Sustainable Mussel Culture: A Millennial Perspective

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Growth in the past decade in the supply of and demand for high quality mussels has been fueled by improvements in technology and cooperative approaches to solving problems. This has resulted in opportunities for those involved in mussel spat collection, grow-out and processing. However, integration of other users of the coastal zone, such as commercial fishermen, into mussel aquaculture is required before there will be widespread acceptance of such activities. Selection of culture sites that have the characteristics required for seed collection and grow-out are based on local knowledge and an approach that uses knowledge of oceanography and mussel biology. Over the past 15 years, flow modeling has resulted in advancements in site optimization by controlling stocking densities, site selection for new lease areas, and the prediction of impacts and beneficial interactions with benthic and pelagic ecosystems. Detailed knowledge of the behavior of larval and bysally-drifting mussels, the effects of currents and food concentration on mussel pumping behavior, energy flow diagrams of mussel populations, and studies of food supply and demand within suspended and bottom culture systems has aided in the development of new culture technologies and further growth of the industry. An environmental code of practice, continued modeling efforts, and cooperation with respect to technology transfer within the industry and the scientific community should help launch the mussel industry in North America into the next century with continued sustained growth.

Introduction

For any type of aquaculture to be profitable, four key elements are necessary:

1. The right species must be cultured for a given area. In North America, the edible mussels are *Mytilus edulis, Mytilus trossulus* and *Mytilus galloprovincialis.* Using native species provides the advantage of reducing the cost of spat collection.
2. Growers should choose the right farm environment (either shallow or deep coastal waters, or offshore). For *Mytilus edulis*, maximum temperature should be below 20°C to prevent summer mortalities. It is preferable for the site to be protected from exposure to wave action, ice, and predatory sea ducks. High primary production is desirable, as are low amounts of inorganic silt and clay. Currents should be adequate to supply the mussel farm with sufficient food to match consumption rates, but not so high that the currents interfere with feeding or attachment of the mussels to cultivation ropes or socks.
3. Cost-effective culture techniques are important, and range from bottom culture to longline culture and raft culture. Improvements in culture technology (continuous longline systems, specialized vessels, cranes and conveyors) are key to decreasing the cost of production to make the product competitive.
4. Production of high quality product and effective marketing are important to provide the consumer with mussels that have high meat yields, are of a uniform size, have no byssal threads (debyssed mussels) or breakage, and a long shelf life. These qualities will increase the price of cultivated mussels for both the growers and the processors.

Developing a business growing mussels requires a number of skills. Usually the work on the water involves skills that commercial fishermen already have and can apply to mussel farming. The process of growing mussels involves a range of activities, including seed collection, seeding (attaching mussels to ropes or socks), maintenance of the farm (setting moorings, predator control, thinning), and harvesting.

Often, local knowledge about currents, ice, predators, bottom type, wave conditions, navigation, pollution sources, political climate, and local patterns of fishing activity will be important in ensuring the farm succeeds. In addition, those who are practical in orientation will be more likely to succeed as they will come up with clever ideas on how to make processes run more smoothly, how to increase efficiency, and how to reduce labour costs.

A key element in the development of a new industry such as mussel culture in North America is the willingness of growers to share information with each other. When a bottleneck in cultivation is experienced (e.g., harvesting through the ice), some individuals will inevitably find a solution and if the breakthrough is shared with a group of like-minded growers, the whole industry will benefit. This "shellfish exchange mentality" is the key to rapid industry development and is in sharp contrast to the capitalist concept that ideas should be kept secret to gain competitive advantage. The driving force within the industry should be that there is a huge demand for high quality shellfish, so everyone gains when new developments are shared.

Shellfish farmers become stewards of local water quality because they require pristine areas for shellfish cultivation. In Maine, growers have teamed up with volunteer water quality samplers to help maintain the status of shellfish growing waters and identify pollution sources to be remediated. Certified samplers are involved in collecting nearly 50% of the water samples used in classifying growing areas, which reduces the cost to regulatory agencies and results in the opening of new areas for cultivation.

