Bulletin

of the
Aquacult... of Canada

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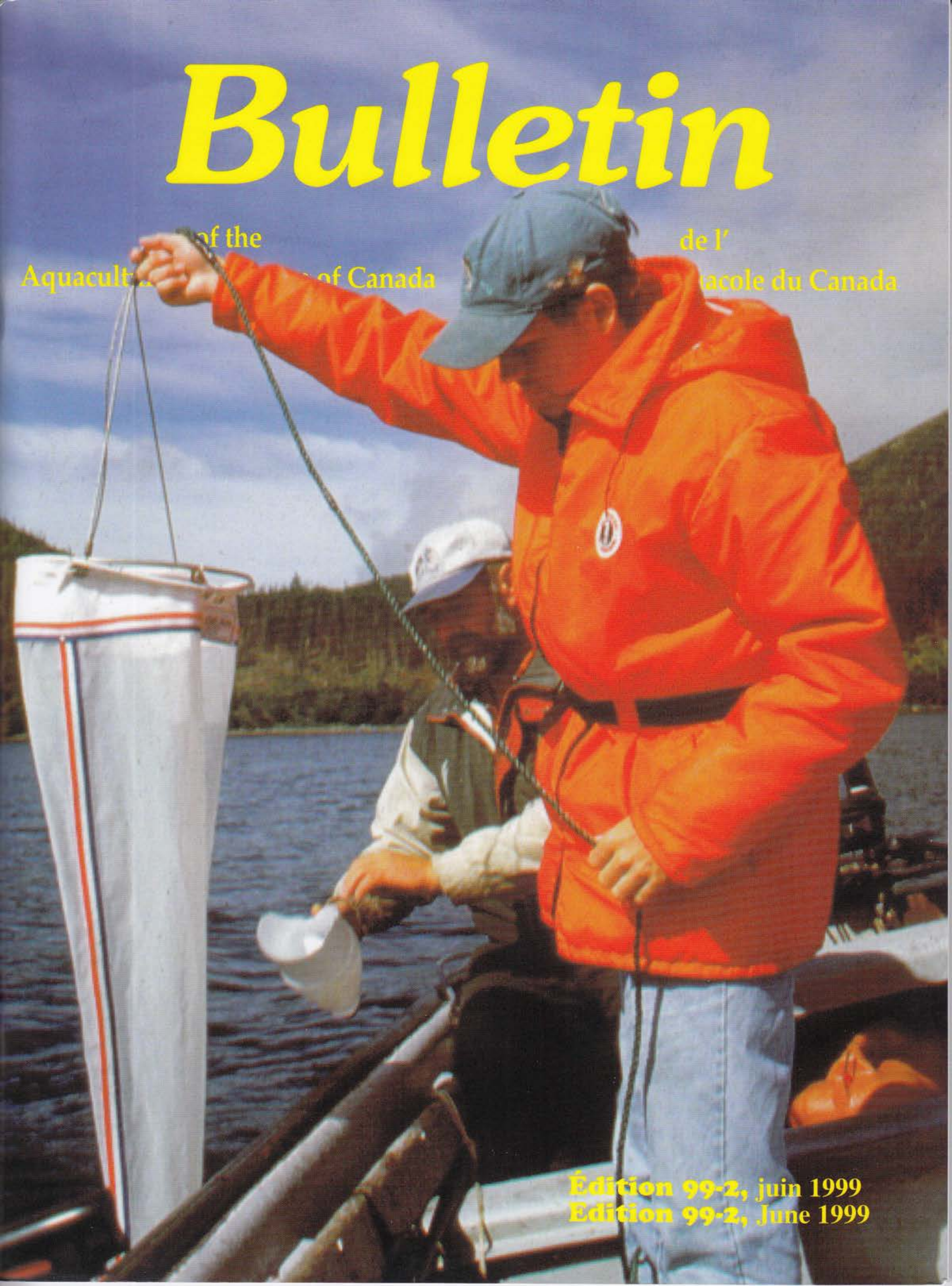

Édition 99-2, juin 1999
Edition 99-2, June 1999

President's Message

Aquaculture Canada, the annual meeting of the Aquaculture Association of Canada is one of the main activities of the association. It provides an opportunity for members — researchers, producers, suppliers, students, educators, government personnel, etc. — to meet, interact and discuss the latest in technology and scientific findings as they relate to aquaculture in Canada. Over the years, the Board of Directors and conference organizing committees have strived to put together a program that offers a diversity of topics, speakers and formats. Recently there have been special invited sessions, contributed papers, technical sessions, suppliers sessions and practical workshops. Topics have focussed on regional/local issues, national issues, and research on existing cultured species and new and upcoming species or technology.

The importance of a strong, diverse, yet topical program is key to a successful meeting in that participants can gain a greater appreciation and understanding of the extent of the industry in Canada.

The annual conference offers students an excellent opportunity to present their research, meet new people, network with potential employers or supervisors and become involved with the association. Student presentations (oral and poster) are often the best prepared and presented of all the talks at the meeting! If students wish to become more involved with the running of the association (i.e., serve on the Board of Directors or on the various AAC committees, etc.), please contact any member of the Board of Directors at the annual meeting to ask how you can become more involved or e-mail me at Jay.Parsons@mi.mun.ca. That is the first small step to helping ensure that the association has a strong future.

Another initiative that the AAC has tried to accomplish at the ***Aquaculture Canada*** conference is to co-host the meeting with regional groups or other aquaculture associations or events where possible. For example, we have previously met with the World Aquaculture Society (WAS), the St. Andrews Aquaculture Fair, the Newfoundland Aquaculture Industry Association (NAIA) and others. Such synergies have been critical in attracting producers and suppliers to the conference and having a well-balanced program consisting of regional and national topics. Any opportunity to combine regional meetings with the national conference provides people with a greater opportunity to attend the joint meeting, cuts down on the number of meetings and saves on travel costs. Joint meetings also help to promote and raise the profile of aquaculture in the different regions and nationally. As well, since its inception the Canadian Aquaculture Industry Alliance (CAIA) has been invited each year to organize a session at ***Aquaculture Canada*** and CAIA holds their annual general meeting in conjunction with this event.

At ***Aquaculture Canada '99*** in Victoria, British Columbia, the AAC will be co-hosting its conference with the Aquaculture Pacific Exchange and Trade Show. By combining an excellent scientific and technical program (spearheaded by AAC Vice-President Linda Hiemstra (Townsend)) with the largest west coast trade show, ***Aquaculture Canada '99*** promises to be another successful AAC meeting! Hope to see you there.

— Jay Parsons

Call for Nominations
Research Award of Excellence

The award recognizes high quality, innovative research that has the potential to have a significant impact on the aquaculture industry in Canada.

Nominations, including a CV and a brief description of the research program, should be sent to Dr. Jay Parsons (jay.parsons@mi.mun.ca).

Bulletin de l'Association aquacole du Canada

Juin 1999 (99-2)

Vous pouvez recevoir le Bulletin en vous y abonnant pour la somme de 40 $ par année ou en devenant membre de l'Association aquacole du Canada (AAC), organisme à but non lucratif. Pour de plus amples renseignements, communiquez avec l'Association aquacole du Canada, 16 Lobster Lane, Saint-Andrews (Nouveau-Brunswick), Canada E5B 1X0; tél.: (506) 529-4766; téléc.: (506) 529-4609; courriél.: aac@mar.dfo-mpo.gc.ca; site Internet: http://www.mi.mun.ca/ mi/aac. La cotisation s'élève à 50 $ par personne (40 $ pour les étudiants et les retraités) et 85 $ pour les sociétés. Le quart de cette cotisation sert à couvrir le prix de l'abonnement au *Bulletin*. Le *Bulletin* est répertorié dans l'Aquatic Sciences and Fisheries Abstracts (ASFA) et le Zoological Record. Envoi de publication – Enregistrement n° 525375. Tout changement d'adresse doit être notifié à l'AAC. En cas de non-livraison, prière de retourner à l'AAC. Port de retour payé.

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Cover: Sean Macneill, a mussel biologist with the Newfoundland Aquaculture Industry Association, deploying a net for assessment of larval stages in the mussel larval/spatfall monitoring program (Cyr Couturier photo).

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Introduction

Molluscan shellfish aquaculture has been practiced for over 2,000 years, and today more than half of the world's production is from aquaculture. Production is expected to increase in the years to come and provide needed socio-economic development in rural areas around the globe. Atlantic Canada alone has experienced increases in production of more than 20% annually since the early 1990s (mussels, oysters, scallops, clams), while at the same time creating important development opportunities for coastal areas.

Most of the production is extensive in nature, relying on natural food production for its long-term sustainability. Because of this, shellfish producers are increasingly aware of the necessity of maintaining environmental and biological integrity of their operations, while realizing some financial success — a bankrupt company cannot employ people! Globally, bivalve aquaculture production is regarded as environmentally sustainable — a "green" coastal activity — and a number of areas have developed voluntary codes of practice for the industry to ensure long term environmental and business sustainability.

One of the questions nagging shellfish producers is how many animals can be produced on an annual or sustainable basis at a site? Determination of carrying capacity — the maximum amount (biomass) of shellfish that can be produced in a given area per unit of time without negatively affecting growth — is needed for business planning purposes and to provide both the producer and investors with some level of comfort regarding the long-term viability of the operation. Carrying capacity is not easy to determine as it varies both seasonally and annually, between areas, and with husbandry methods and species. In the past decade, several models have been developed for predicting carrying capacity of shellfish sites or bays, and each has strengths and weaknesses. The most useful models employ physical information on tides, winds, and currents. However, carrying capacity studies require an immense amount of information to have reasonably good predictive ability, and the information gathering process and experimental work is time consuming and expensive. A full evaluation of a small inlet or bay may cost a million dollars or more, and the results may only be applicable to one particular area. Funding agencies generally lack the vision, and producers do not have the financial means, to support such endeavours. Such studies are clearly needed however and are important for a comprehensive understanding of the processes involved in determining the carrying capacity of shellfish sites.

The idea for an industry workshop on mussel production capacity was conceived over 3 years ago in response to questions from Newfoundland shellfish producers regarding the *carrying capacity* of their sites. The term *production capacity*, borrowed from manufacturing and land-based agriculture practices, is actually more accurate since it incorporates biological components of production, husbandry or business components, and the environmental capacity of the sites. All three components are linked and are essential for the long term viability of bivalve culture. The concept is not new, and one can find examples in Asia where the importance of human practices (husbandry), environmental conditions and biology have long been recognized as interdependent and critical to farming success.

The workshop convened at Aquaculture Canada '98 had three objectives: 1) provide a summary of shellfish production capacity research currently being conducted in Atlantic Canada, 2) provide an overview of mussel husbandry practices and their effects on production capacity, and 3) summarize the information on production performance of various blue mussel species being cultured. This issue of the *Bulletin* contains information on production capacity research, encompassing articles on recent findings on the physical (Page et al., Newell), biological (Robinson et al., Grant), genetic (Myrand et al.) and behavioural (Manuel and Lobsiger) aspects of production capacity. The next issue will contain articles on husbandry and species performance.

I am grateful to workshop speakers for addressing the conference and for submitting articles for these proceedings. Funding for the workshop was provided by the Aquaculture Component of the Canada/Newfoundland Economic Renewal Agreement (ACERA), the Canadian Centre for Fisheries Innovation, the Atlantic Canada Opportunities Agency, and the Marine Institute of Memorial University. The publication of the proceedings was supported generously by a grant from ACERA. Finally, a special thank you to Thomas Landry, DFO Moncton, for coordinating and chairing the session on mussel species performance.

Cyr Couturier, Workshop Convenor
Marine Institute
Memorial University of Newfoundland

Preliminary Models of Seston Depletion and Growth Variation in Cultured Mussels

Jon Grant

The culture of bivalves in coastal waters is dependent on the supply of suspended food sources which become limiting under high culture density. Simulation models have been used to describe the energetics of bivalves in relation to their food supply. Once density is high enough to reduce individual growth rate, the carrying capacity of the environment is exceeded. Models applied to the growth of *Mytilus* spp. in Nova Scotia indicate that seston depletion causes a relatively steep reduction in growth rate. A traditionally used criterion of 50% for seston depletion through culture areas may thus have a severe growth penalty, although there are few field data allowing a test of this prediction. This growth penalty and thus the variance in growth observed in socks or rafts is partially a function of position with respect to flow and seston. A range of model seston depletion up to 50% of ambient seston by filtration results in a coefficient of variation (CV) in meat weight of 46%, in the range observed from field samples. Seed size is also a source of variation in growout. Model simulations using seed of varying sizes (CV = 50%) indicate that the resulting CV in growout size is 23% and suggest that seed variation is less important than culture conditions for production. These studies indicate that carrying capacity expressed as stocking density vs. production must be structured in terms of seston food limitation. In addition, the factors responsible for variation in growth rate and meat weight must be better understood to proceed from trophic carrying capacity models based on an average individual to those based on diverse populations.

