ECOSYSTEM INTERACTIONS WITH MUSSEL CULTURE IN NEWFOUNDLAND COASTAL WATERS

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Abstract

Environmental impact of bivalve aquaculture and requirements for sustainable bivalve production are closely linked. Shellfish aquaculture depends on the environment to supply food and remove degradation and waste products. Cultured bivalves consume plankton that are produced over a much wider area than the physical footprint of the shellfish farm resulting in localized, high rates of organic matter deposition and remineralization in both water column and sediments. There is thus the potential for feedback from the waste products of animal metabolism to the production of autotrophic and heterotrophic bivalve prey. We examined the impact of high density shellfish culture on pelagic and benthic ecosystem processes in a two-year field study of mussel farms and nearby reference sites on the northeast coast of the Island of Newfoundland, Canada. The farms were located in sheltered bays and differed in sustainable stocking density and time to market. The biomass of microplankton, but not mesozooplankton, differed significantly between farm and reference sites, with in-farm microplankton being up to two-fold greater than in other Newfoundland coastal waters. Although sediment organic matter, redox, and sulfide levels did not differ between farms and reference sites, there were differences in benthic infauna, and higher rates of sediment-to-water fluxes of NH_4^+ and PO_4^+. Our results indicate the potential for significant feedback from mussels on *in situ* planktonic processes which in turn influence mussel production. Site-specific responses indicate however, that bathymetry and stratification play a key role in determining the magnitude of the feedback and hence system productivity.

Keywords: mussel aquaculture, benthic pelagic coupling, nutrient release.

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Introduction

Extensive shellfish aquaculture operations have the potential to substantially modify their environment. Unlike intensive finfish farms where a primary environmental concern is the consequence of increased organic matter loading, shellfish farms represent a net addition of habitat to an existing ecosystem. The introduction of suspension feeders can alter seston properties and dynamics and modify the fluxes of material and energy through the ecosystem. If as is frequently the case, substrate is the limiting factor for benthic organisms, the addition of shellfish can substantially increase secondary production of a coastal ecosystem. On the other hand primary production limits benthic productivity then the addition of suspension feeders may result in foodweb shifts as they compete with other secondary producers and transfer water column primary production to the benthos. Benthic remineralization of limiting nutrients and the subsequent release back into the water column may also be modified by the presence of mussels or other grazers and suspension feeders, and thus may influence planktonic productivity creating a positive feedback and influencing the ecological capacity of a coastal system.

Benthic processes may be responsible for up to half of the nutrient mineralization in estuaries (Heip et al. 1995; Herman et al. 1999; Ysebaert et al. 2002) and benthic production frequently dominates secondary production in estuaries and coastal regions. Yankhe (2006) calculates that benthic primary production represents 1/3 of total primary production in the south Atlantic Bight. Microphytobenthic communities also contribute significantly to denitrification and N_2 fixation rates in coastal systems (Sundbäck and Graneli 1988). Thus, the addition of benthic habitat and additional suspension feeders to a coastal environment will affect not only the flux of seston from the water column to the sediments (as a result of particle repackaging and hydrodynamic regime modification) but also the benthic pelagic coupling and nutrient dynamics (directly by excretion and indirectly by modification of sediment properties).

Here we present the results of a two-year study of the ecosystem consequences of mussel aquaculture in two coastal inlets on the Northeast coast of Newfoundland. At these sites, the presence of mussels significantly alters planktonic community structure and productivity and benthic-pelagic coupling of nutrient fluxes. These modifications, influenced by site specific hydrography and bathymetry, result in enhanced mussel production at the shallower of the two sites and increased planktonic production at both.

Study Sites

Two mussel farms located in northeastern Newfoundland, Fortune Harbour and Charles Arm, were selected for this study (Fig. 1). Blue mussels (predominately *Mytilus edulis*) have been cultured on long lines at each farm site for at least two decades. These sites are typical of the sheltered locations commonly used for aquaculture within the Province. Like most mussel farms in Newfoundland, the study sites are small, semi-enclosed inlets with a narrow opening to the open ocean, are ice covered in winter, and receive little anthropogenic input. The sites were chosen for their year-round accessibility, logistic

support received from growers at these locations and the existence of background information from previous research initiatives at these farms.