The role of mussel processors is also critical to the development of the industry. Farmers must be given a fair price for their product, and incentives for increasing yield and meat yield will lead to a better product. Processors need to continually strive to increase the shelf life, reduce breakage, and provide a fair weight to consumers. New regulations with respect to HACCP (hazard analysis and critical control points) help to assure shellfish safety and allow the industry to be pro-active with respect to problem areas. The cost of complying with the new regulations, however, must be absorbed by the industry, which reduces profitability.

Financing and business management are very important aspects in developing mussel aquaculture. While venture capitalists may require 20% interest for high risk investments, low interest loans are important for the farmers and processors to be able to make the necessary investments to develop their farms. While this concept is well understood in Canada, it is still a hard sell in the United States.

Site Selection for Seed Collection and Grow-Out

In order to grow more mussels, the industry needs more sites. Good site selection is a major factor in industry development. Site selection depends on the cultivation phase: areas of good seed collection and areas for good grow-out of mussels should be chosen carefully. Our studies in Maine on seed collection[1,2] demonstrate the importance of hydrodynamics on the concentration of mussel larvae and juveniles (up to 1 mm) that drift using a drifting byssal thread. Areas that are good for seed collection and growth and survival of spat to a size which can be attached to ropes or socks (about 10-35 mm shell length) are not necessarily the best places for grow-out of mussels to market size. In addition, areas with high spat densities (> 100 000 per meter) result in slower growth of the seed mussels than areas with moderate densities (i.e., 10 000 per meter). Where currents provide good vertical mixing, spat will attach to lines over 10 m long, but where currents are slow and there is vertical stratification of the water column, spat may be concentrated in the upper 2 to 3 meters.

Selection of good sites for the grow-out of mussels depends on the type of cultivation. For bottom culture, mean current speeds of 15 to 20 cm/s are necessary to support moderate grow-out densities (i.e., 200-400/m^2)[1,3-5] of mussels in Maine. This is because of the reduction in current speeds near the bottom of the benthic boundary layer, and the tendency of water to become depleted of phytoplankton and detritus in the downstream direction over regions of mussel tissue biomass of 1 kg/m^2. For longline culture, lower currents (5 cm/s) are adequate due to the generally large spacing between the longlines. For raft culture, moderate currents (10-15 cm/s) are necessary to prevent depletion of over 50% of the food to the mussels in the inside of the rafts. Current speeds above 25 cm/s may have a negative effect on mussel growth and attachment to lines in suspension culture, while they may be fine for bottom culture, especially in deep water.[6]

Aquaculture structures such as rafts and longlines, and even mussels seed spread on the bottom, also may affect ambient current speed and direction. In the case of bottom culture, mussel beds extending up to 12 cm off the bottom increase bottom roughness and vertical mixing, improving their food supply. In longlines, large arrays may reduce flow through a site. For rafts, increased flows under and around the rafts generate vertical mixing and complex vortices. Understanding these flow effects aid in developing sites for mussel aquaculture. In addition, ambient hydrodynamics play a large role in the carrying capacity and holding capacity of a site (see next section).

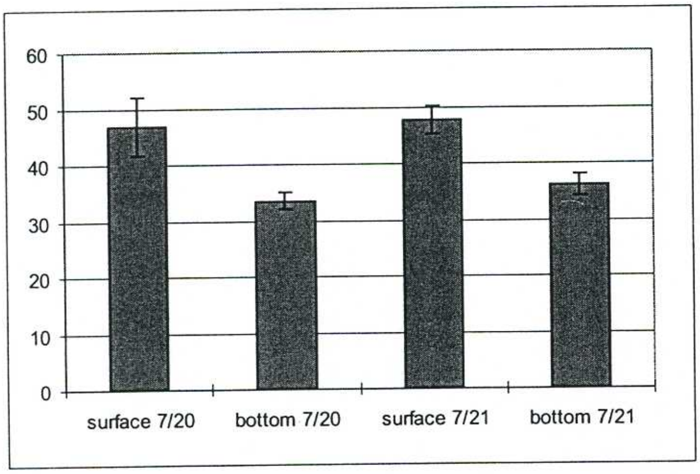


Figure 1. Percent organic seston from surface water and bottom water during marine snow investigations at Roque Island, Maine in a shallow, low current embayment.