Introduction

Bivalve aquaculture is often considered to be food limited due to the high filtration capacity of suspension feeders to deplete the water of particles.(10) The determination of carrying capacity is thus a trophic problem, and dependent on understanding the quality, quantity, and utilization of suspended food sources such as phytoplankton. Because these trophic relationships can be described through models, there has been considerable effort spent on simulating bivalve food intake and growth as a function of food supply and other environmental factors like temperature.(28) Once the growth of a single animal can be represented, a leap is made to the population where denser concentrations of bivalves multiply food consumption until food becomes limiting and growth rate suffers. Carrying capacity may thus be defined as the density at which the growth of individual animals begins to decline. A distinction may be made between carrying capacity as defined above and production capacity which relates to maximal yield, but the difference is largely one of units (biomass versus production), and both values transpire from simulation models.

Ideally, the information from models of individual bivalves would be used to generate plots of stocking density versus bivalve growth,(6) allowing seeding to be optimized for a given site. Although this relationship has been depicted based on empirical data for several culture locations,(23) there are a number of considerations which complicate this approach. For example, in suspended mussel culture, there are several scales of stocking density, including numbers per sock, socks per area of longlines, and number of longlines per lease. The seston depletion that limits growth can occur at any of these scales.(13,27) Similarly, there is temporal food variability which makes the density-growth relationship derived from a model quite site-specific; the model may be adapted to various sites, but its predictions are local. Localized areas of seston depletion will result in variable growth and thus a wider size range in harvested biomass.

In addition to seston depletion, there is inherent size variation and differential growth among individual bivalves. Models often utilize a representative average individual, but as any grower knows, the range in meat size of a given shell length is variable for both spat and adults. The level of variability is particularly evident in shellfish such as scallops that are sold by meat count. This type of variance is caused by both genetic and physiological factors in addition to the food environment.[15,17]

The present paper seeks to explore the nature of mussel growth as a function of food limitation derived from a model of suspended culture of *Mytilus* spp. in coastal Nova Scotia,[11] including the effect of variance in individual size. In addition, measured weight variance in cultured mussels is compared to model estimates as an indicator of model veracity. For brevity, the model is presented as a brief overview of previous work in this field, but new results are generated and discussed with applicability to suspended mussel aquaculture in Atlantic Canada.

A model of mussel growth

As indicated above, the growth of mussels is modelled on the basis of food available in the field, with phytoplankton the primary food source, supplemented by suspended detritus. The uptake and utilization of food by mussels is represented as a bioenergetics model by balancing digestion (absorption) and respiration as scope for growth.[1] The energy budget is configured from published relationships relating feeding and absorption to both the quantity and quality of suspended food. Allometric relationships are used to adjust the energetic rates for body size as the mussels grow. Because *Mytilus* spp. are among the best known marine invertebrates, there is an abundance of published literature available to parameterize the model equations.

The primary study site for model development and testing has been Upper South Cove near Lunenburg, Nova Scotia. The cove is on average 7 m deep and is protected from the open waters of Mahone Bay. Mussels are grown on longlines by Dale Cook of Corkum's Island Mussel Farms. A detailed description of the site including suspended food sources is found in Grant and Bacher[11] and Grant et al.[12]

The model used in the present paper is a simplified "statistical model" described in Grant and Bacher[11] in which there is only one food source which includes both phytoplankton and detritus (suspended particulate organic carbon, POC), and ingestion of this food is described by a single empirical relationship based on laboratory experiments with natural seston.[2] For the present paper, the model has been used to predict mussel weight as a function of seston depletion. Weight is quantified in terms of milligrams of organic carbon of body tissue because the model is carbon-based, assuming that tissue has a carbon content of 40%.

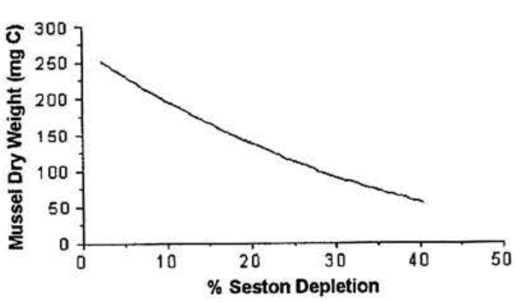

Figure 1. Model output for Upper South Cove, Nova Scotia, relating seston depletion (reduction in particulate organic carbon relative to default) to mussel dry tissue carbon weight achieved during the fall.

The seston-growth relationship

Seston depletion is a well described process in which filtration by suspension feeders regulates the concentration of particles in the water column.[30] The density of suspension feeders thus becomes self-limiting.[6] In order to examine this phenomenon using the model, seston delivered to the mussels was decreased by small percentages to simulate crowding and the resulting reduction in predicted growth was recorded. Growth is quantified as the mussel shell-free carbon weight in October of the first year, a time of peak annual weight. The default level of seston (0% depletion) is based on the normal levels of organic matter recorded in Upper South Cove.[11]

The results of this exercise (Fig. 1) indicate that mussel weight drops off non-linearly with seston depletion such that the cost to mussel growth for even a small amount of seston depletion is significant. For example, a 10% reduction in seston results in a 25% reduction in peak weight. The reduction in size is more severe for initial values of seston depletion; as the mussel becomes food-limited, further seston reduction matters less. Loss of food is expressed as a non-linear decline in body size (Fig. 1) since in the model ingestion is dependent on both weight and food levels as power functions.

The effects of variance in mussel size

The effects of seston depletion (Fig. 1) indicate the extent to which crowding interacts with food to cause variation in mussel growth. However, the simulations are for an average mussel and do not include the effects of variation in seed size and their influence on subsequent growth. To examine this factor, dry tissue weight of juvenile mussels in the model was varied from 20 to 140 mg C dry weight (default = 80 mg; shell length = ~30 mm). This range was chosen to represent ~50% coefficient of variation (CV = SD/mean), corresponding to the range for mussel weight seen in the field for a given shell length. Using model growth, autumn body weight was predicted for each initial seed weight and the CV in tissue weight was calculated.

The results are plotted in Figure 2 and compared to the CV in dry tissue weight for a small range in shell length (53 to 57 mm) based on our previous measurements of mussels collected in the field.[14] CV of dry weight in field mussels is seasonally dependent with higher values in summer and fall due to varying reproductive condition. The CV predicted by the model results (varying seed weight) for the fall is only 23%, less than any of the seasonally observed values. The model does not include reproduction for year 1 mussels, so it is expected that fall CV in the model is lower than observed values. However, fall model CV is only half of that observed even in winter and spring, indicating that size variation of seeded mussels is not the sole cause of size variation in adults. In comparison, the CV of mussel weight for growth predicted in Figure 1 is similar to the observed CV for non--reproductive periods, i.e. a range of 0 to 40% seston depletion results in a CV of meat weight of 46% (Fig. 2).

Concluding remarks

Seston depletion is a commonly observed, though poorly quantified, aspect of suspended bivalve culture. Reduction of phytoplankton and other particles by suspension feeders has been documented in laboratory experiments, and flume tunnel and other measurements in the field.[4] In dense raft culture of mussels, there is observed seston depletion through the raft, as well as growth reduction of mussels in the center or on the downstream end.[16,20,24] It seems inevitable that as bivalves feed on a particulate field, there will be a reduction in the food, unless the renewal (e.g. by tides) is greater than the depletion through filtration. Increased flow will thus ameliorate seston depletion, leading to an observed relationship between flow and bivalve growth. This process has been formalized as a seston depletion index (SDI), by relating the % seston reduction to filtration capacity relative to water turnover.[30] These authors provide comprehensive application of the seston depletion index to benthic bivalves.

A major question relative to carrying capacity is how much seston reduction is acceptable. In carbon budget calculations such as those done by Carver and Mallet,[3] carrying capacity was defined as the stocking density at which there was 50% seston depletion. The relationship shown in Figure 1 suggests that even small reductions in food supplies have a significant effect on mussel growth. The present work seeks to extend these observations by making a link between growth and seston depletion from a modeling standpoint, specifically addressing the nature of the falloff in growth with reduced food. This is clearly only a first step, since a more desirable relationship is between stocking density and growth reduction as we have done in previous work,[5] a surprisingly rare output of carrying capacity models. Further development of the models discussed herein will include this population aspect.

It would be ideal to groundtruth the predictions in Figure 1 using field data on growth. There are a variety of studies which have attempted to relate seston depletion to growth, mostly for bottom mussels[7] or infaunal bivalves.[26] The role of mussel reefs in processing organic matter has received extensive attention.[4] There are, however, relatively few studies of suspended culture which attempt to relate seston depletion and growth rate. In most cases, change in shell length has been used as a measure of growth.[8,20] Unfortunately, shell growth is often unrelated to tissue growth;[18] in studies of mussels grown on rafts in Spain, growth in wet weight showed a much larger response to position on the raft than did shell growth.[9] Perez Comacho et al.[25] demonstrated a 40% reduction in wet weight resulting from a 40% reduction in phytoplankton availability (chlorophyll scaled to current speed and rope density) when comparing several sites in Galicia. Assuming that reduction in chlorophyll through rafts was twice that of POC,[24] and that wet weight can be compared to dry weight as a biomass measure, a 20% reduction in POC would produce the 40% reduction in weight, in agreement with the prediction in Figure 1. As individuals are sheltered from flow at sock or longline scales, growth will suffer compared to animals exposed to ambient flow and

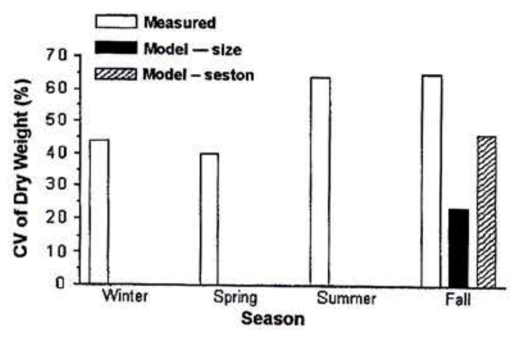

Figure 2. Coefficient of variation (CV = SD/mean) of mussel dry tissue weight for animals of similar shell height (53 to 57 mm, n = 45), compared to modelled CV based on seed stock with initial CV = 50% (Model – size, n = 21) and modelled CV based on the range in weight resulting from a range in seston depletion from 0 to 40% (Model – seston, n = 18) (see Figure 1).

food. This will clearly lead to variance in mussel size, as has been described for natural aggregations of *Mytilus*.[22]

Most considerations of carrying capacity consider a stocked biomass of similar individuals, whereas variation in actual meat weight is substantial, partially due to the variability in food availability as discussed above (Fig. 2). The simulations examining variation in initial body weight indicate that seed size affects adult weight simply because the early detriment in size is not made up during the annual growth trajectory. Empirical studies have also related growth rate to initial size.[29] The seasonal change in weight variation (Fig. 2) underscores the additional importance of reproductive condition to body weight. It is apparent that initial size, food limitation, and reproduction can account for the variance in mussel meat weight observed in field animals (Fig. 2).

It is also known that the source of seed leads to variance in size and growth rate, partially due to inclusion of both *Mytilus trossulus* and *M. edulis* [19] but also due to physiological differences in stocks.[17] Studies of scope for growth among individuals in various parts of the raft indicate that reduced feeding rates (even at equivalent food levels) of interior mussels leads to reduced growth rate.[21] Recent studies by Hawkins and Day[15] show that variance in growth also arises from the efficiency of protein metabolism. It is clear that environmental variance in models will be imparted via seston, temperature and other factors, but work by Hawkins and Day[15] and Navarro et al.[21] suggest that variance in physiological components is also needed to represent bivalve populations through models. Although the present set of simulations can adequately describe suspended mussel culture, it usually represents an average individual. The economics of mussel farming depend on large numbers of individuals seeded from a diverse set, and cultured under various conditions of food and flow. Further understanding of the impact of both genetic and environmental factors on growth, and their incorporation into models of growth and its variability, will strengthen management capability and optimization of farming practices. This is particularly important in Atlantic Canada where new sites are still being exploited and potential for shellfish production is unknown.

T his work was supported by the Natural Sciences and Engineering Research Council of Canada.

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What did We Learn about Summer Mortality of Suspension-cultured Mussels in the Magdalen Islands, Québec?

