluorometer were calibrated by comparing *in situ* voltage readings to *in vivo* chlorophyll concentrations measured for water samples (r^2= 0.967). The goal of each Acrobat survey was to rapidly (within 1-2 h) collect 3-D (latitude, longitude and depth) data on phytoplankton concentrations as quickly as possible before the distribution changes with tidal flushing. Data were averaged over the mussel farm depth range to examine the full influence of the farm on phytoplankton concentration. Survey data from the Hogsfjord were also averaged for areas up-current of the farm and immediately below the farm to serve as reference (no effect of mussels) areas.

To examine the potential effects of phytoplankton depletion on the size of the phytoplankton at the coastal ecosystem scale, a survey of six mussel aquaculture embayments in Prince Edward Island (PEI) was conducted in August, 2008. Between 5 and 10 water samples were collected in each bays from 2 m depth (within the depth interval of mussel socks). The water was filtered through 0.2 and 3.0 µm Nuclepore filters and chlorophyll *a* concentration was determined from the *in vitro* fluorescence (Turner Designs fluorometer calibrated against pigment from spinach) of 90% acetone extracts of the filtered material. The picophytoplanton contribution (f_{pico} = fraction of total chlorophyll *a*) was calculated as $CHL_{0.2}$ – $CHL_{3.0}$)/$CHL_{0.2}$. The average f_{pico} was compared with a phytoplankton depletion risk index for each embayment calculated as water clearance time/residence time (e.g. Dame and Prins, 1998).

Results and Discussion

The synoptic survey of a mussel farm in Hogsfjord, Norway showed farm-scale depletion within the depth of the farm (1-3 m depth), but not up-current or below the farm depth (Fig. 1). The zone of depletion extended down-current from the farm. Although this fjord is sparsely farmed, any increase in farming activity in the adjacent areas should account for the effect of particle depletion on production carrying capacity. The high percentage of the farm experiencing greater than 20% depletion (Fig. 1) also suggests that the stocking density may be affecting optimal production at the farm scale.

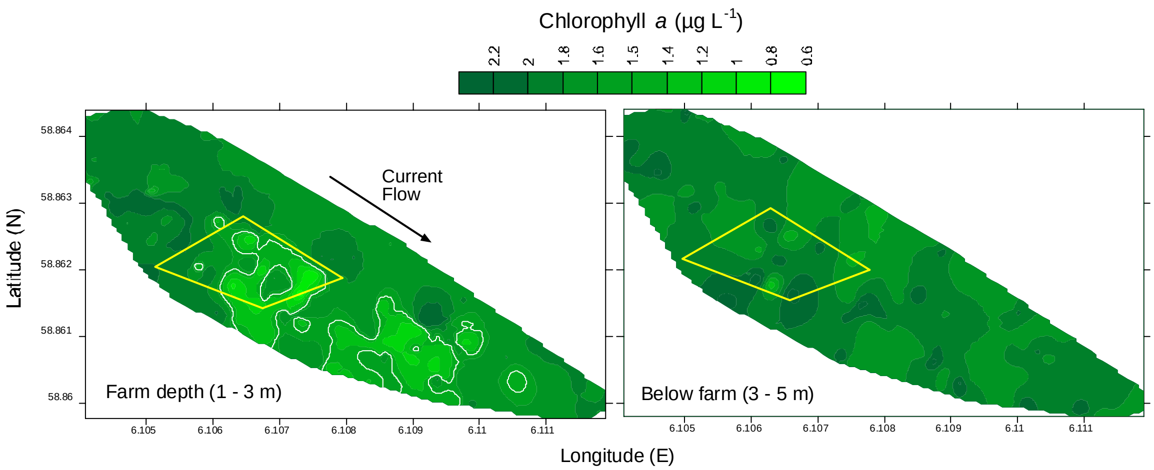

Figure 1. Example maps of the phytoplankton biomass (chlorophyll *a*) around a mussel farm (outlined in yellow) in Hogsfjord, Norway showing food depletion within the depth zone of the farm (left), but not up-current (left) or below the farm (right). Contours outlined by the white line represent the zone exhibiting greater than 20% food depletion.

A large fraction of Tracadie Bay is used for long-line mussel farming and the Acrobat survey approach was used to collect high resolution chlorophyll measurements over the depth of the bay (1 m below surface to 1 m above bottom) along a 4 km transect running in a N-S direction (Fig. 2). This transect approach was repeated at different stages of the tidal cycle to examine differences in phytoplankton concentrations during ebb tide. During this period, the phytoplankton that enters the bay during flood tide is expected to be gradually consumed by resident filter-feeders. A 30% reduction in the mean transect phytoplankton concentration was observed over the 3.8 h period after high tide (Fig. 2). This rapid rate of phytoplankton depletion confirms the predictions of a fully coupled physical/biological model of seston depletion by mussel culture activities in Tracadie Bay (Grant et al., 2008). The rapid bay-scale depletion rate indicates that mussel culture is exerting a strong control over of phytoplankton levels in this bay.