Food concentration and quality are also very important aspects of site selection for mussel culture. Studies at our sites in Maine identified over 900 species of phytoplankton, with 95% of the biomass being diatoms. While high levels of chlorophyll a are generally an indicator of a good grow-out site, particulate detritus with a high nitrogen to carbon ratio(4) is also important after seasonal declines in phytoplankton occur. Particulate inorganic matter (PIM) tends to dilute the high quality food for mussels especially in shallow, inshore waters with extensive mudflats. Since mussels have a fixed digestive tract volume, the higher percentage of that volume which is pure phytoplankton, the better the assimilation will be into absorbed organics in the diet. Further offshore in deeper waters, the PIM concentrations decline and food quality of over 90% organic matter in the seston is common. This explains the high meat yields, rapid growth rates and thinner shells of mussels in suspension culture, and points to the possibilities of mussel culture in offshore waters as new technologies are developed.

Recent studies involving researchers from Maine and New Brunswick(7) have also identified a factor that results in slower growth of mussels on the bottom than in suspension culture: *marine snow.* Marine snow is formed, especially in low current areas, when phytoplankton, colloidal carbohydrates, bacteria and inorganic particles stick together in large aggregates, some reaching over 1 cm in length! Our studies showed that these particles form around high tide and settle to the bottom, resulting in a large pulse of particles, mostly composed of PIM, to the bottom. This causes a decrease in food quality for the mussels (Fig. 1,2), and they produce pseudofeces in an attempt to sort the high quality food from the PIM. Nearby in the surface water, mussels suspended from ropes continued to feed at high rates with no pseudofeces. In areas with higher current speeds, vertical mixing supplies mussels with more high quality food and because of the turbulences, marine snow is less likely to form. Therefore, mussels in suspension culture grow better due to higher food quantity and quality.

Holding Capacity

The ICES (International Council for the Exploration of the Sea) working group on the environmental interactions of mariculture (includes fish farms) is a group that meets annually to discuss national production trends, use of chemicals, significant new research results and directions, and development of a program of work related to the ICES Mariculture Committee and Marine Habitat Committee. The working group includes representation from Canada, EU countries, South Africa, and myself from the United States. Originally under the direction of Harald Rosenthal, and more recently Ian Davies of Scotland, the committee discussed the holding capacity of sites (the capability of a particular marine site to

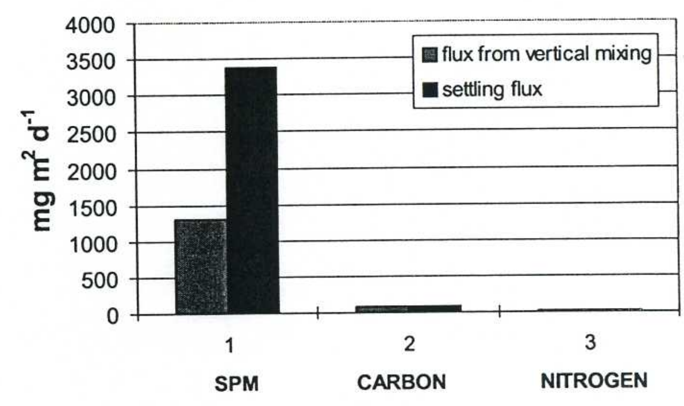


Figure 2. Comparison of the vertical flux of carbon, nitrogen and SPM (suspended particulate matter, mostly inorganic) to the settling flux observed in 24-hour deployments of sediment traps at Roque Island, Maine.