B. Myrand, R. Tremblay, J.-M. Sévigny,
H. Guderley, and J.H. Himmelman

In the past, suspension-cultured mussels from the Magdalen Islands were often decimated by summer mortality. In some years, up to 80% of 2-year-old mussels were lost in August. Transfers of local stocks to various sites showed that the Amherst Basin (AB) stock is more resistant to summer mortality than other stocks and the results suggest that mortalities are related more to genetic factors rather than to environmental ones. The genetic characterization of the stocks showed that the resistant AB mussels are significantly more heterozygous than those from the House Harbour (HH) and Great Entry (GE) lagoons. In contrast to the AB stock, the HH and the GE stocks show significant deficiencies in heterozygotes. These genetic characteristics translate into metabolic differences as heterozygosity is negatively correlated with metabolic needs (maintenance metabolism). Further, more homozygous individuals have a lower survival (LT_{50}) than more heterozygous individuals in various stressful conditions. Therefore, the resistance of the AB mussels may be explained by their lower metabolic needs during critical periods of the summer, particularly in August, because they can rely on higher energetic reserves for reproduction, growth, and resistance to stress. Conversely, stocks with higher metabolic needs are more prone to summer mortality because they have lower reserves. Reproduction is a stressful event because it uses energy that would otherwise be available for other functions. According to the Life Cycle Theory, reproduction may lead to survival reproductive costs, especially under stressful conditions. Summer mortality was observed only when a complete spawning in late June to early August coincided with summer seawater temperatures of 20°C or higher. It seems that susceptible stocks pay survival reproductive costs under stressful temperatures because of their higher metabolic needs. In contrast, the lower metabolism of the AB mussels may leave enough energy to enable them to cope with these conditions (high fecundity in stressful conditions). Now, all mussel growers from the Magdalen Islands use spat collected in Amherst Basin. We are confident that our understanding of summer mortality in the Magdalen Islands and the use of the resistant stock from Amherst Basin will prevent summer mortalities in the future.

Introduction

Since the first attempts to develop blue mussel culture in the Magdalen Islands in 1973, mussels were occasionally decimated by summer mortalities. These mortalities always occurred in August during the warmest period of the year and sometimes up to 80% of the 2-year-old commercial-sized (> 50 mm) mussels were lost.[(1)]

A solution was needed to minimize such losses, otherwise the survival of the mussel industry in the Magdalen Islands was at risk. We carried out a large study between 1989 and 1997 but, except for a small event in 1997, no summer mortalities occurred after 1991. Therefore, we had to attempt to understand summer mortalities when most of the time no summer mortalities occurred. The paper summarizes the main results of the study.

Differential susceptibility of stocks

In 1989, spat from different local stocks were transferred to various sites for a 2-year-period (Fig. 1).[2] At the end of the experiment, there were no significant differences in survival among sites. This was not surprising given the overall similarity of the environmental conditions prevailing in the Magdalen Islands (~65 km long). In contrast, significant differences in survival were observed among stocks. The overall survival of mussels from the Great Entry lagoon was only 11%. It was not much better for those taken from the Bay of Pleasance (13%) and the House Harbour lagoon (22%). However, 82% of the mussels from Amherst Basin survived throughout the experiment. Thus, it seemed that mortalities were basically related to genetic rather than to environmental factors.

Genetic characteristics of the stocks

We examined the genetic characteristics of mussels from Amherst Basin (AB), the House Harbour lagoon (HH) and the Great Entry lagoon (GE).[3] We found that the differential susceptibility of the stocks was not related to variable mixtures of *Mytilus edulis* and *M. trossulus*. Mussel populations of the Magdalen Islands were largely dominated by *M. edulis* as only about 3.5% of the individuals were assigned to *M. trossulus* in each lagoon according to MPI marker. Apparent gene flow ($N_e m = 86$) was high between the lagoons and mussels of the Magdalen Islands form a panmictic population with similar allelic frequencies in all populations. The main difference was observed in the heterozygosity of the stocks. An individual is said to be heterozygous at a given locus (position on a chromosome of a gene coding for a given protein) when it exhibits two slightly different forms of that gene. In contrast, an individual is homozygous at a given locus when it has only one form. By extension, a stock is more heterozygous than another when the individuals are, on average, more heterozygous when compared at the same loci. The degree of heterozygosity measured at 7 different loci for the resistant Amherst Basin mussels (3.37 ± 0.10 heterozygous loci) was significantly higher than for the House Harbour (2.36 ± 0.11) and the Great Entry (2.21 ± 0.10) mussels. Further, the susceptible stocks from House Harbour and Great Entry lagoons showed important heterozygote deficiencies as their observed heterozygosities, *Ho*, were 0.34 and 0.32 compared to the values, *He*, expected under the Hardy-Weinberg equilibrium: 0.52 and 0.53, respectively. In contrast, the observed heterozygosity of the Amherst Basin mussels (0. 50) was in the range of the expected value (0.56).

Heterozygosity vs. metabolism

The observed differences in the heterozygosity of the stocks may have important consequences because we observed a highly significant inverse relationship between the degree of heterozygosity of an individual

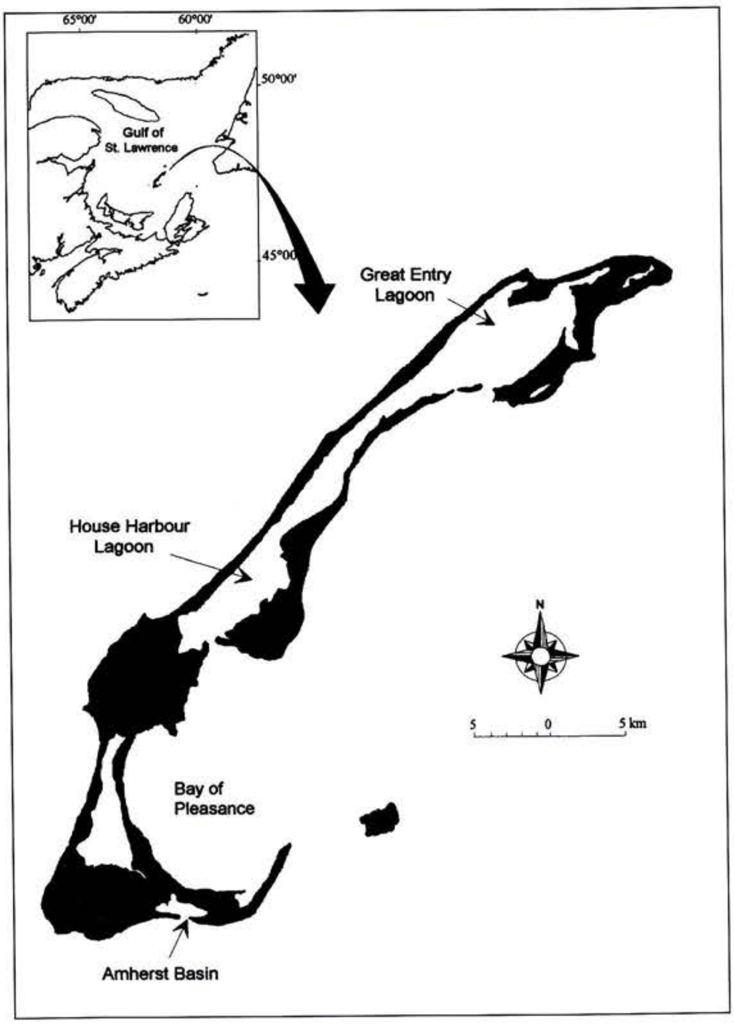

Figure 1. The Magdalen Islands.

and its maintenance metabolism (energy needed to fulfill its vital functions). This relationship was observed at 5 loci in 1993 and 1994 for the two stocks with the most different susceptibilities to summer mortality: resistant Amherst Basin mussels and susceptible Great Entry mussels.[4] We observed the same trend for both stocks held in suspension-culture for either 1 or 2 years. Thus, more heterozygous individuals need less energy for their vital functions. These observations at the individual level were found also at the population level. Indeed, the Amherst Basin mussels which are, on average, more heterozygous than the Great Entry mussels have, on average, a lower maintenance metabolism. Furthermore, a greater proportion of the maximal metabolism in the GE mussels was devoted to maintenance metabolism during mid-August. This may have a negative impact upon their survival as they needed a greater proportion of their energetic demand to fulfill their vital needs during this period.

Additional series of measurements were obtained in August 1997 for the AB and HH mussels. This time, each individual was examined at 7 rather than at 5 loci. Again, a clear inverse relationship between the degree of heterozygosity of an individual and its maintenance metabolism was found for these two stocks. The resistant AB stock had a significantly higher degree of heterozygosity than the susceptible HH stock (4.00 ± 0.18 vs 2.43 ± 0.19 heterozygous loci) and a significantly lower maintenance metabolism (0.52 ± 0.03 vs 1.16 ± 0.04 mL $O_2 \cdot ind^{-1} \cdot h^{-1}$).[5]

The lower maintenance metabolism of the AB mussels probably provides them with an energetic advantage over the more susceptible mussels from the HH and GE stocks. Once their vital needs had been fulfilled, the surplus of available energy may be used for other functions like growth, reproduction and resistance to stress (and thus eventually for survival).

Performance of two stocks with different susceptibilities to summer mortality

We examined the performance of the two stocks (AB and GE) that had the greatest difference in susceptibility to summer mortality under identical environmental conditions to test the hypothesis that the AB mussels have an energetic advantage over the susceptible GE stock.

We observed no difference between the stocks in shell growth rate over a 2-year period (1993-1994) under field conditions.[6] This finding was not surprising as shell growth has not been clearly related to heterozygosity in the literature.[7] However, we did observe a greater production of tissues in the AB mussels during this period. The net increase in the dry mass of tissues was estimated to be 1.55 g for the GE mussels compared to 1.82 g for the AB mussels — a 17.4 % difference in favour of the AB mussels.[6]

Fecundity of both stocks was also estimated under field conditions during this period.[6] In both years, the mean fecundity of the AB mussels was higher. In 1993, it was estimated that the 1-year-old AB mussels released approximately 33% more eggs than the GE mussels (2.8 vs. 2.1 million eggs). In 1994, the AB mussels spawned approximately 7.9 million eggs compared to 5.5 million eggs for the GE mussels — a difference of 44%.

Thermal sensitivity was examined during the summer of 1992.[8] Maintenance metabolism was measured once a month at temperatures ranging from 5° to 25°C and Q_{10} values were calculated. This parameter can be described by an example: for instance, a Q_{10} value of 2 indicates that maintenance metabolism doubles with an increase in seawater temperature of 10°C degrees. So, the higher the Q_{10}, the greater is the corresponding increase in maintenance metabolism. The thermal sensitivity of both stocks was usually similar, except in August. During this period, the GE mussels showed a significantly higher thermal sensitivity than the AB mussels with Q_{10} values over the 20 to 25°C range of 2.46 ± 0.13 vs 2.10 ± 0.12, respectively. Interestingly, water temperature usually reaches 20 to 21°C for some days during August in the lagoons. Further, the GE mussels showed some difficulty in acclimating their metabolism to this temperature as suggested by the significant increase of their maintenance metabolism in August. Therefore, the combination of these two factors both occurring in August — an increase in the maintenance metabolism and a higher thermal sensitivity — may help to explain the greater susceptibility of the GE mussels to summer mortality when water temperature peaks.

The oxygen:nitrogen ratio and the Scope for Growth were also measured.[4] The O:N ratio is measured from the oxygen used for respiration and the excreted nitrogen. A small ratio indicates that mussels must be getting their energy from proteins rather than from glycogen, their usual main energetic reserve. Thus, an O:N ratio lower than 25 is considered to be indicative of difficult times for mussels. Again, in August, the GE mussels appeared to be in a more stressful situation as their O:N ratios were smaller than the AB mussels and also lower than 25. So, they had to rely more on proteins for their energy. The Scope for Growth is an estimate of the energy available for production once the energy lost through respiration and excretion is subtracted from what was assimilated. In August, the Scope for Growth was negative for Great Entry mussels, indicating that they could not invest energy into production but instead had to use their reserves to satisfy their energetic needs. So, the GE mussels had greater difficulties than the more resistant AB stock, at least during August, even though they faced identical environmental conditions. However, it must be stressed that the years (1993-1994) when most of the measurements were done could be considered as favourable for mussels since no summer mortality occurred. But even under relatively favourable conditions, important differences were observed.

In the absence of " reliable" summer mortalities, we exposed mussels to artificial stress until mortality reached 50% (LT_{50}) in the stocks. Mussels were exposed to prolonged air exposure on a weekly basis between early June and late September 1994, and the survival time of the GE mussels was systematically shorter than that of the AB mussels.[6] In 1997, we examined the survival of mussels facing two different types of stress: an anaerobic stress (prolonged air exposure) and an aerobic stress (mussels maintained in oxygenated filtered seawater at about 27°C with no food added).[5] This time, we compared the susceptible HH mussels to the AB mussels in two replicates conducted in August. We obtained the same results in the two replicates, and the HH mussels had a lower survival in both types of stressful conditions. We had an additional and unexpected stressful condition in 1997 as some mortality occurred in the lagoon among the extra mussels left in pearl-nets during the laboratory experiments. The HH mussels suffered a 40% mortality compared to less than 1% for the AB mussels. The degree of heterozygosity of the mussels that survived the various stressful conditions in 1997 was measured and compared to that of the initial populations used for each experiment. The HH mussels had a lower degree of heterozygosity than the AB mussels at the onset of both replicates. Further, the HH survivors were consistently more heterozygous than the corresponding initial population. In contrast, no such selection favouring the survivorship of more heterozygous individuals could be seen among Amherst Basin mussels. We don't yet have a clear explanation for that.