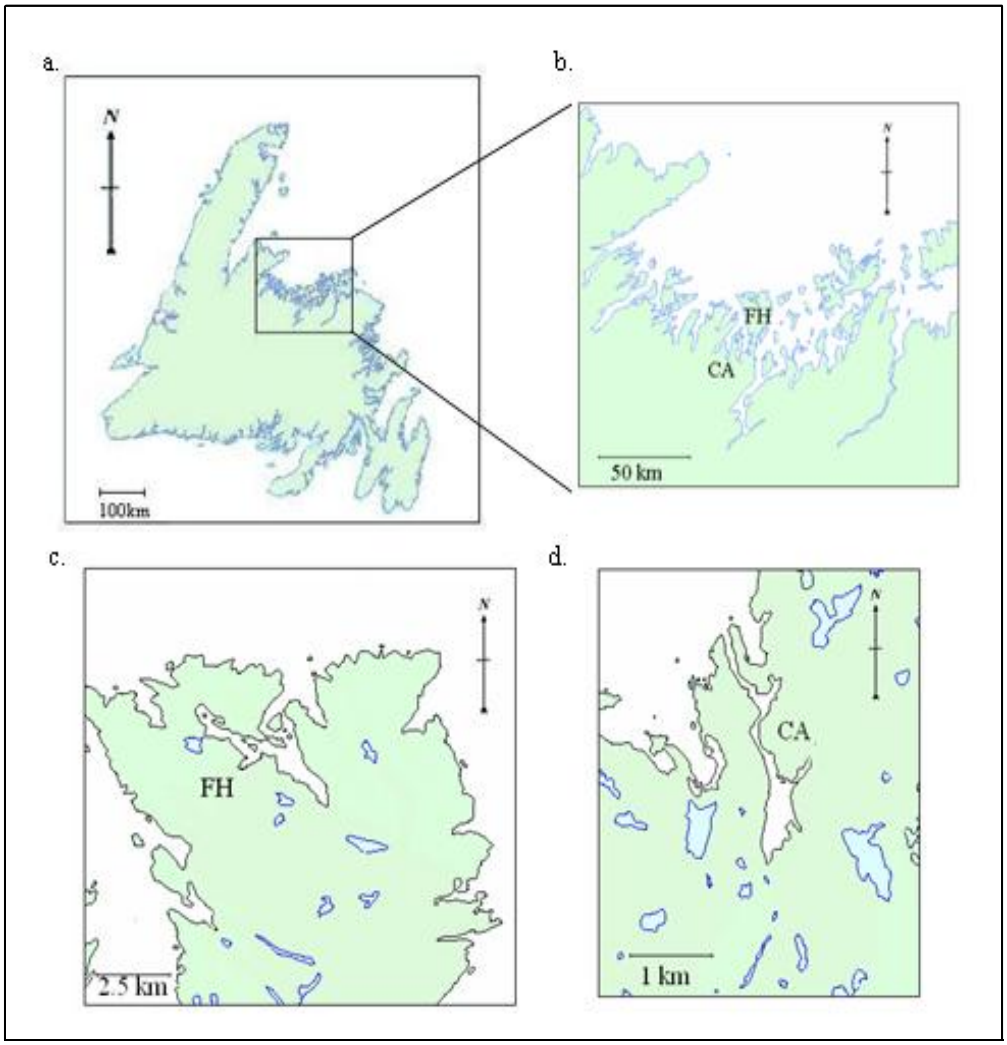

Figure 1: a) Map of Newfoundland highlighting Notre Dame Bay b) Notre Dame Bay showing Fortune Harbour (FH) and Charles Arm (CA) c) FH d) CA. Green shading- land; blue shading- freshwater; no shading (white)- seawater.

Nearby coves was selected as a reference site for each of the farms. These coves were similar in depth, size and openness to the outer coast. No aquaculture occurred in either reference site. Saunders Cove, the reference for Charles Arm, is located just to the east of Charles Arm. Fortune Harbour consists of three "arms" with the farm occupying the Northeast Arm. Southeast Arm was similar in size and was selected as the reference for this site. Both are constricted by shallow sills at the mouth of Fortune Harbour and have deep central basins.

The currents at both farms are weak with minima of< 2 cm s^{-1} at the heads of both farms and maxima of 5-10 cm s^{-1} and 3 cm s^{-1} at the mouths of Charles Arm and Fortune

Harbour, respectively (Coffin 2001; Timko, de Young, and Foley 1999). Charles Arm flushes 1-2.75 times per week (Penney et al 2001). The tidal ranges are 0.75 m at Charles Arm (Penney et al 2001) and 0.92 m at Fortune Harbour (Coffin 2001). Charles Arm has very little freshwater input and tidal exchange is the dominant source of water movement (Penney et al 2001). The bottom waters in this site exchange infrequently with the outer coast. The deep central basin of Fortune Harbour remained stratified throughout the two years of our study and became increasingly anoxic through that period.

Sample collection and analysis

The farm was visited eight times over two years. Samples were collected by boat during the ice free period (June – December) or through the land fast ice (March). All stations were located by hand held GPS and where possible, the same stations were sampled during each visit.

Water column profiles for conductivity, temperature, pressure, oxygen, turbidity, fluorescence and PAR were taken using a Seabird 25 CTD except during March 2002, when through-ice sampling necessitated the use of a smaller SBE19 equipped only with temperature, pressure and conductivity sensors. Oxygen measurements were calibrated using Winkler titration of surface and deep water from 2-3 stations at each site and fluorescence was calibrated using chlorophyll *a* determinations made at each station.