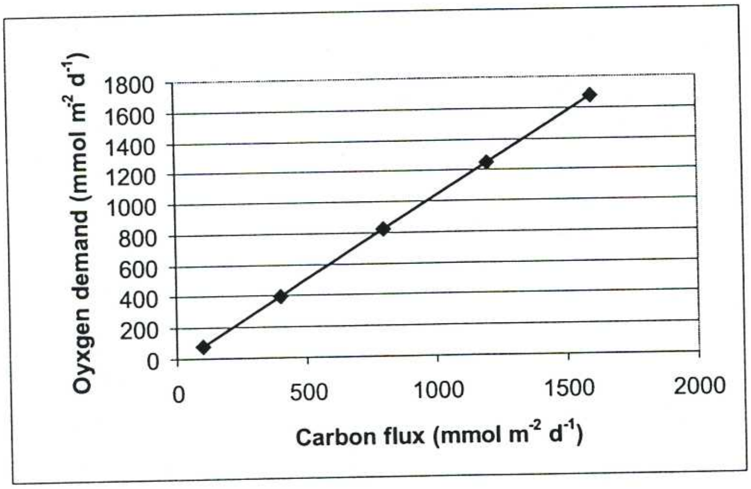


Figure 3. Oxygen demand as a function of organic carbon flux (from Findlay and Watling[7]).

benthic biomass beneath fish and shellfish farms was observed in moderate and strong current areas but lower current sites could be overloaded with sedimenting organic matter. Findlay and Watling[8] plotted the oxygen demand from the bottom as a function of the organic carbon flux from salmon pens, and compared low and high current sites in Maine with respect to their holding capacity (Fig. 3). The oxygen required for the benthic metabolism to match the net carbon sedimentation at a site was a function of current speed, which diffuses oxygen to the bottom. At minimum 2-hour current speeds of over 5 cm/s, they found adequate oxygen flux for the sites they studied (Fig. 4).

grow fish or shellfish without causing undesirable effects). They recently reviewed the current state of development of predictive 2D and 3D mathematical models of fish farming which integrate environmental physics, husbandry practices and environmental interactions of mariculture. The goal was to balance the organic deposition of biodeposits and fish feed with the ability of the benthic ecosystem to accommodate the waste, thereby ensuring sustainability and also maximizing farm productivity. The stimulation of

The enhancement of benthic and pelagic biomass around and underneath finfish and shellfish farms is leading to numerous investigations of aquaculture structures such as artificial reefs. Fouling organisms such as kelp, marine polychaetes, sea urchins and hydroids on mussel ropes attract fish grazers and other organisms. Crabs feeding on mussels falling from the ropes may enhance lobster biomass. Sedimented fish feed from salmon pens can attract fish, crabs, sea urchins and benthic bioturbators. Marine worms become a source of food for flounders. In eastern Maine, anglers from over 100 miles away drive to salmon pen sites for good fishing! Nets and mooring lines can form a substrate for attachment of mussel seed, sea scallops and clams.

Since the assimilative capacity of the benthos is a function of oxygen flux, and oxygen flux is a function of current speed, it is useful to consider flow models as a tool in predicting the holding capacity of different sites. Panchang et. al.[9] and Dudley et al.[10] have used flow models such as DUCHESS, SMS and AWATS to provide 50-m resolution flow models that incorporate particulate waste dispersion, rates of resuspension and ambient hydrodynamics into a useful first order diagnostic tool for predicting the holding capacity of different sites.

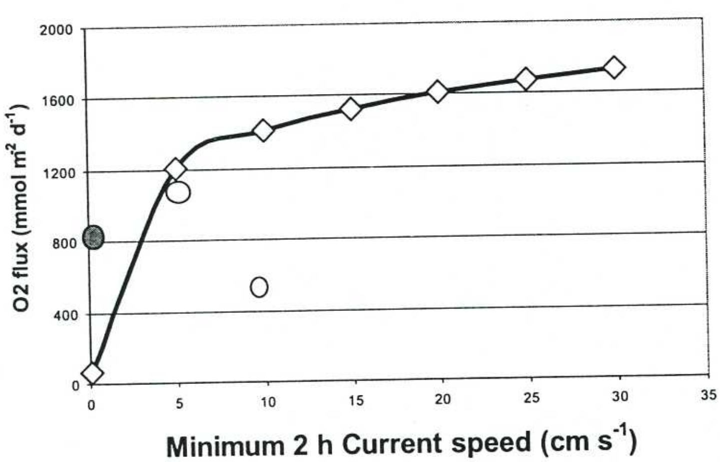


Figure 4. The oxygen required for the benthic metabolism of the net carbon sedimentation as a function of the minimum 2-hour current speed at three sites (from Findlay and Watling[7]). The two white circles to the right of the line were sites that had moderate to strong currents and adequate oxygen flux. The shaded circle to the left (low current site) had inadequate oxygen flux. However, at that site winter wave-induced resuspension and transport off the site resulted in little net carbon sedimentation on an annual basis.[8]