So, it seems that the susceptibility of mussel stocks to summer mortality is at least partly related to their high maintenance metabolism, particularly in August when water temperature reaches stressful levels. In addition, food quality seems to decrease during this period as suggested, for example, by the reduced proportion of organic matter in the seston and the reduced assimilation efficiency of food by mussels.[4,10] Available food could possibly not satisfy the metabolic needs during this period of high energetic demand. The impact of a higher metabolism on susceptibility to summer mortality is also suggested from the lower survival in stressful conditions of those HH mussels with a lower heterozygosity and a higher maintenance metabolism. In contrast, it seems that the maintenance metabolism of the AB mussels may be low enough to bring them through difficult or stressful conditions. If so, then the next question should be —How to explain the irregularity of summer mortality in susceptible stocks?

Summer mortality: A reproductive cost?

According to the Life Cycle Theory, an individual cannot maximize investments in all its metabolic functions (maintenance, growth, and reproduction) when resources are limited.[11] Trade-offs are needed so that, for example, a higher investment in reproduction should leave less energy for maintenance or growth. If a trade-off between reproduction and maintenance results in lower survival, it is called a "survival reproductive cost". Such costs are known to be amplified in stressful conditions because maintenance metabolism requires more energy to adapt to these conditions. Consequently, reproductive costs vary according to the environmental conditions. Clearly, this concept offers an attractive explanation to the irregular occurrence of summer mortality in the susceptible stocks.

We followed reproduction and survival of mussels from the susceptible GE stock in the lagoon and at sea between 1991 and 1993.[10] Summer mortality occurred only in 1991 among the mussels left in the lagoon. It began in early August with the end of a major spawning event when water temperature reached the stressful level of 20°C. At the end of this spawning, all gametes had been released so that the energetic reserves were probably exhausted. This spawning just preceded a stressful period of high temperature and a possible decrease in food quality. In contrast, the mussels at sea had no major spawnings in late July 1991 and showed no summer mortality. All spawnings except one (when summer mortality occurred in the lagoon in 1991) resulted in partial releases of gametes followed by some resorption of the unspawned gametes. We observed no summer mortality after these partial spawnings even though water temperature sometimes reached stressful levels. Resorption of gametes probably provided the extra energy needed to cope with difficult conditions.

We could not get evidence as strong as we would have liked because summer mortality occurred only once during our study. But our observations suggest that summer mortality of the susceptible stocks is a survival reproductive cost paid in stressful conditions after reserves had been depleted by a complete spawning.

Conclusion

Our understanding of the summer mortality phenomenon in the Magdalen Islands is as follows. First, there are resistant and susceptible stocks to summer mortality. Mussels from the more resistant stock are characterized by a higher heterozygosity which is correlated with a lower maintenance metabolism. Thus, the surplus of available energy is probably enough to cope with stressful conditions.

Mussels from the more susceptible stocks have a lower heterozygosity which is related to a higher maintenance metabolism. Less energy is available for other functions, so that trade-offs between maintenance, growth, and reproduction are amplified. Further, these trade-offs are higher under stressful conditions when maintenance needs extra energy. Summer mortality of the susceptible stocks seems to occur only under stressful conditions when maintenance needs extra energy but reserves have been depleted by a complete release of gametes. If so, it could be considered as a survival reproductive cost.

Since 1993, spat collection for mussel culture in the Magdalen Islands has been limited to Amherst Basin in order to ensure the collection of young mussels that are more resistant to summer mortality. Then, sleeves are transferred to the House Harbour and Great Entry lagoons for further grow-out. We are confident that this practical solution is also a reliable solution to summer mortality in the Magdalen Islands.

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Oceanographic Component of the Canadian Department of Fisheries and Oceans Science Strategic Research Program Project for Coastal Oceanography for Sustainable Aquaculture Development (COSAD)

F. Page, D. Greenberg, G. Bugden, R. Losier, J. Shore, E. Horne, S. Robinson, B. Chang, and T. Sephton

The overall rationale and objectives of a multi-disciplinary project aimed at enhancing understanding of the physical and biological processes controlling shellfish and finfish aquaculture production is described. The project is called Coastal Oceanography for Sustainable Aquaculture Development (COSAD). It is an initiative supported by Strategic Science Funding from the Canadian Department of Fisheries and Oceans. Although the project has elements pertaining to both shellfish and finfish aquaculture, only the oceanographic effort that relates to shellfish production is discussed in this article.

Introduction

In 1996 a gathering of scientific authorities in the field of coastal oceanography and aquaculture development was convened to discuss the needs for oceanography in relation to aquaculture carrying and holding capacity issues. The group concluded that the top priorities included: increase knowledge of coastal circulation patterns, develop circulation models in key areas of aquaculture production, develop an understanding of what and how much shellfish eat, identify site selection criteria, and estimate carrying/holding capacity.

As a result of the meeting, the Coastal Oceanography for Sustainable Aquaculture Development (COSAD) project was conceived and planned as a 3- to 4-year, interdisciplinary, multi-divisional, and multi-institutional project. The overall objective was to develop indices of shellfish and finfish production capacity that could be used in site selection and carrying/holding capacity considerations. In order to achieve this objective new information would need to be gathered and analyzed and new models developed. The new information would concern: shellfish feeding behaviors and needs; finfish energetic needs; temporal and spatial patterns of water circulation, hydrography and suspended shellfish food; and information generated from new circulation models. The project concept was generally supported by each of the Maritime Provinces and the aquaculture industry through the DFO Atlantic Zone Aquaculture Science Committee.

The largest concentration of shellfish growers in Atlantic Canada is in Prince Edward Island (PEI). The annual value of the PEI mussel industry alone is approximately $25 million dollars. A high proportion of the island's coastal embayments are being used for mussel cultivation and attention is beginning to be paid to the fact that space is becoming limited and production may be nearing capacity in some areas. Hence, growers and governments are interested in learning more about the oceanographic conditions influencing the production efficiencies and limits of the mussel industry. For example, although production differences within a bay may be recognized by the industry, the reasons for these differences are not well understood. This uncertainty is leading to speculations concerning the capacity of some grow-out sites to withstand subsequent development. In addition, environmental groups are beginning to become interested in examining the environmental consequences of mussel aquaculture. Despite these uncertainties, the success of the mussel growing industry in PEI is encouraging efforts to develop the potential for shellfish culture in other areas of Atlantic Canada and these are becoming more frequent and ambitious.

This article describes the overall vision and scope of the COSAD project and then focuses on the oceanographic aspects that are of relevance to the shellfish component of the project. The article concludes with a brief status report on the project. A companion article discusses the biological portion of COSAD.[1]

A general overview

From a relatively simple point of view the potential for shellfish production can be considered to be controlled by the balance between the demand and supply of food. Demand is influenced by shellfish abundance, density, location, behavior, and other factors. Food supply is function of time and location and is influenced by factors such as water circulation, hydrography, and local and non-local production. The oceanographic aspect of COSAD helps to address the spatial and temporal variation in the supply of food.

In order to best develop an understanding of shellfish production, the COSAD project proposed to compare and contrast conditions in different mussel growing areas that represented a range of environments in which mussels grow and could potentially be cultured. The areas included the shallow inlet-type situation, typical of the mussel growing areas in PEI, and the tidally-energetic areas typical of the Bay of Fundy. The specific locations selected for study included Tracadie Bay and Murray River in PEI, the Quoddy Region of southwestern New Brunswick, and the Annapolis Basin in Nova Scotia. Information from other areas within Atlantic Canada would be acquired by maintaining communications with alternatively-funded initiatives.

Within each of these areas, microscale process-oriented field and laboratory studies, development of circulation models, description/mapping of currents and hydrographic conditions, definition and mapping of potential shellfish food indicators, and production modeling studies would be undertaken to one degree or another. A major theme of these efforts is to study a range of temporal and spatial scales. Hence, some process studies are focused on the individual mussel or mussel socks (microscale) and are aimed at enhancing the existing understanding of the physical and biological processes and feeding behaviors underlying the feeding dynamics of the blue mussel. Farm scale surveys will help describe the variation within a farm and help address the impact of farms on the circulation and food content of the water passing through them. Bay-wide studies (mesoscale and macroscale) will provide information on the spatial and temporal variability of the environment at larger spatial scales so the smaller scale studies can be placed in a broader context. Circulation modeling studies will provide estimates of the 3-dimensional water circulation within target areas which can be used to estimate exchanges of water and shellfish food, among other things, between and within farms. Other modeling efforts will more explicitly link the oceanography to mussel production. Together the studies will determine key environmental parameters and indices of site suitability and production potential that would ultimately contribute to estimates of carrying and holding capacity. These will in turn contribute to advice concerning aquaculture siting and production limits.

Some oceanographic specifics

The specific aim of the oceanographic microscale effort is to study the temporal availability and flux of potential shellfish food in close proximity to mussels whose feeding behavior is being monitored. Hence, water velocities, fluorescence and optical backscatter, and local winds will be continuously monitored at sites for time periods of about two weeks. Turbulence measurements may also be taken.

The aim of the farm- to bay-scale (mesoscale) oceanographic effort is to describe (map) the spatial and temporal (tidal and seasonal) variation in water velocities, temperature, salinity, plankton (chlorophyll/fluorescence, zooplankton/particle size), and light transmission of the target area so that the mesoscale variation in these aspects can be determined and the microscale process measurements can be interpreted in the context of, and extrapolated to, the larger bay-wide scale. The effort will involve field observations and modeling components.

The field approach will be to conduct transects within and between farm sites and to repeat these several times over a tidal period and over several seasons. The transects will be conducted using a vessel-mounted, vertically-profiling acoustic current meter and a hull fixed or towed instrument package including an optical plankton recorder, a conductivity, temperature and depth (CTD) probe with a fluorometer and optical backscatter sensor. The measurements will cover spatial scales ranging from within farms (10 m), to between farms (100 m) and across bays (1000 m). The measurements will contribute to our understanding of the patterns of flows and suspended materials within farms, influence of upstream sites/cages/mussel lines on downstream sites, exchange of water and food between sites, identification of potentially suitable farm sites, and background knowledge necessary for estimating carrying capacity.

The circulation modeling studies will focus on the development of 3-dimensional circulation models (macroscale). In support of this effort, current meters and temperature and salinity recorders will be deployed at strategic locations within the study areas to monitor flows through the major channels and in the major areas of interest. Meteorological conditions will be monitored at a shore-based station in the vicinity of the study area. The model will estimate tidal and residual flows, and will emphasize forcing by tides and winds. The model output will be used to estimate flushing rates, tidal excursions, exchanges between locations and flux rates of suspended material between selected areas.

The physical-biological linkage models will use the above oceanographic data and circulation models in conjunction with mussel feeding models and aspects of the biological component of the project to examine the balance between the supply and demand of the potential mussel food.

Progress to date

In 1996/97 very limited funds were received and some essential equipment was purchased. In 1997/98 additional funding was received and additional equipment was purchased and field trips were made to the major study areas to obtain initial impressions of the areas and some preliminary data to aid in more detailed planning. In 1998/99 the major field and modeling activity was to begin and in 1999/2000 the work would be narrowed down to more completely address the most promising avenues. Unfortunately, as of the time of this presentation, the indicated funding for the 1998/99 fiscal year of the COSAD project is much less than the amount requested. Hence, large portions of the project have been eliminated. With respect to the oceanographic effort, some needed equipment cannot be purchased, the seasonal aspects of the studies have been dropped and the number of study locations has been reduced to two. The remaining sites are Tracadie Bay in Prince Edward Island and the Passamaquoddy Bay area of southwestern New Brunswick. In these areas, and at this time, it is hoped that much of the mesoscale oceanographic work that was originally envisioned for the summer period will be undertaken. Unfortunately, the funding shortfall resulted in the elimination of most of the biological aspects of the COSAD program[1] and because of this the microscale initiative has been reduced to a single trial effort at one location in Tracadie Bay. Hopefully, results from the efforts remaining will be presented at subsequent Aquaculture Association of Canada meetings. Unfortunately, it will not be possible for the work to develop the desired linkages between the oceanography and shellfish production.