Sediment: Sediment samples were taken with an Eckman grab and kept at near ambient temperature on blue ice in a cooler until processing. Grabs were rejected if the sediment water interface was not intact.

Microplankton and bacterioplankton: Samples for chlorophyll *a* were collected onto 25mm GF/F (i. e. > 0.7μm) and 5 μm Poretics filters (> 5.0 μm) and stored at -20^{o} C until analysis. Samples for bacteria, and protists were collected into 200ml Nalgene bottles and preserved with gluteraldehyde (2% final concentration). Preserved samples were stored in the dark at about 4^{o} C.

Chlorophyll samples were analyzed within 1 month of collection. Chlorophyll *a* was extracted overnight in 90% acetone at -20^{o} C and fluorescence was measured using a Turner Designs fluorometer equipped with a wide-band filter set. The fluorometer was calibrated using pure chlorophll *a*. The chlorophyll *a* concentration in the <5 μm size fraction was determined as the difference between total (GF/F) and > 5 μm size fractions.

Abundances of bacteria were determined from water samples preserved in 2% glutaraldehyde within 2 weeks of collection. Bacteria samples were filtered onto 25mm diameter, 0.2 μm black polycarbonate filters, stained with acridine orange (Hobbie et al. 1977) and counted on a BH2- RFC Olympus epifluorescence microscope at a magnification of 1250x using blue-light excitation (BP440, DM455, AFC+Y475). A minimum of 600 cells per filter (10 or more random fields counted; CV~15%) were counted for determination of bacteria.

Flagellates were preserved and counted using the method described in Lovejoy et al. (2000).

Mesozooplankton: Zooplankton samples were collected using vertical net tows at three to six stations at each farm and reference site in August and November of 2001, and March and July of 2002. A 50-cm diameter ring frame was fitted with a 110-µm mesh net measuring 2.5 m long. The net was equipped with an inside and outside flowmeter to monitor distance traveled and clogging. Triplicate samples were collected at each station. Two were fixed in 500-ml jars in 70-90 % ethanol for determination of mean abundance and the other frozen fresh in 100-ml jars for later determination of biomass. Samples were collected at each farm and its reference site on successive days at the same time and tidal stage.

Benthic infauna: Grab samples for infauna were returned to shore and washed with filtered seawater through a series of sieves with 5 mm, 1 mm and 0.5 mm mesh size to retain macrofauna greater than 0.5 mm. Collected macrofauna were fixed in 4% formaldehyde buffered with borax and transferred to 70% ethanol for long-term preservation. Samples were also stained with rose bengal in order to facilitate identification. Preserved specimens were enumerated and identified to the lowest possible taxonomic level under stereo and compound microscopes in order to construct a species-abundance matrix. Various taxonomic guides and keys were used to identify macrofauna (Gosner, 1978; Gosner, 1979; Pocklington, 1989; Wallace et al., 1989; Ramey, 2001; Harris, 2003; Quijon and Snelgrove, 2005).

Sediment chemistry: Sediment temperature and redox potential were taken from each grab with an Orion redox probe. The redox probe was calibrated using a zobel standard solution. Readings in mV were converted to eH using the temperature corrected calibration factor (214) provided by the manufacturer (Thermo Orion, 1997). A cutoff 60ml syringe was then used to collect three 50ml samples of the surface sediment from each grab. These were frozen for later analysis of total nitrogen (TN) and total carbon (TC), total phosphorus (TP), and percent organic matter. Back at the lab, they were dried overnight at 80°C. TN and TC were determined simultaneously using a PE2400 (Perkin Elmer) Series II CHNS/O analyzer calibrated using an Acetanicide standard. Percent organic matter was then determined as loss on ignition for 5 hours at 550 °C (Kristensen and Andersen, 1987). TP in the sediment was determined after ashing at 550 °C by the method of Andersen (1976). Samples for sulfide analysis (Wildish *et al*. 1999) were also taken with a cutoff syringe, transported in a cooler to shore and processed within 3-4 hours.

Nutrient regeneration: Nutrient regeneration rates were determined by following the concentration of ammonium and phosphate in water overlying cores taken from the Eckman samples. The cores were incubated for 24 hours and sampled at 6 hour intervals. Every six hours, three cores were selected for each site and triplicate 50ml water samples for NH_4 and PO_4 determination were removed from the overlying water. NH_4 was

determined colorimetrically by the method of Ikeda (2000) and PO^4 by the method of Murphy and Riley (1962). All NH_4 and PO_4 measurements were made within 6-8 hours of sampling. Areal release rates were calculated as the change in nutrient concentration over time.

Zooplankton: Preserved samples were returned to the Ocean Sciences Centre, Memorial University, for storage and processing. Within two to three weeks of return samples were removed from alcohol and split in half with a Folsom splitter. One of the splits was transferred to 4% buffered formaldehyde and used later for species identification. The other split was sieved through 500 μm and then 80 μm mesh. The greater than 500μm fraction (hereafter referred to as the large animal fraction) was transferred to 4% buffered formalin to be used for image analysis of large animal size distributions. The small animal fraction was then transferred to filtered sea water from Logy Bay, Newfoundland and used for Coulter Counter Multisizer II® counts and analysis of size distributions.