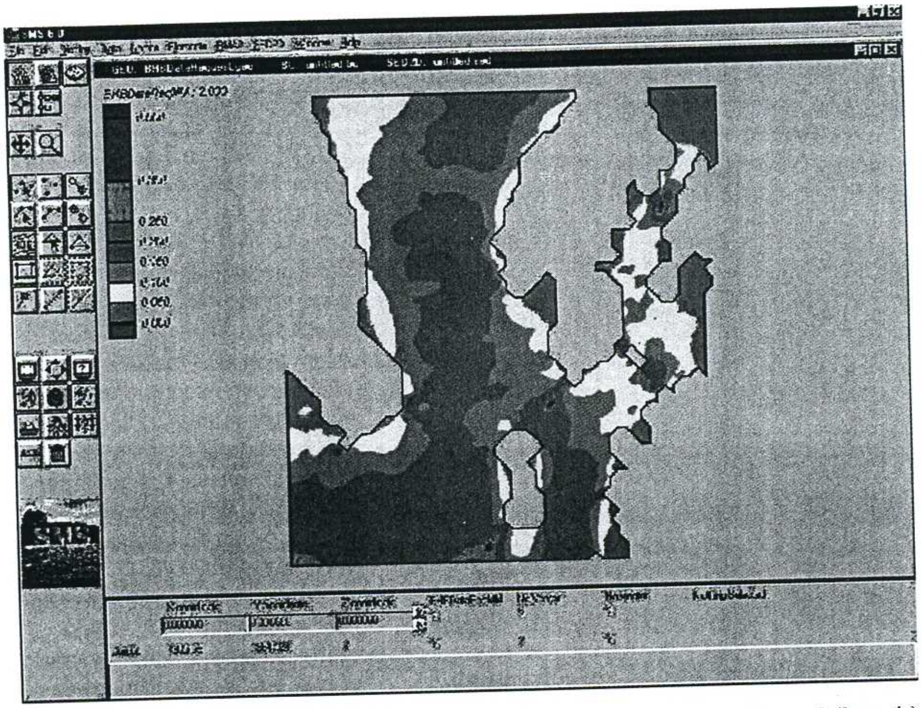


Figure 5. Output of DUCHESS/SMS flow model for mean current speed (in m/s) for a coastal embayment in Maine.[11]

Carrying Capacity

To optimize the harvest yield of market-sized mussels without reducing growth rates at a given site, one can consider the "carrying capacity" of that site. Whether in suspension or on the bottom, at a given time of year mussel biomass may reach a level above which there will be density-dependent growth. Under those circumstances, modelling the relationships among seeding densities, current speeds and food concentration may provide useful results when planning farm management activities. Using the mussel production model MUSMOD,[11] a market-sized mussel of a 4- to 5-gram meat size could be achieved at the Mud Cove site within a year at about 300 mussels/m^2, whereas the same growth rates could be achieved at a density of 600 mussels/m^2 at the Schieffelein site due primarily to higher summer and fall food densities at the latter site.

The carrying capacity of mussel rafts was the subject of a recent study by myself and Dr. John Richardson from