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Carrying Capacity Research in the Nearshore Environment: Planned Shellfish Work for the Canadian Department of Fisheries and Oceans Science Strategic Research Program on Coastal Oceanography for Sustainable Aquaculture Development (COSAD)

S.M.C. Robinson, D.J. Wildish, F.H. Page, T. Landry and T.W. Sephton

The traditional development of an aquaculture industry begins with basic questions such as 1) will the target species survive and grow well enough for the industry to be economically viable in the proposed location, 2) what conditions represent the best site characteristics, 3) what is the capacity of cultured production from an area and can this be predicted prior to development, and 4) what type of biological and physical interactions will occur on the farm sites. Although these questions are all important, the amount of work done on the first question is generally far greater than that done on the subsequent questions, despite the financial and social costs associated with over-capacity. The goal of COSAD is to develop a practical method for industry and management to assess the potential production capacity of an area by studying a range of environments and determining the common elements that drive production in culture systems. Tracadie Bay on Prince Edward Island and Passamaquoddy Bay in the Bay of Fundy were chosen as the two study sites because they exhibit a wide range of environmental conditions. The evaluation of the suitability of these sites for aquaculture production will be derived from continuous and detailed measurements on the feeding behaviour of the shellfish (initially mussels) coupled with measurements of water quality parameters. These measurements, once they are confirmed in the laboratory, will hopefully provide an index of suitable food conditions as well as indications on threshold values that can be scaled to provide accurate assessments on how much food the cultured animals remove from the water. The data will be linked to the measured biochemical and somatic growth rates of the animals. Once an understanding is gained at the level of the organism (microscale), the observations will be linked to the physical oceanographic portion of the study looking at circulation and flows at both the farm- and bay-wide spatial scales.

Introduction

A number of realities are structuring the development of the coastal zone for the production of food. The first is that the demand for marine foods is increasing at a time when landings of traditionally harvested fish are levelling off. Combined catches for all fish from Europe and North America appear to have peaked at about 15 million tonnes [(2)] (Fig. 1). If this demand for food and marine products is to be met, there is a need to supplement the wild harvest as well as to produce new products for non-traditional markets (i.e., seafood products unique to Asian cuisine). Secondly, there is an intensive search for new opportunities to support coastal communities. In many coastal areas, the fishing industry is not providing enough wealth to maintain the existing infrastructure, particularly in this time of spending reductions by governments.[(3)] Alternate employment in other primary sectors is often not viable and the opportunities for youth are few. Because of the existing infrastructure (i.e., boats and gear) and marine experience within the coastal communities, aquaculture is viewed as a viable alternative to fishing.

In 1996, a proposal was submitted to the Canadian Department of Fisheries and Oceans Science Strategic Research Program in response to their call for research on critical issues in the marine environment. The projects had to be large scale and multi-disciplinary, and have multi-regional implications. This strategic research program was designed to put teams of scientists together to work collectively on large projects that normal government research budgets could not address. The following is an overview of part of a project devised to investigate the physical-biological linkages in relation to the development of both finfish and shellfish aquaculture. The project was called *Coastal Oceanography for Sustainable Aquaculture Development (COSAD)* and was accepted for funding in the program. This article will review the shellfish biological portion of the study. Another article in this issue outlines the physical oceanographic segment. [1]

Background and rationale

It is our prediction that the focus in the marine environment for the next decade will be on the physical and biological processes associated with the near-shore coastal environment and how human activity will be influenced and shaped by these processes. As the pressure of human habitation and intervention increases in the coastal zone, there will be increasing competition for usage of the resources and the conflicts between traditional and new users will grow in both occurrence and intensity. Many of these conflicts are evidenced by the difficulties that aquaculturists have finding suitable sites for their operations and include conflicts with traditional fisheries, concern from environmentalists on habitat degradation, and objections from owners of waterfront properties.

Today, when an aquaculture operation is initiated, there is generally a hierarchy of questions that an operation will go through in a sequential pattern:

1. Will the desired organisms survive and grow well enough to be economically viable in the chosen area, usually near the farmer's place of residence?
2. Which of the available sites within a particular geographic area should be selected for the farm?
3. How many animals can be physically grown on the site?
4. What sort of interactions with the other organisms or the environment will be encountered during the farming operation?

This is a natural evolution of an industry, but there can be major problems associated with this individual approach compared with group development. The first problem is the amount of information required to make a decision at each succeeding question increases and the likelihood that the information is available decreases. The result of this paucity of data generates a risk-taking mentality where the underlying assumption is that the natural environmental system in which the farm will be operating will be able to

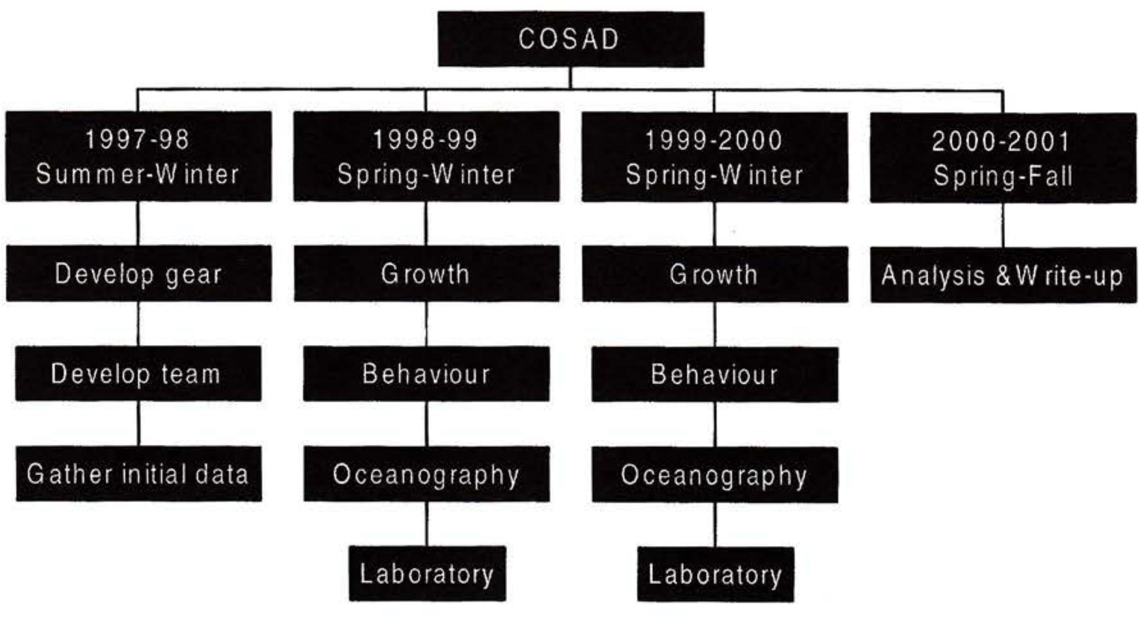

Figure 1. Landings (mt) of all fish harvested in North America and Europe from 1961 to 1995. Data are from the United Nations Food and Agricultural Organization statistical on-line database.[2]

absorb any impacts the farming operation may cause and that the effects will be localised.

Another problem is that there is a cumulative effect of the decisions taken. Without knowing what the final working conditions will be, each decision affects the previous one so that it is usually quite difficult and expensive to reverse the decisions made to that point. For example, if an industry grows in an exponential-type of developmental pattern and finally runs into problems with habitat deterioration, lowered productivity and disease problems related to stress, who will volunteer to cut the size of their operation or bow out of the industry for the good of the whole? The newest entrants are those with the least amount of equity in their sites and the largest debt-load. This situation can create significant management and political pressure. The only solution to this type of issue is to have a realistic expectation of how large the potential industry can be in an area prior to the intensive development and then to decide how to manage and allocate the existing resource. If there is some feeling for the potential size of an operation, then decisions can be made on how many operations can be contained within an area or whether some other species should be examined if there is a better economic return to be had.

Shellfish are typical of organisms that are tightly and directly linked to the aquatic environment with respect to their life-history processes. Sessile animals such as oysters, mussels or clams rely on currents to bring them food, remove their wastes, provide oxygen for their metabolism, communicate with their conspecifics for synchrony of spawning, and to distribute their reproductive products. Obviously, any changes to the water quality characteristics would have an immediate effect on this group of animals. Because of the direct linkage between shellfish and the environment, we decided to focus on this group of organisms first.

Concepts in the program's theoretical framework

The idea of carrying capacity originally dealt with the asymptotic population growth of organisms and was modelled mathematically with the logistic curve. The concept of a resource that grows exponentially and then later slows down until it eventually stops due to feed-back mechanisms has been an attractive model for many applications. Carrying-capacity terminology has been used to describe activities such as fish and shrimp ponds, fishing operations, human habitation, effluent disposal, stocking of cod in Norwegian fjords, and oyster production. Each of these examples reference carrying capacity in a slightly different manner. Attempts at developing basic carrying-capacity models for shellfish (particularly mussels) have been attempted in the Maritimes.[4,5] For aquaculture and the purpose of this study, we choose to define carrying capacity as the maximum biomass of animals per unit volume that optimises the production of the culture operation in a defined area on a long-term continuing basis.

In an exhaustive study done in New Zealand on the dynamics of an intertidal sandflat, one conclusion reached was that it was important to understand how the various spatial observations and measurements were linked from the small scale to the large scale.[6] By understanding how observations on the environment made at the organism level (microscale) relate to similar observations at the farm scale (mesoscale) and then the bay scale (macroscale), we can then better extrapolate when we calculate the carrying capacity of the bay. Without this level of understanding on issues such as the transport of material and food throughout the bay, the variability in the accuracy of the predictions can only increase. Understanding the implications of the physical transport was one of the key limitations in a related study on carrying capacity for oysters in Marennes-Oleron Bay in France.[7]

If we are to understand how farm-environment relationships work, then detailed measurements will have to be made with high temporal resolution — a feature notably absent from most historical data sets available on environmental variables. This almost certainly necessitates the use of data-logging instruments, as it is almost impossible to deploy personnel in the field to sample at the required rates. This conclusion has a couple of implications. First, we are limited to the suite of machines that are available for data-logging and secondly, there will be a high initial capital cost and ongoing maintenance expenses. Once the basic mechanisms that are driving the system are understood, index variables can hopefully be derived which can result in more efficient and effective sampling. An example of an index is growth (either in length or weight), often used as a standard measure. Although this is a good index of how the farm may be performing, without knowing the factors that affect growth and their mode of action, it becomes difficult to address problems if growth begins to decline abnormally. Therefore, one of the goals in COSAD is to understand what the animals perceive as good and possibly "bad" food conditions and to relate this to increase in growth.

To achieve this, we will use another integrative measure. Just as growth combines many different elements (anabolism, catabolism, stress, reproductive state, etc.) into a single measure, we plan to use behaviour as an integrator. As the animal responds to the various environmental factors, this should be reflected in the initial feeding behaviour of the animal. Studies have shown that the exhalent siphon opening is proportional to the filtering rate[8] and hence feeding rate. Because bivalves have pseudofaecal rejection mechanisms, not all of the seston filtered is necessarily eaten and thus it is important to keep track of the proportion rejected. This will be important information in the upward scaling process as we extrapolate from:

1) feeding observations,
2) definition of food,
3) the rate of removal by a known biomass,
4) the mesoscale mapping of food resources, and
5) the movement of these food patches by mathematical circulation models.

Objectives

The goal of COSAD is to study a range of environments and determine the common elements that drive the production in culture systems in order to develop a practical method for industry and management to assess the potential production capacity of an area. The objectives of the shellfish biology component of COSAD for the 1998 and 1999 seasons were:

- Develop a system to monitor the feeding behaviour of shellfish (initially mussels);
- Correlate the behaviour of feeding with concurrent environmental conditions and the biological production performance of the animals;
- Compare the behavioural responses in the field with controlled conditions in the laboratory flume;
- Determine the various feeding thresholds so that environmental measurements can be scaled to biological production;
- Link the microscale (individual mussel) feeding data based on the behavioural work to the mesoscale (farm) conditions measured in the physical component of COSAD;
- Compare the results with other models on carrying capacity and production.

Methods

We chose to address the objectives in three linked modules: mussel production, shellfish feeding and shellfish feeding calibrations in the laboratory.

Mussel production

The purpose is to track the gross growth performance of the mussels at the various sites throughout the two bays to document spatial differences and the consistency of growth trajectories throughout the year. Spatial differences will also be documented within a site to assess the possibility of shadow effects (i.e., food limitation) within a farm. Growth will be assessed using shell dimensions, wet weight, dry weight, ash free dry weight and possibly biochemical indices (RNA/DNA ratios).