Frozen samples were returned to the Ocean Sciences Centre and kept at -20 ºC until analysis. They were thawed at 5 ºC and suspended in (1 m) filtered sea water from Logy Bay, Newfoundland. Measured aliquots were filtered onto pre-ashed, pre-weighed GF/C filters. Each sample was washed with distilled water in a ratio of 5mL distilled water for every 200mL SW used. The filters were then lyophilized at -60 ºC overnight brought to room temperature and weighed. Using this method, any small amounts of remaining salt adhere to the edges of the container in which the samples are lyophilized.

Samples from three stations were chosen at random from all stations sampled each farm and reference site for each of the time periods following a computer-generated list of random numbers. Measured aliquots of formalin-preserved splits of the samples were taken with a Stempel pipette and the animals identified under a Wild® dissecting scope. Enough aliquots were counted to reach counts of at least forty individuals for each of the major taxa and whole samples were sometimes counted for enumeration of rare species. Usually ~500 animals were identified and counted from each split. References used for identification included Todd and Laverick (1991), Newell and Newell, (1977) and the ICES zooplankton identification leaflets.

Pelagic Effects

Microplankton

Chlorophyll levels in Charles Arm were on average twice as high as those in Fortune Harbour (Fig. 2). The two sites also differed in size distribution of the phytoplankton. The duration of the chlorophyll maximum was extended in Charles Arm compared to Fortune Harbour and primary production was 2X greater in Charles Arm. In general, no differences in total chlorophyll were observed between the farms and their reference sites.

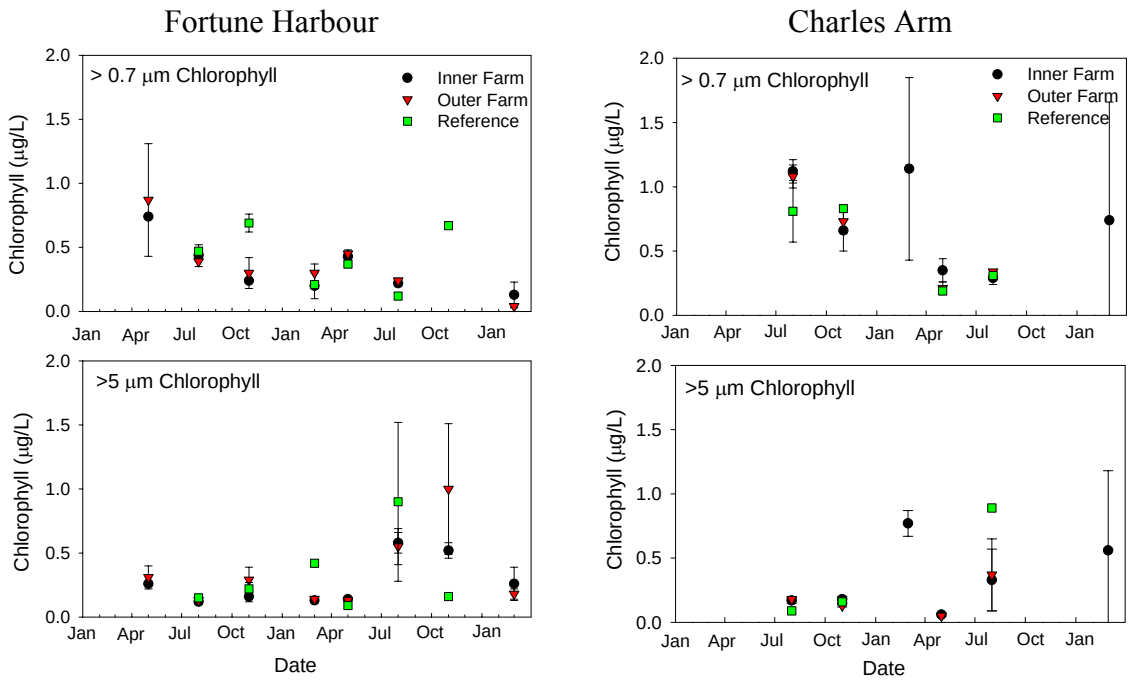

Figure 2. Chlorophyll *a* levels at farm and reference sites through the study. Top panels show total chlorophyll (> 0.7 μm) and lower panels show the > 5 μm fraction.

Bacterioplankton abundances were generally higher in both farms than in their respective reference sites (Fig.3). During the spring and summer bacteria were ~50% more abundant at Charles Arm than in the Fortune Harbour farm.

Microzooplankton abundances were variable throughout the study period and abundances in Charles Arm were ~ 5X higher than those observed in Fortune Harbour (Fig. 3).