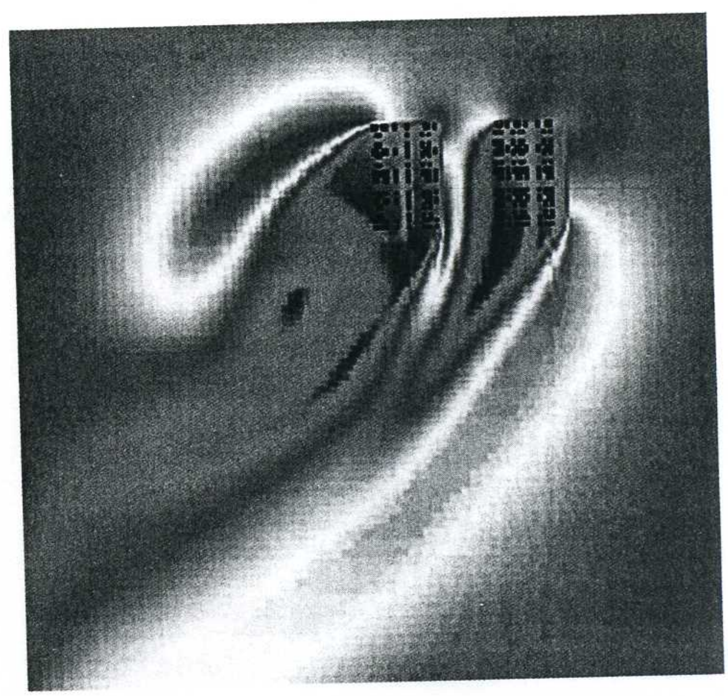


Figure 6. Flow through mussel raft system (colored by speed).

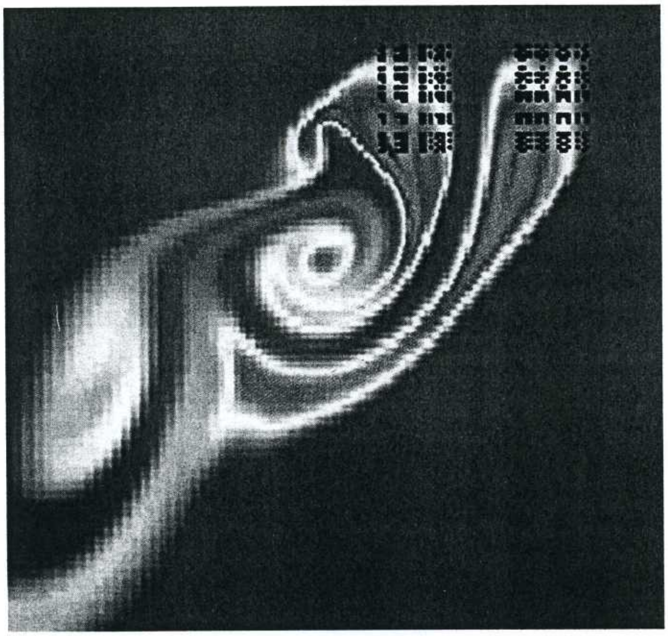


Figure 7. Chlorophyll a (colored by concentration).

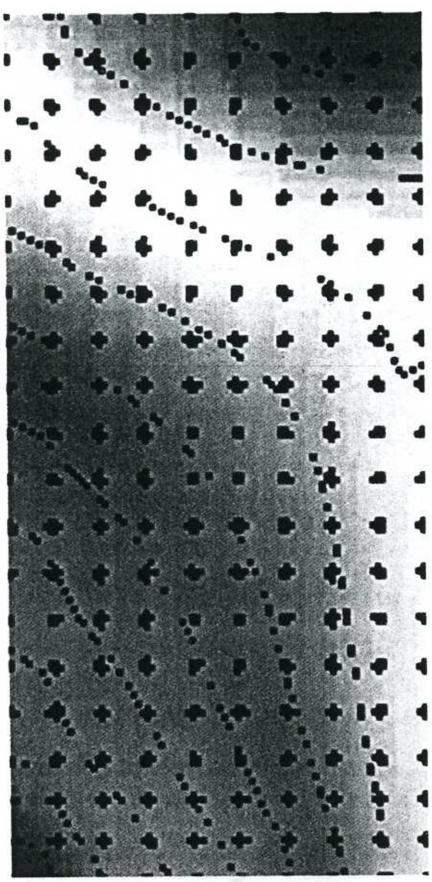


Figure 8. Predicted yield within raft(colored by biomass).