A survey of the size-structure of the phytoplankton in six Prince Edward Island embayments in August 2008 (Tracadie Bay (TR), St. Peters Bay (SP), Cascapedia Bay (CP), Montague and Brudenell River estuaries (MB), St. Marys Bay (SM) and Murray River estuary (MR)) found that those bays that are at the highest risk of significant bay-wide particle depletion from mussel culture were dominated by picophytoplankton (Fig. 3). Picoplankton apparently dominated in these areas because they are too small to be captured by mussels, while their predators (ciliates and flagellates) and major competitors for light and nutrients are rapidly removed by the mussels. Although past research indicates that the average picophytoplankton contribution in PEI bays should not exceed about 25% of total phytoplankton biomass, levels between 50 to 80% were

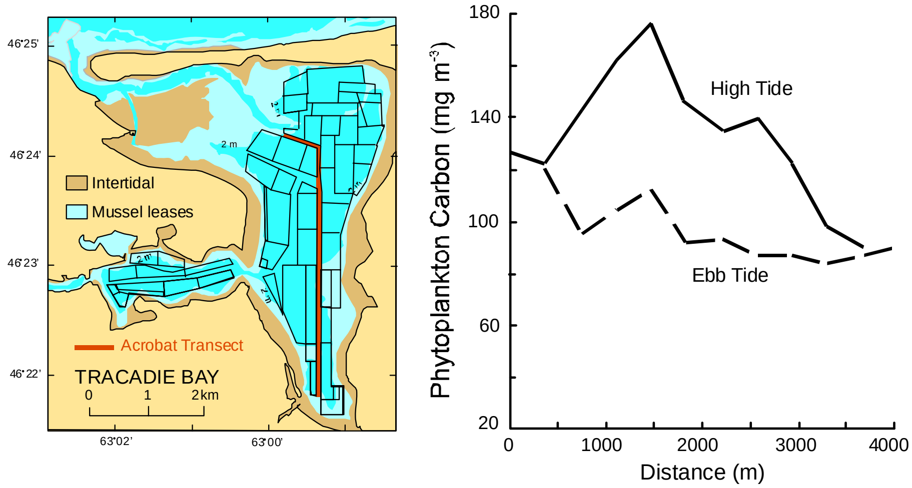

Figure 2. Map of Tracadie Bay, Canada (left) showing the distribution of areas leased for mussel culture and the location of the N-S transect (red line) that was repeatedly surveyed using the Acrobat tow vehicle. Phytoplankton concentrations on June 17, 2003 (shown on the right assuming a carbon to chlorophyll a ratio of 50) were depth averaged over 12 distance intervals starting at the southern extent of the transect.

observed in several bays, including Tracadie Bay. For aquaculture, this means that food availability for mussel growth can be much lower than is measured using standard water filtration and fluorometric techniques. From the perspective of coastal ecosystems, this result represents a significant destabilization of the basis of the marine food-web. A change in phytoplankton size can be expected to alter competition and predator-prey interactions between many resident species. In addition, the change in phytoplankton size can affect particle transport dynamics via reduced settling velocity and altered flocculation processes. The latter is dependant on particle size and the production of sticky exopolymers by diatoms, which are consumed by the mussels. These ecological effects need to be considered in the determination of the regions ecological carrying capacity for shellfish aquaculture.

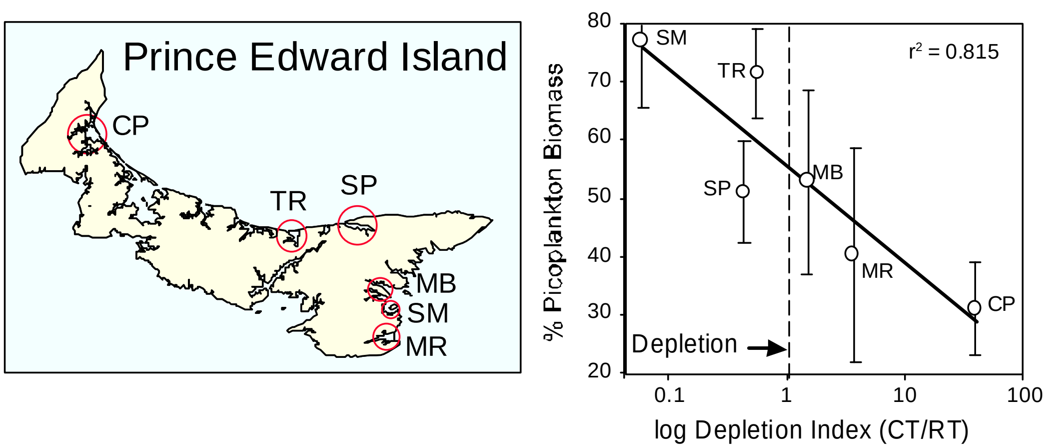

Figure 3. Mean contribution of picophytoplankton in six PEI embayments containing different levels of mussel culture (August 18-22, 2008). The picophytoplankton contribution (f_{pico}) is plotted against a phytoplankton depletion risk index that compares bay flushing characteristics (RT = residence time) with the biofiltering capabilities of the resident mussel farms (CT = clearance time). Depletion index levels below 1 indicate bay-scale depletion.

The extent and magnitude of ecosystem interactions with mussel culture are always site-specific with site vulnerability depending on factors controlling food consumption and waste production (e.g. intensity of mussel production and food concentration) and dispersion. The rate of dispersion determines the capacity of the local environment to prevent excessive food depletion and benthic impacts. Dispersion is controlled by hydrographic and physical factors including current and wind speed, tidal range and water depth. The relatively high susceptibility to bay-scale phytoplankton depletion of the shallow, semi-enclosed tidal lagoons and estuaries in Prince Edward Island results from their relatively low-energy hydrodynamic features, shallow depth and the relatively large areas leased for mussel culture. Our results suggest that low-cost and relatively simple measurements of the picophytoplankton contribution (f_{pico}) in a mussel culture embayment serve as a practical indicator for monitoring the status of both production and ecological carrying capacity. Decision thresholds based on measured f_{pico} values can be set using available data on natural ranges observed in marine systems.

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