Shellfish feeding

A time-lapse video recorder will be used to capture images from a submersible colour camera every 0.7 seconds of mussels feeding *in situ*. Viewing the area

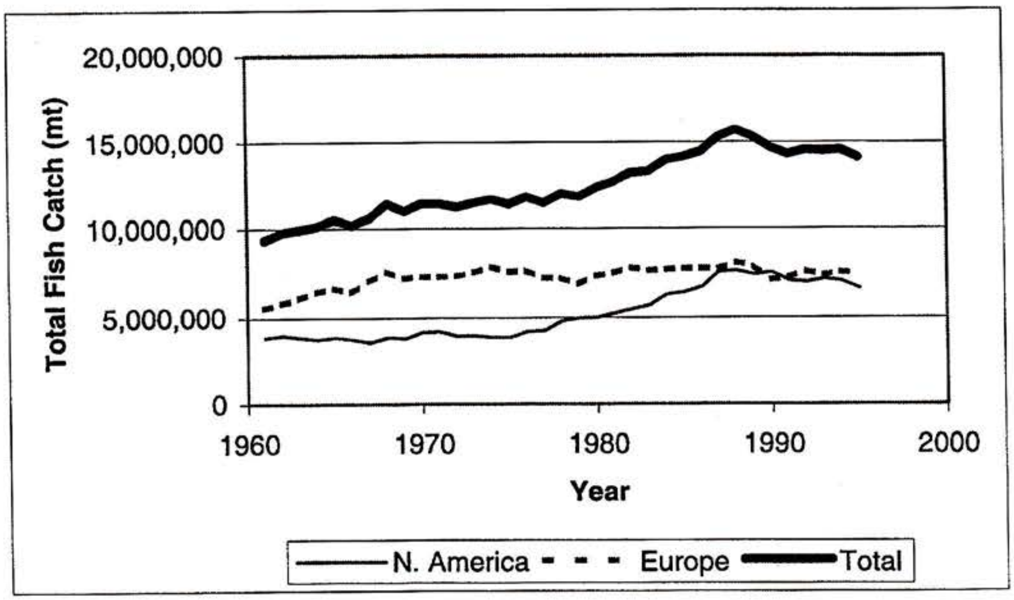

Figure 2. Research timetable for the biological portion of the COSAD Project.

of the exhalant siphon will assess the filtration rate. The entire video system is portable, runs on 12 V batteries and is housed in a raft that can be deployed at any location desired. Two duplicate systems will be used to record two separate sites simultaneously. Concurrent with the video observations, continuous oceanographic environmental data (temperature, salinity, oxygen, optical backscatter, flocs, chlorophyll, current speed and light) will be recorded with data logging instruments hung from the raft. These systems will be deployed for 3-week durations at set periods throughout the year at both study sites. The recorded video tapes will be analysed automatically using Optimas™ image analysis software. The resulting data will be analysed using time-series techniques.

Shellfish feeding calibrations in the laboratory

In order to verify the observations made in the field and to refine estimates of the threshold levels of feeding we will undertake experiments in the flume laboratory at the St. Andrews Biological Station. Some of the experiments planned are: test of day vs night feeding, defining sestonic food quality to mussels, and confirming the relationship between filtration rate and the area of the exhalant siphon. Several calibration studies are also planned to ensure the samples taken in the field are analysed properly. The research schedule for these activities is shown in Figure 2.

Study sites

During the initial planning of the project, 7 sites were considered for inclusion in this study: two on Prince Edward Island (Tracadie Bay and Murray River), three in Nova Scotia (the Bras d'or Lakes, Country Harbour and the Annapolis Basin), one in New Brunswick (Passamaquoddy Bay) and one in Newfoundland (Cape d'Espoir). However, due to budgetary restrictions, only two sites were chosen, Passamaquoddy Bay and Tracadie Bay, and these were selected because of their extremes in physical features (Fig. 3). Also, there were aquaculture operations in both these areas that seemed to be experiencing carrying-capacity problems and therefore would immediately benefit from any information generated.

Passamaquoddy Bay is a large bay approximately 9 km across and 22 km long located near the mouth of the Bay of Fundy on the New Brunswick side and bor-

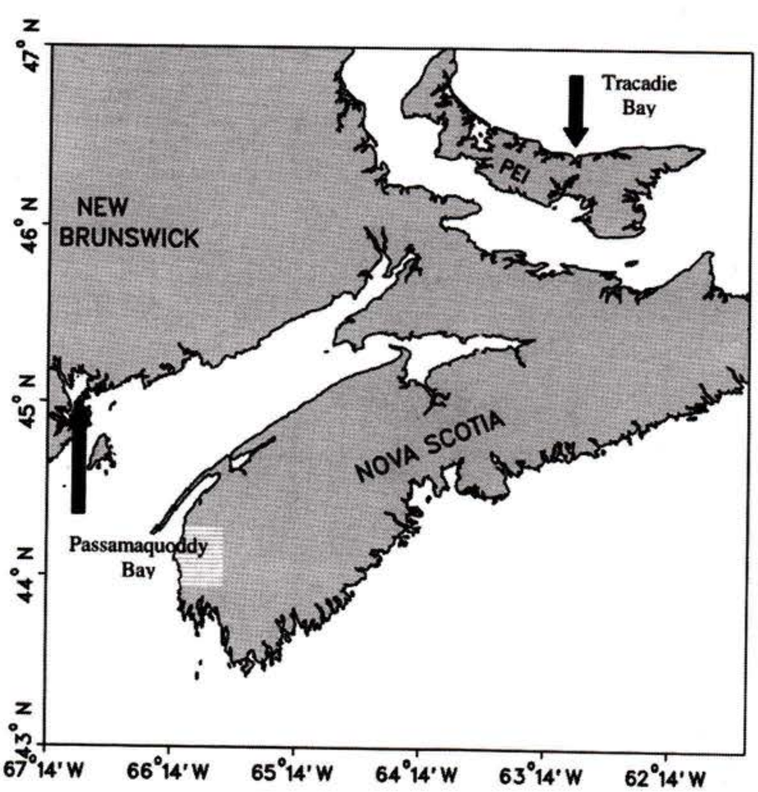

Figure 3. Location of two study sites chosen for COSAD: Passamaquoddy Bay in the Bay of Fundy and Tracadie Bay in the Gulf of St. Lawrence.

dering the United States. It has two large islands near the mouth (Deer Island and Campobello Island) and the surrounding landmass is mainly basaltic in composition, much of it forested with coniferous trees. Maximum tidal range is about 8.3 m and there can be very strong currents in restricted areas around the islands.[9] Except for localised areas where freshwater from the rivers enters, the bay generally remains ice-free year-round. Water temperatures at 5 m can range from –0.8 °C in winter to 16.6 °C in summer.[10] Maximum water depth is 72 m with the bottom composed primarily of depositional silt-clay sediments.

Tracadie Bay is enclosed and approximately 6.5 km wide and 7.4 km long on the north shore of Prince Edward Island. It attaches to the Gulf of St. Lawrence via a narrow channel through sand dunes. The surrounding landmass is comprised mainly of sandstone and the bay is encircled by farmland with a small amount of coniferous forest. There is a small inlet on the western side (Winter Bay) that has a small river at its head. Maximum tidal range is about 0.75 m and currents are generally weak except within the narrow entrance to the bay. The bay generally freezes over from December through until April. Water depth in the bay is less than 7 m and in many areas is less than 2 m. There are extensive eel grass (*Zostera marina*) beds throughout the bay. The sediment is composed primarily of sand- and silt-size particles.

Present status

Preliminary data were gathered in the summer months of 1997 on Prince Edward Island from both Tracadie Bay and Murray River. Meetings with the aquaculture industry on Prince Edward Island were also held to explain the concept of the project. A team began to be developed that included participation from the St. Andrews Biological Station, the Gulf Fisheries Centre, Bedford Institute of Oceanography, Atlantic Veterinary College, the Prince Edward Island Department of Fisheries and Aquaculture, PEI Shellfish Growers Association, and some New Brunswick salmon growers as well as new post-doctoral scientists and technicians. The fall and winter of 1997 saw the successful development of the first video system and the development of the automated process for analysing videotapes.

However, in the spring of 1998, major problems arose when management at the Department of Fisheries and Oceans (DFO) decided that other internal priorities took precedence over the carrying-capacity issue and withdrew $150,000 (43%) from the overall budget of the COSAD project. This effectively terminated the project as it was originally planned. A decision was made by the project leaders to focus on what could still be effectively done. It was decided that the physical oceanographic portion of the study should continue in a modified/reduced fashion as well as some monitoring of the growth of mussels in Tracadie Bay. The fin fish biology aspect of the program (not described here) was dropped. The PEI Shellfish Growers Association was alarmed that the shellfish biological portion of the study was cancelled and wrote DFO asking for the reinstatement of the program. There has been no resolution of this issue to date.

The authors thank the various industry members that supported the COSAD project and their assistance with developing and running the program. Thanks also to the Canada/Newfoundland Economic Renewal Agreement (Aquaculture Component) and the Canadian Centre for Fisheries Innovation for sponsoring this session at the 1998 Aquaculture Association of Canada annual meeting.

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The MarineCanary:™
Using Time-lapse Observation of Mussel Behaviour to Assess the Marine Environment

J.L. Manuel and Ulrich Lobsiger

The MarineCanary™ uses careful observation of bivalve feeding behaviour to monitor water quality and food supply. An Activity Index, which measures feeding behaviour, has been developed and currently is being tested and calibrated. The Activity Index can be visually assessed from time-lapse recordings, and has the potential to provide very rapid assessment of aquatic conditions long before the effects appear as gains or losses in productivity. Preliminary results from one field trial reveal considerable variability in mussel (*Mytilus edulis*) feeding activity through the day. Laboratory experiments suggest that Activity Index reflects the amount of particulate food removed from the water. If food is available in excess of the ingestion capacity of the mussel, the Activity Index correlates with growth (= the food removed), not the food available. The Activity Index has a pattern more similar to the consumption of oxygen and/or scope for growth than to clearance rate. In this paper, we briefly discuss potential uses for this type of biomonitoring tool, including applications for productivity estimates, site choice and management, and site capacity estimates.

Figure 1. Mussels attached to a scallop shell in the laboratory. The mussels pictured exhibit a variety of Activity Indexes.

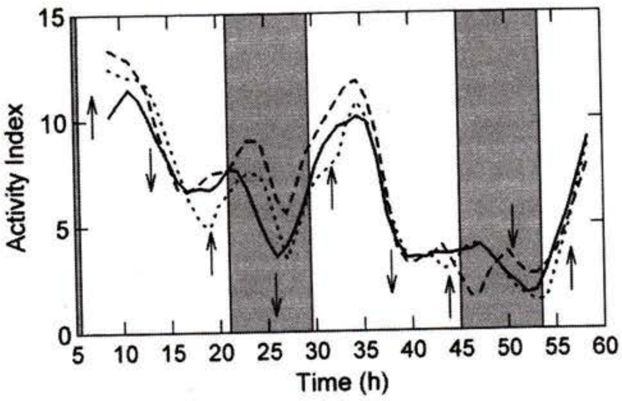
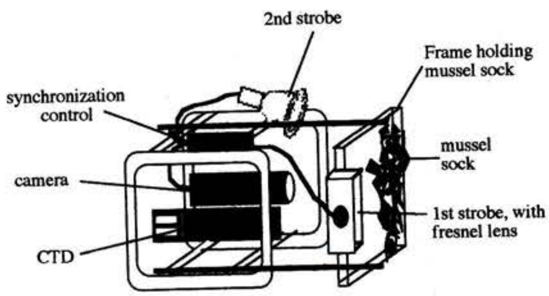
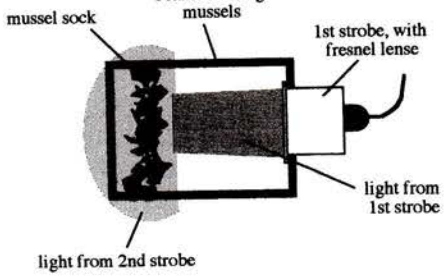


Figure 2. Activity of mussels during the first two days of the light experiment. Shaded regions are times of darkness. Day length corresponds with local sunrise and sunset. Solid line = diel light, dotted line = dark treatment, dashed line = light treatment. Data points are smoothed with LOWESS, to reveal the pattern of behaviour. Arrows pointed upwards indicate the time of high tide, arrows pointed downwards indicate the time of low tide.





Background

It is well known that bivalve filter feeders (such as mussels, clams, scallops and oysters) alter their feeding activity in response to environmental parameters. A variety of parameters such as quantity and quality of food in the water,[1] pollutants,[2,3] toxic algae,[4] etc., affect bivalve feeding behaviour. At lower speeds, currents affect feeding by replacing food removed from the water column by filter feeders and/or re-suspending particles from the bottom. Very high current strength inhibits feeding,[5-7] perhaps by interfering with the physical capacity of the animal to pump water. Many bivalves will improve the quality of food ingested by preferentially sorting food of poorer quality into pseudofaeces, so particulate matter in the water column does not always reflect the ration ingested by the filter feeder. Very high concentrations of inert particles can interfere with extraction of food particles by overloading the sorting mechanisms of the animal.