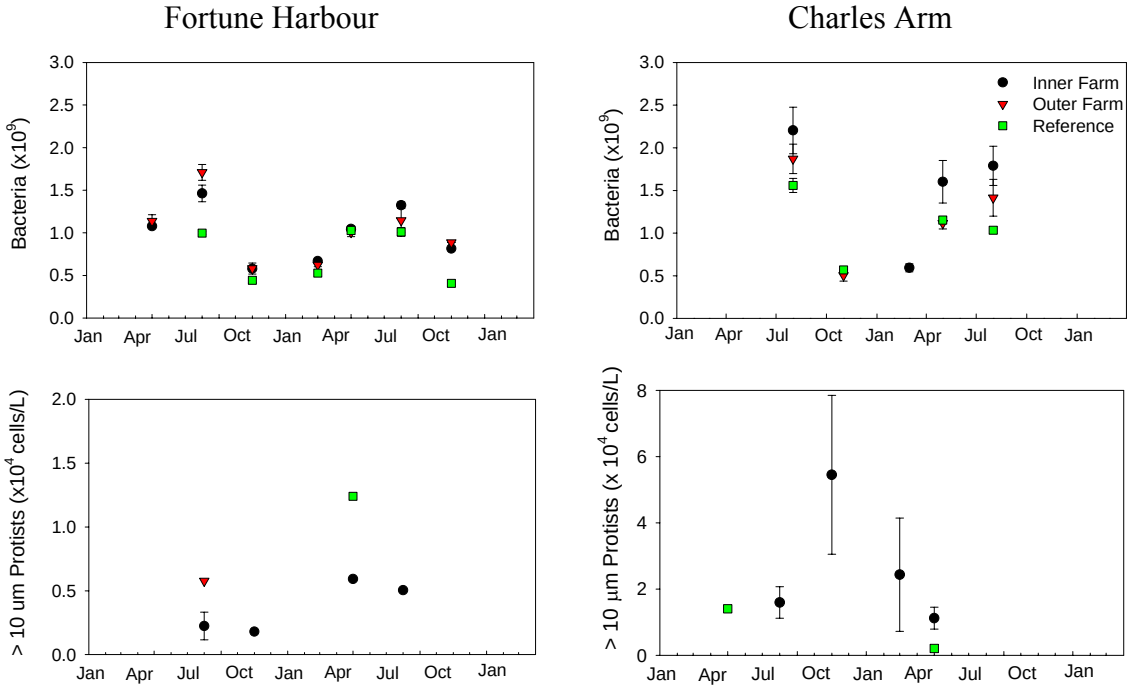

Figure 3. Bacterioplankton (upper panels) and microzooplankton (lower panels) abundances at farm and reference sites. Note the change in scale for the two microzooplankton panels.

Zooplankton

Acartia sp., *Oithona* sp., *Temora* sp. and *Pseudocalanus* sp. dominated the zooplankton community at all sites in Notre Dame Bay in all seasons i.e., Meroplankters were generally rare (Stavey, 2003). In addition to the common species, medusae including *Obelia* sp., and *Aurelia aurita* were present in the size range studied in all sites in August 2001 and July 2002 (and to a lesser extent in November 2001) but these are not included in the study as they were not routinely captured in our net. A small number of *Calanus finmarchic*us were present at the sites in July 2002. Siphonophore cormidia were present in FH in November 2001 and March 2002. CA farm samples contained large centric diatoms and mussel faecal pellets in March, even though most of the sites were ice covered. *Mytilus* veligers were abundant at all sites in July 2002, especially so at the farms.