Earth-Tech (Concord, NH) where we investigated the optimization of mussel production through the use of oceanographic and biological models. Using the software FLOW-3D, we utilized 14-m square rafts with 400-500 11-m long droppers for data collection and building the initial 3D flow model. We developed a sampling strategy for current and food particles over horizontal and vertical scales to tune the model with field data. We then provided model simulations to improve raft design and placement at field grow-out sites. Flow fields in the vicinity of the farm were modelled using DUCHESS and SMS.[10] In Figure 5, the light green regions represent areas within the study domain that are suitable for mussel raft culture.

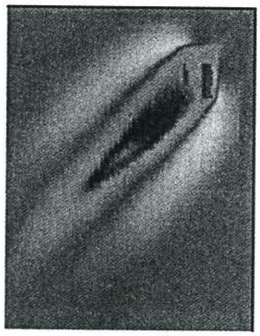
Using data on current velocities, distribution of chlorophyll, POC and PON, we were able to use Flow 3D and estimates of mussel consumption to investigate effects of raft orientation to flow, raft aspect ratio (i.e., 1:1 to 1:4 dimensions), number of ropes and rope diameter, raft size and multiple rafts on the mean flow through each raft and on the food concentration. An example of using FLOW-3D for analyzing current speed is shown in Figure 6, chlorophyll a in Figure 7 and predicted yield in Figure 8.

We were able to investigate quantitative effects of aspects such as the number of ropes and rope diameter in a table comparing mean velocities of the model runs; such data is useful for farmers in managing their lease sites. For example, if ropes are just seeded and 10 cm in diameter, a mean velocity of 6.3 cm/s will be observed through the raft at a density of 500 ropes per raft. However, in order to maintain a flow of over 5 cm/s when the mussel ropes grow to a diameter of 20 cm, they need to be thinned to 300-400 per raft (see below, Fig. 9).

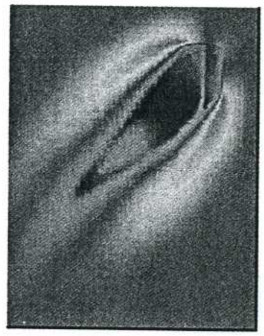
While modelling has its benefits for both investigation of production capacity and for different farm management scenarios, it must be used in concert with field measurements of water velocity and food concentration. Growth data in relation to density within each culture unit and at different locations within the farm site provide valuable data for tuning growth models.

Conclusions

The importance of good husbandry, not only with respect to farm production but also with respect to the environment and other users of the coastal zone has led several areas to develop environmental codes of practice. These will become increasingly important as



300-10cm



400-20cm

500-30cm

Mean Velocity (m/s)

	Rope Diameter (cm)		
# of Ropes	10	20	30
300	0.076	0.055	0.042
400	0.070	0.050	0.037
500	0.063	0.043	0.030

Figure 9. Effects of number of ropes and rope diameter on mean flow through a Maine mussel raft: results using FLOW-3D.[11]

competition for limited coastal water intensifies. Through continuing integration of aquaculture into integrated coastal zone management, and through efforts to create jobs while maintaining environmental sustainability, we will continue to see growth in the industry. With cooperation and technology transfer within industry, research , government and volunteer sectors, we will see continued reduction in labour costs and increased productivity.

A combined oceanographic and biological modelling approach is important in site selection, yield optimization and predicting the environmental interactions of both shellfish and finfish aquaculture. Sites with moderate currents, adequate water depth and good husbandry can result in adequate dispersion of organic particles, aerobic breakdown in the sediments, and actual enhancement of benthic biomass. Continued modelling efforts and cooperation between the US and Canada (COSAD (Coastal Oceanography for Sustainable Aquaculture Development)) and other regions will help in the choice of good sites for the development and proper management of mussel culture sites. Since shellfish act as a natural control of eutrophication in coastal ecosystems, removing nitrogen from the system when they are harvested and through coupled nitrification/denitrification under aerobic conditions in the sediments, we may actually see the encouragement of mussel and other shellfish farms in the coastal zone as a way of improving coastal water quality!

In summary, there are several ways to maintain and increase sustainable mussel culture into the next century, using new tools that can improve efficiency and reduce the need for a "trial and error" approach to aquaculture development.

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