Many changes in filtering activity result in changes in external appearance. The blue mussel (*Mytilus edulis*) varies shell gape, the position of the mantle, the appearance of the mantle and the degree of extension of the mantle in response to external conditions (Fig. 1). TrisMar Research Incorporated is developing the MarineCanary™ a biomonitor tool that uses careful observation of such changes in bivalve appearance to assess the marine environment. The MarineCanary™ produces detailed, non-invasive observation of how animals and/or individuals respond at a given location. Such a tool may be used in conjunction with other standard water quality monitoring devices, but the major advantage is as a tool that can be used without more expensive and

Figure 3. An early prototype of the MarineCanary™ that used a DS-4 underwater 35-mm camera with wide-angle lens and time-series programming capability to record images.

time-consuming analyses. Effectively, the MarineCanary™ uses living animals to assess and integrate the various parameters that affect feeding. With careful interpretation, one may relate this feeding behaviour to biological, chemical or physical oceanography at a given site. Use of such a tool, however, requires a thorough understanding of exactly what is being recorded. It is essential to know why the visual appearance of an animal changes to interpret those changes when encountered in the field.

This presentation summarises preliminary results from several field and laboratory studies with the blue mussel, *Mytilus edulis*. The experiments were designed to elucidate which environmental parameters invoke the various visible changes in mussels as they feed. We emphasise that the results are preliminary. Data are not fully analysed, and will be reported in more detail elsewhere. Here we present an overview of our understanding at the moment. Because this is an overview, we will not present in great detail the materials and methods for each experiment. This in no way implies that those details are not extremely important, and we encourage those interested in more information to contact Dr. Manuel.

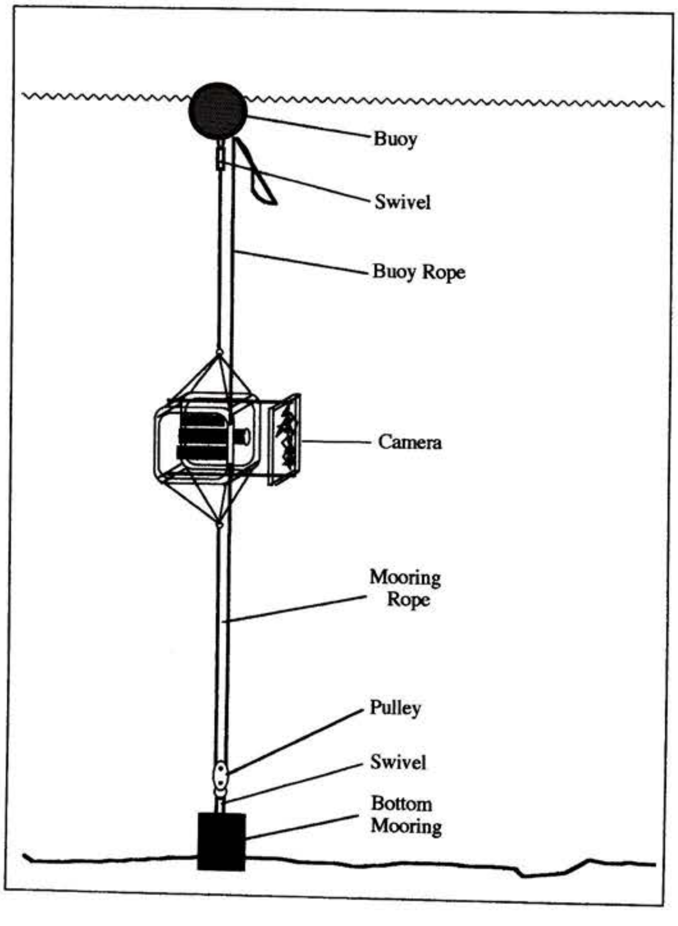


Figure 4. Deployment of the MarineCanary™ in the field.

Determination of Activity Index

Behavioural indices were determined from direct observation of the animals or images recorded during the experiment. The Activity Index was developed from our observations of mussels in the laboratory, and in particular, responses of mussels to food. Those aspects of appearance that vary temporally, but seem to have some correlation among different animals are the ones likely to be the best candidates for a behavioural index that reflects responses to changes in water quality. Our Activity Index is calculated from observations of shell gape, mantle extension, and mantle position. Shell gape is recorded as (from lowest to highest) closed, slit, half-open or open. Mantle extension is recorded as (from lowest to highest) retracted, half-open, full and extended. Mantle position is recorded as meshed or open. Different states are assigned numerical values, and the Activity Index is the sum of the values for shell gape, mantle extension and mantle position. The Activity Index ranges from a minimum of 0 to a maximum of 15. Mean Activity Index is calculated from the average values of as many animals as possible (usually 10 to 25), given the experimental set-up.

Shell gape, mantle extension and mantle position exhibit considerable, but not perfect, correlation in response to food. The fact that the correlation is not perfect suggests that they may respond to different stimuli, and future experiments with other stimuli may show greater independence of the values. At present we are developing a protocol that will allow us to collect these three data via an image analysis protocol, which will produce continuous variables. Until that protocol has been thoroughly tested, recording two somewhat correlated values from each individual reduces variability and operator error in the assessment of the Activity Index for each animal. This method of assessing activity does have the advantage of allowing assessment of animals byssed together in the varied positions that are seen "naturally" in a mussel sock or on a hard substrate.

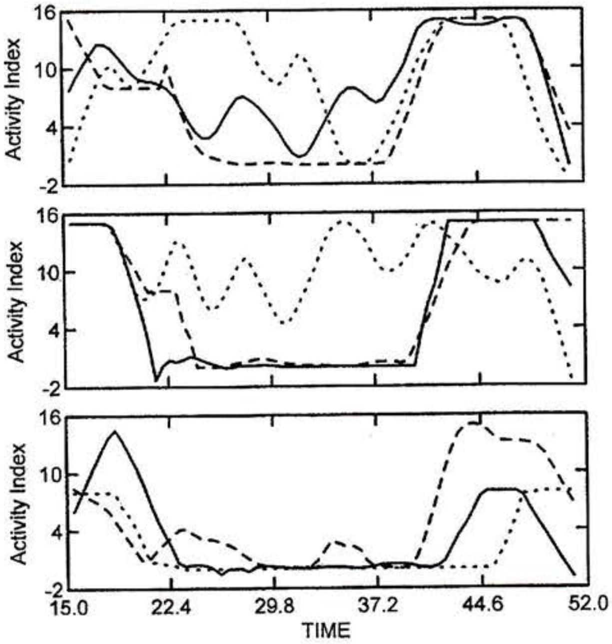


Figure 5. Activity Index recorded for 9 individual mussels. All mussels were on the same sock and data cover the same time period. Each line indicates the activity of one mussel.

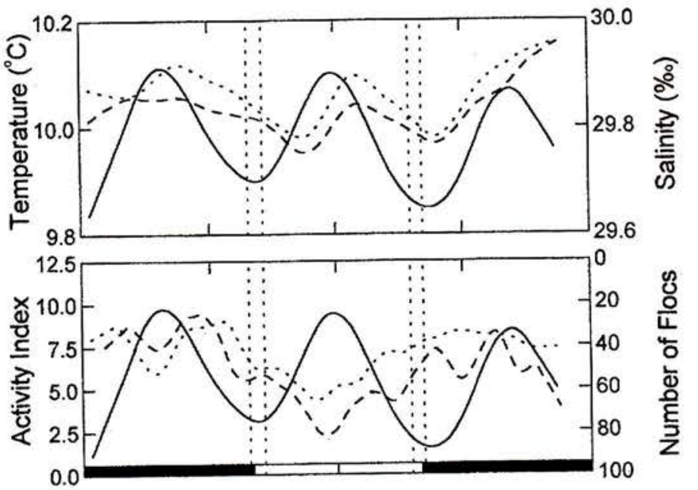


Figure 6. Mean Activity Index of mussels in a section of mussel sock from October 30 to November 1, 1996, in Mahone Bay, Nova Scotia. Black boxes below each graph indicate periods of darkness. Open boxes indicate times of daylight. Dashed vertical lines show dawn and dusk. The solid black line in each panel is the depth profile, indicating tidal phase. Data were plotted against time and smoothed using LOWESS, a smoothing algorithm that is useful for observing trends in relationships. Top panel: dashed line is temperature, dotted line is salinity. Bottom panel: dashed line is mean Activity Index, dotted line is the number of flocs per sample. Note that the scale for number of flocs is inverted, for ease of comparison with Activity Index.

Sensitivity of the Activity Index

Since we intended to collect images during the night, it was necessary to determine whether light would affect the feeding behaviour of mussels. We had three treatments: constant light, constant darkness and diel light. Animals in all three treatments had similar mean Activity Indices (Fig. 2). More interesting was the pattern of feeding behaviour that was not related to light. The experiment was conducted at the Aquatron facility at Dalhousie University in tanks with a flow- through water supply. In that facility, water is drawn from the Northwest Arm of Halifax Harbour, filtered through a sand filter (back-flushed every morning at 7:00 am) and pumped up into a large holding tank. From there it is distributed throughout the facility. Mussels, under these conditions, showed an increase in feeding behaviour about 3 h after each high tide, and a decrease in feeding about 3 h after each low tide in the Northwest Arm. This result was surprising to us. We later established that a P1 filter bag (which removes most particles above 1µm in diameter) removed this tidal signal from mussel feeding behaviour.

Reality check: Do mussels alter feeding behaviour in the field?

There is a plethora of literature indicating changes in feeding behaviour occur in the laboratory. Our initial observations suggested that mussels were not feeding continuously in the lab, but we did not know whether this would be the case in the field. We deployed a prototype MarineCanary™ at Indian Point Mussel farms in Mahone Bay in Nova Scotia in the fall of 1996 (Fig. 3, 4). Mussel behaviour was determined directly from the slides. Newell and Shumway[8] suggest variability in feeding rate may be related to particle concentrations. We decided to examine larger particles in the immediate vicinity of the sock by placing a collimated light to the right of the sock. A portion of each slide containing particle images was digitised, and an image analysis program (OPTIMAS) was used to collect information on the number, size, fractal dimension, etc., of particles in the immediate vicinity (<10 cm) of the sock. An attached CTD (courtesy of the National Research Council's Institute for Marine Biosciences, Halifax) provided concurrent temperature, salinity and depth profiles.

Individual mussel behaviour was by no means uniform. Figure 5 shows the changes in Activity Index of nine individuals in a mussel sock between October 30 and November 1 1996. Activity Indices are plotted on three separate panels to make the individual paths easy to distinguish. It is evident that recording the activity of only a few of these mussels would provide very different results, depending on which mussels were selected. Because of this variability, we average the Activity Indices of as many individuals as possible when calculating the mean Activity Index.

The first field deployment, in Mahone Bay, on October 30 -November 1, 1996 (Fig. 6) was during a time of very calm weather. Small changes in salinity and temperature were correlated with the tidal cycle. Mussel activity shows an inverse correlation with particle number. Both particle number and mean Activity Index show a combination of tidal and diel effects. Mussels opened more at night than during the day, and feeding seemed to decrease at high tides and increase at low tides. We deployed the apparatus again ten days later on November 12 - 14 (Fig. 7). During that deployment, we found a more thoroughly mixed water column. Temperature and salinity no longer reflect the tidal cycle. Mussel activity showed little correlation with particles in the water. The diel cycle had disappeared. Tides did have an effect on feeding behaviour, but the nature of the effect had changed. Mussels increased activity at both high and low tide, and decreased activity during times of greater flow. However, the largest effect on behaviour came from a wind event that began near sundown on the second day. The wind event changed the water over the site, as evidenced by a rapid drop in salinity and temperature. Concurrent with this event, mussel activity increased considerably.

Thus, what at first glance appeared to be diurnal behaviour with a bit of noise, was in fact complex responses of individual mussels to the aquatic environment, probably food supply. Reductions in Activity Index were not similar to the reduction in clearance rates often found with higher food concentrations in laboratory experiments. Images with a lower Activity Index also had more individuals that were completely closed. The lowest number of animals open was 1, the highest 74 (all visible mussels open).