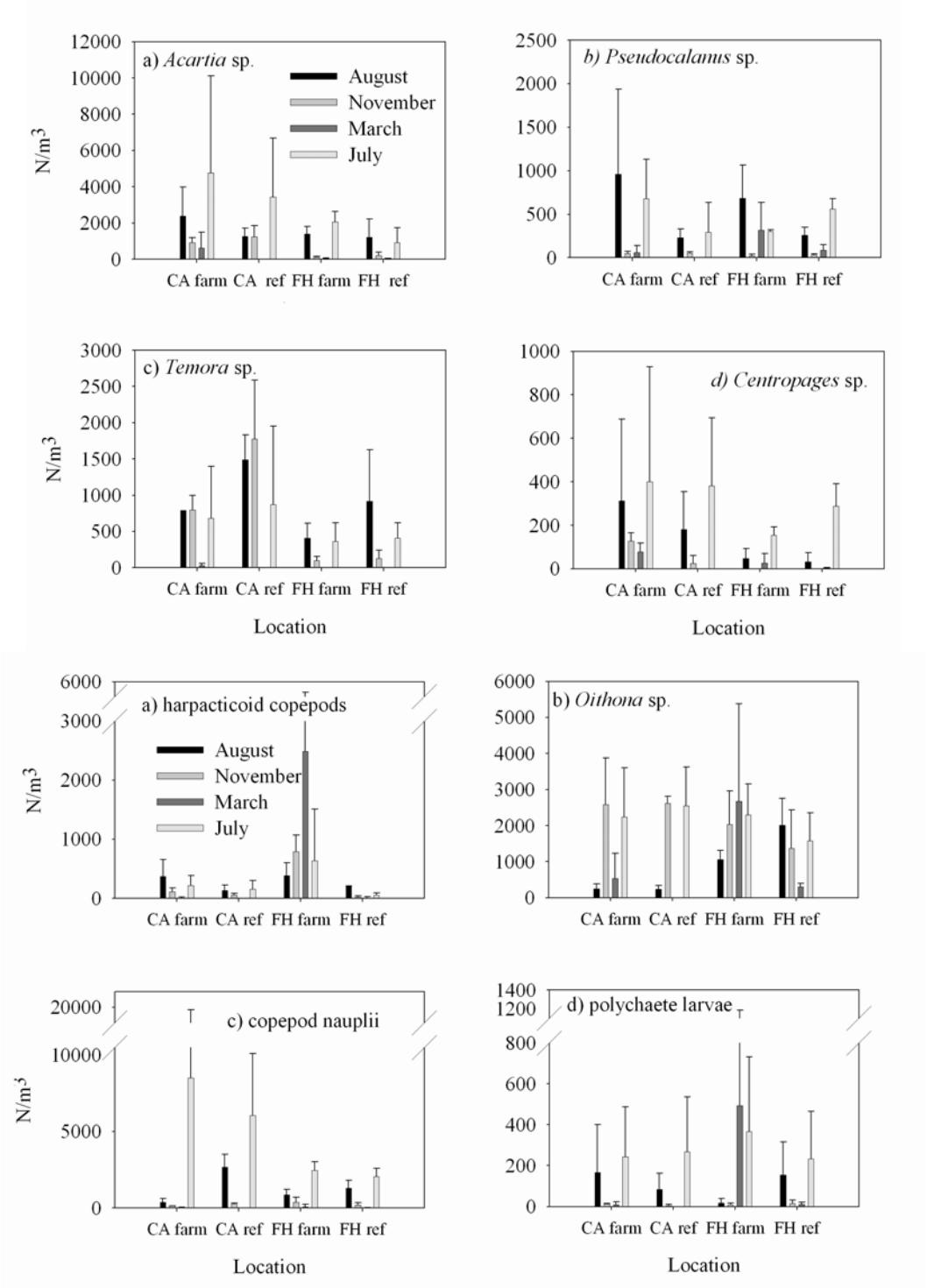

Figure 4. Volumetric abundance of (N/m^3) major calanoid copepods (upper 4 panels) amd major non-calanoid copepod zooplankton (bottom 4 panels) in the four study periods. The error bars represent the mean of three stations per location.

Like many other shallow coastal areas, the zooplankton communities in Notre Dame Bay area are characterized by the predominance of several small species, including *Acartia* sp., *Pseudocalanu*s sp., *Temora* sp. and *Oithona* sp (Fig. 4). While the size distributions and total abundance were not significantly affected by mussel farming, the community composition of the farms differed from their reference sites in some study periods. The abundances of *Pseudocalanus* sp., *Acartia* sp., *Centropages* sp. and harpacticoid copepods were higher at the farms than at the reference sites while the abundances of copepod nauplii, *Oithona* sp. and *Temora* sp. were lower at the farms compared to the reference sites. These differences may be related to direct ingestion of some groups, differences between the food fields of farms and references, or competition with mussels for available food.

Benthic Effects

The farms differed in terms of sediment characteristics and benthic macrofaunal community composition.

Sediment characteristics

Sediments at all sites were hypoxic or anoxic (Edwards 2003). The effect of mussel farming was observed in changes in sediment composition (Fig. 5) and nutrient regeneration rates (Fig. 6). There was no significant difference in redox or sulfides between farms and their reference sites. However, % organic matter (as LOI), total nitrogen, phosphorus and carbon present in the sediments were significantly elevated over the reference sites. Phosphorus was released from sediments under the Fortune Harbour farm but not the Charles Arm farm or at the reference sites (Fig. 6). Sediments from both farm sites released significantly more ammonium than the reference sites.

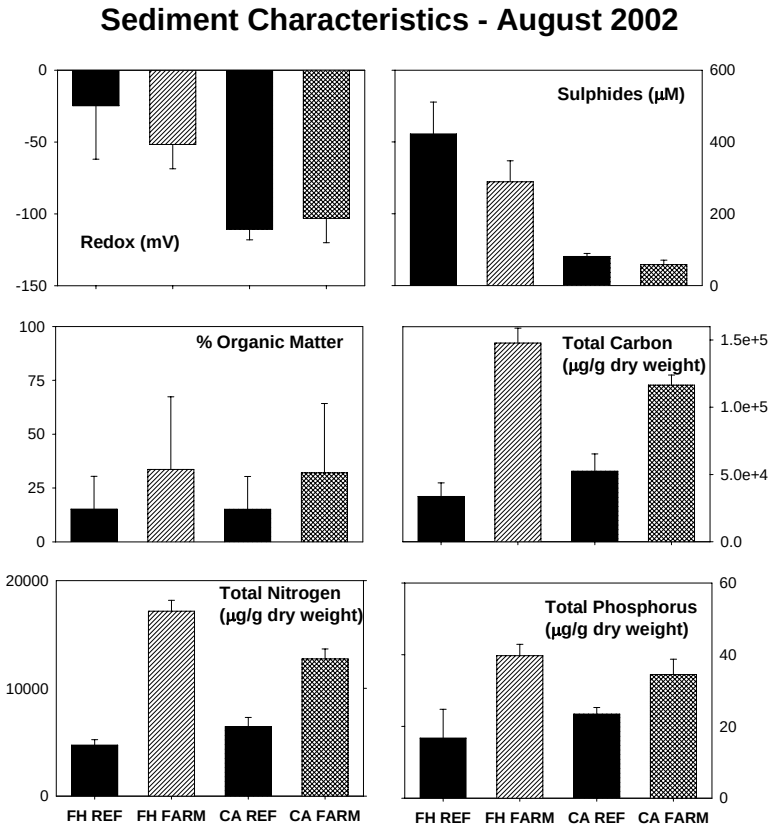

Figure 5. Representative sediment characteristics for farm and reference sites. Error bars represent the standard deviation.

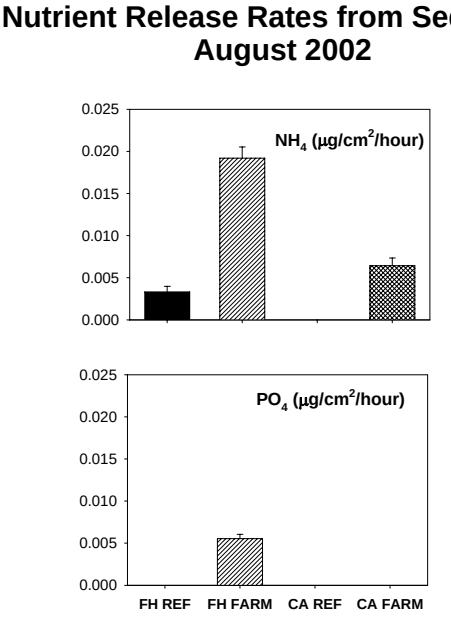

Figure 6. Nutrient fluxes from sediments at farm and reference sites.

Benthic Macrofauna

Benthic macrofaunal communities in sediments with mean grain size larger than 500 µm at both farms showed differences in taxa and abundance relative to reference sites (Ryan 2007). Communities in sediments with mean grain size smaller than 500 µm also differed between farm and reference sites, and all of these stations (farm and reference) had sediments with negative redox values and were dominated by organisms indicative of organic enrichment. Sandy stations in FH and CA are dominated by very low numbers of large polychaetes (relative to those collected at muddy stations) and other smaller invertebrates. Muddy stations, found only in FH, conversely, exhibit some characteristics of organic enrichment. These sediments are dominated by small, opportunistic polychaetes including *Capitella* spp. and *Polydora* spp., which are often used as indicator species for organically polluted sediments (Pearson and Rosenberg, 1978). At least one station in the farm is completely devoid of benthic macrofauna and has sediments with a strong hydrogen sulphide odour, which is not apparent at the CA site.

Distribution of infaunal trophic groups also differed between farm and reference sites (Fig. 7). Farm sites with both course and fine sediments were dominated by deposit feeders while reference sites had more detritus feeders. Fine sediments found only in Fortune Harbour had proportionally more subsurface feeders while courser sediments had more surface feeders.

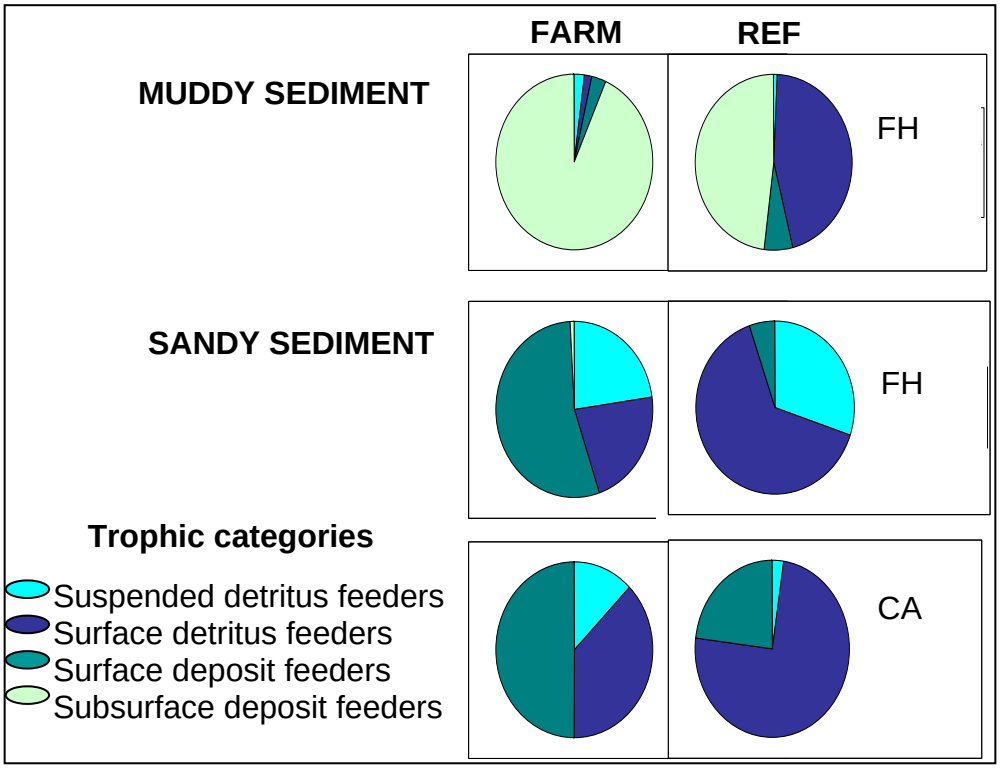

Figure 7. Proportion of total number of macrobenthic species in four feeding groups determined following Nickell (2004) and Maurer et al. (1999).

System Response to Mussel Farms – Influence of Site Specific Characteristics

The presence of a mussel farm in these coastal inlets affected most benthic characteristics and had more limited effects on those of the water column. Intersystem differences did however result in large differences in both planktonic and in farm productivity (Tab. 1). The chlorophyll maximum observed in Charles Arm was twice as high as that in Fortune Harbour and the duration of this period of maximal primary productivity was greatly extended. As a result, primary production at Charles Arm was double that of Fortune Harbour. Bacterioplankton biomass was also enhanced on the farms resulting in microzooplankton biomasses that were 5-fold higher in Charles Arm and usually double those typical of Newfoundland coastal waters. Total macrozooplankton abundance and size distributions were not affected by the farms but individual species abundances differed, influenced by farm related differences in prey fields, refuge availability and/or the presence of predators or competitors.

	Charles Arm	**Fortune Harbour**
Area (km^2)	0.8	1.0
Z max (m)	20	35
Mussel biomass (10^3 kg)	200	150
Production (10^3 kg/yr)	180	375 → 45
Time to market (months)	24	30 - 36
Maximum Chl*a*	~ 2	~ 1
Timing of Chl*a* Max.	July - January	April/May
Primary Prod. (10^6 gC/yr)	14	7.9
NH_4 Flux (µg/cm^2/day)	0.12	0.5
PO_4 Flux (µg/cm^2/day)	Not detected	0.12

Table 1. Characteristics of mussel farms at Charles Arm and Fortune Harbour.

Benthic conditions were also influenced by the presence of the mussel farms. Under farm sediments were enriched in organic matter, total carbon, nitrogen and phosphorus at both farms. C, N and P were slightly higher in Fortune Harbour sediments than in those from Charles Arm. Nitrogen regeneration under farms was significantly increased at both sites while phosphorus regeneration was only observed for sediments under the Fortune Harbour farm. This is a function of the lack of oxygen in the overlying waters of the deeper sites in Fortune Harbour, a condition observed during the second season of our field study and attributed to the lack of renewal of bottom waters in the winter storm season of the previous year. Under such conditions, phosphate would remain mobile and be released into the overlying water rather than becoming immobilized at the oxic sediment interface.

While infaunal abundances were generally low, species distribution and trophic characteristics were also affected by the presence of the farms. Infaunal communities under the farms tended to be dominated by deposit feeders while detritus feeders dominated in the sediments at the reference sites.

Although the two farms were similar in areal extent, stocking density was higher in Charles Arm and annual production was 3-fold greater while time to market was a year shorter.

Bacterioplankton abundances were elevated at both farms likely as a result of excretion and nutrient regeneration by the mussels and water column decomposition f fecal material. Phytoplankton and microzooplankton, the main components of mussel prey fields, were significantly elevated only at the Charles Arm farm. Even though nutrient regeneration from under the Charles Arm farm was significantly lower than in Fortune Harbour, the absence of permanent stratification during the summer in the shallower inlet meant that the regenerated nitrogen was available for planktonic production during the period when nutrient limitation normally restricts productivity. As a result, the duration of elevated phytoplankton biomass was increased by 4-5 months and shifted from the spring to summer and fall.

Conclusions

Our results indicate the potential for significant feedback from mussels to *in situ* planktonic processes which in turn influence mussel production. Site-specific responses indicate however, that bathymetry and stratification play a key role in determining the magnitude of the feedback and hence system productivity.

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