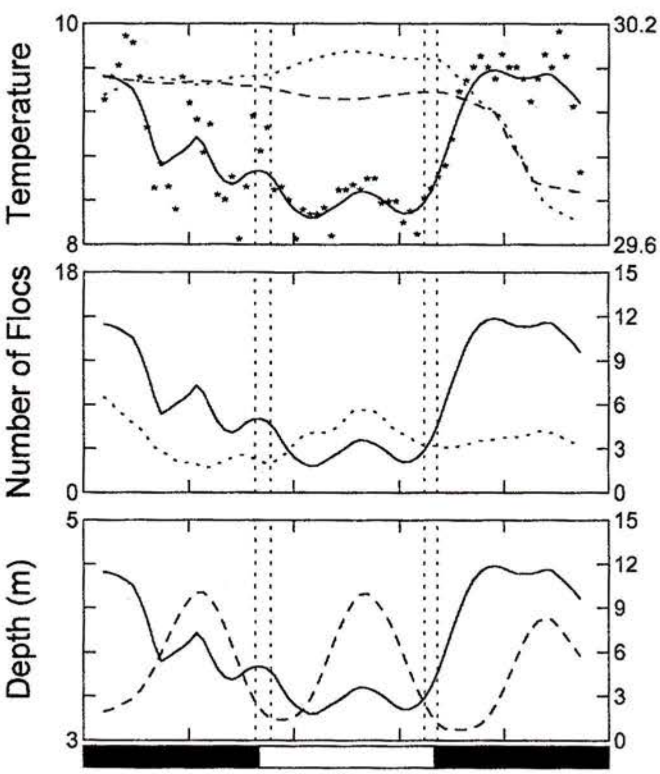


Figure 7. Mean Activity of mussels in a section of mussel sock from November 12 - 14, 1996, at the same site. Data were plotted against time, and smoothed using LOWESS, a smoothing algorithm that is useful for observing trends in relationships. The solid line in each panel is mean Activity Index. Top panel: dashed line is temperature, dotted line is salinity. Middle panel: dotted line is the number of flocs. Bottom panel: dashed line is depth (tidal phase).

Just what are we measuring when we record the Activity Index?

Could the Activity Index be a response to gut fullness? We conducted a number of experiments to try to describe the types of environmental parameters that might affect feeding activity. Figure 8 is an example of one such experiment, conducted with each treatment in a separate 60-L bucket. In this experiment, the stationary phase CHGRA was close to crashing, and we wondered whether such an old culture might produce exudates to inhibit feeding behaviour. We thus used equivalent volumes of the culture, and the difference between the two CHGRA cultures reflects the difference in numbers of cells fed. In this and other experiments, we found a visible increase in mean Activity Index in response to food (positively correlated with the amount of food supplied), temperature, salinity, and cornstarch (also positively correlated with the amount fed). Responses to temperature and salinity changes could be greatly magnified by feeding the mussels just before beginning the experiment. We found no visible response to gelatine, glucose, glycine or milk. Milk was removed from the water, but the mussels produced white pseudofaeces strings shortly thereafter. We have also observed that the Activity Index is affected by the size of the mussel, previous feeding regime, and currents, but these effects have not been quantified.

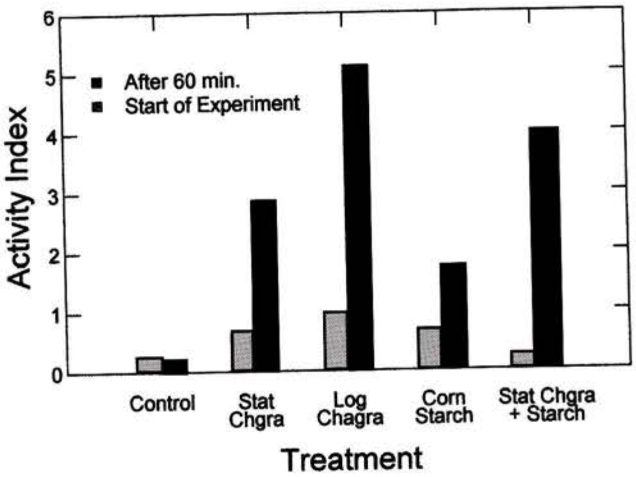


Figure 8. Changes in mean Activity Index of mussels exposed to various treatments. Shaded bars indicate mean Activity Index at the beginning of the experiment, black bars indicate mean Activity Index 60 minutes after exposure. Response to treatment was usually highest 30 - 60 minutes after exposure.

Activity Index and growth of mussels

Of course, what a mussel farmer is really interested in is growth rate. Growth rate depends on the amount of food ingested. The amount of food ingested depends on the quantity and quality of food available, and the rate at which that food is removed from the water. There are many factors that affect the quantity of food available, but from the point of view of the mussel, it is controlled by the concentration of food and the rate at which food is replaced (flux).

Willows[9] produced an optimality model of bivalve feeding. Briefly, in this model, the filter feeder has a long tube (the gut) for processing food. The effort put into feeding is determined by optimising the food retrieved for the effort expended, and the quantity of food retrieved is limited by the capacity of the gut and the rate at which material passes through it. Interestingly, Willows' model predicts a number of behaviours that are consistent with our observations of visible changes in feeding behaviour. When there is more particulate matter in the water than the mussel can stuff into its gut, it sorts a portion of that off into pseudofaeces, which is rejected and does not pass through the gut. The model predicts that below the pseudofaeces threshold, as ration increases, pumping will increase.

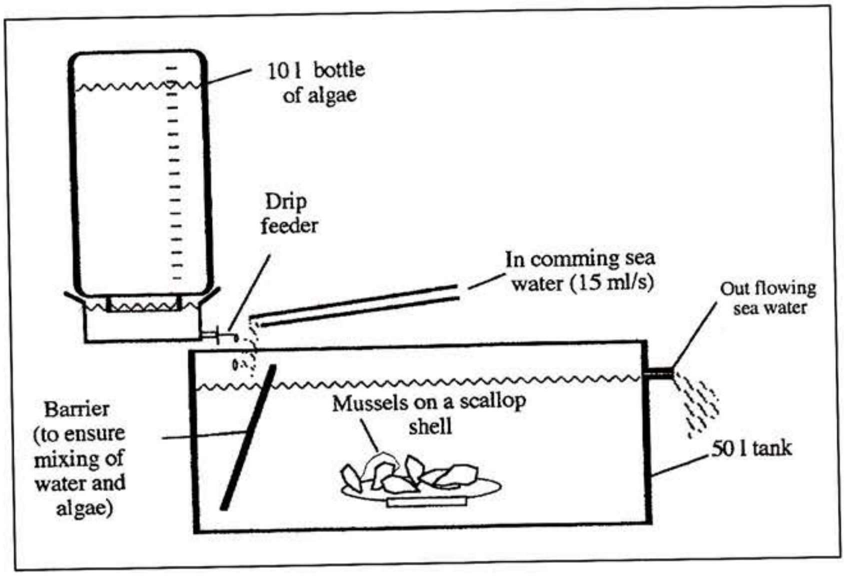


Figure 9. Flow-through drip feeding set-up for comparing mussels' response to different levels of food. The incoming seawater has been filtered through a P1 bag filter to remove most particles above 1 µm in diameter. That eliminated a tidal influence on behaviour seen in previous experiments (see Fig. 2)

This latter prediction of

pumping behaviour appears consistent with how the Activity Index behaves. Our experiments with food indicate that the maximum Activity Index is associated with levels of food near the pseudofaeces threshold, and when milk particles were sorted into pseudofaeces, we did not see an increase in Activity Index. That suggests that Activity Index is correlated with the amount of food ingested, not with clearance rate or the amount of food available. Clearance rate is inversely correlated with food level, even though the amount of food ingested increases with increasing concentration of food in the water. The amount of food available in the water may also be beyond the ingestion capacity of the mussel, or below the minimum threshold required to induce feeding activity. We decided to compare different growth rates, produced by different levels of feeding, with mean Activity Index.

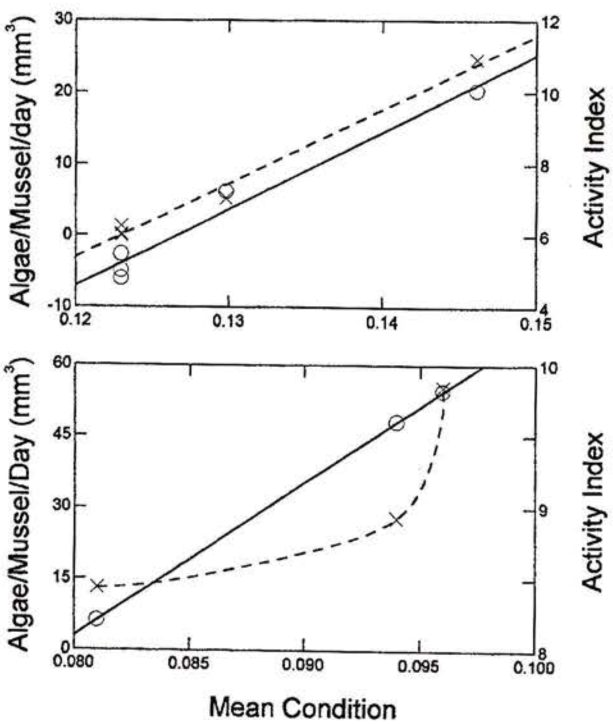


Figure 10. Activity index and food ration plotted against the mean condition of mussels. Food ration is the average wet volume of algal cells fed to each mussel each day. Activity Index was recorded daily, and then averaged over the experiment. Solid lines and circles are mean Activity Index, dashed lines and x's are the quantity of algae fed per mussel per day. Each experiment ran for 17 days. Top panel: In the first experiment (30 x 5-cm mussels per treatment), mussels were fed 0, 250, 1200, 5200, or 23000 cells/mL *Isochrysis galbana* clone ISO. Bottom Panel: In the second experiment (25 x 4.5-cm mussels per treatment), mussels were fed 10000, 20000 or 40000 cells/mL *Isochrysis galbana* clone TISO.

We conducted two experiments in flow- through tanks (~35 L for the first experiment, ~50 L for the second experiment), with food added via drip feeders designed to provide a constant level of food (Fig. 9). Different levels of feeding were achieved by diluting cultured algae with seawater. The wet volume of algae fed was calculated by multiplying the cells fed per day by the volume of an average algae cell (determined with a multisizer Coulter Counter). Fresh food was added each day about noon, and the following morning the mean Activity Index for mussels from each feeding level was recorded. Also recorded were video images of mussel clumps, but that data have yet to be analysed. Growth rate was assessed by condition index, calculated by dividing dry body weight by dry shell weight at the end of the experiment. Condition index is a reasonable way to approximate growth.[10,11] We randomly distributed mussels among the different groups, and assumed similar condition indices in each group at the beginning of the experiment.

The first experiment (Fig. 10) was designed to identify responses to lower levels of food. The control treatment was unfed. The lower two food levels produced condition indices equal to the unfed control. This could be interpreted as the "maintenance ration". Above that, the relationship between Activity Index and food level seems approximately linear. The relationship between the amount of food fed and condition index shows a similar pattern.

The second experiment (Fig. 10) explored the relationship between Activity Index and growth at levels that exceeded the pseudofaeces threshold. Again, the Activity Index has a linear relationship with condition index. However, because the quantity of food delivered was greater than the ingestion capacity of the mussels, the relationship between food delivered and condition index was very curvilinear.

Summary

If food is available in excess of the ingestion capacity of the mussel, the Activity Index correlates with growth (= the food removed), not the food available. When the ration (food consumed) increases, oxygen consumption increases as well. [12, 13] Thus, relative to the quantity of food available in the water, the Activity Index has a pattern more similar to the consumption of oxygen and/or scope for growth than to clearance rate. Milk powder that appeared to be sorted into pseudofaeces did not increase the Activity Index. Glucose and glycine are two substances that mussels are known to absorb directly from seawater. Neither produced any noticeable change in the Activity Index. Mussels are able to digest and utilise cornstarch as food and cornstarch produced changes in the Activity Index. The addition of similar amounts of gelatine did not. In summary, preliminary results of lab experiments suggest that our Activity Index reflects the amount of food removed from the water, and may be correlated with scope for growth.

Utility of the Activity Index

The accuracy of laboratory estimates of scope for growth in bivalves depends heavily on accurate prediction of a number of parameters. One of the more important of these is the rate at which particles are removed from the water. Even if the filtration rate is measured daily, there is still no accounting for the variations in filtration that occur throughout the day. Our observations suggest that competition for water that has not been previously filtered by another mussel may have an important influence on Activity Index. To a large extent, this depends on the flow of water (flux) replacing food around and over a clump of mussels. It is difficult to re-create such water movements in the lab, especially given the expected changes with tidal phase and weather conditions.

It would be useful if it were possible to measure how much food animals actually removed from the water, rather than measuring each of the various parameters and trying to predict how animals will respond to each combination of factors. If measuring food ingestion could be reduced to visual observation and a few simple measurements, valuable information can be collected *in situ* frequently enough to correlate feeding with short term events such as tidal events, direction of flow, wind events, etc. This would be a very powerful management and/or research tool.

Observation of feeding behaviour could be useful in a number of ways. If food is brought onto an aquaculture site from a particular direction, this could have important implications for site layout. If animals are feeding for only a small part of the day, that may suggest the site is overloaded. Direct observation of animals would allow immediate response to problems on the site: problems that might otherwise not be recognised until there has been loss of productivity, mortalities or drop-off.

The MarineCanary™ may also prove useful for site selection. One of the more important aspects of site selection is the flux of food to the site. If mussels reduce feeding during part of the tidal cycle when the site is unoccupied, addition of a large biomass of filter-feeders will certainly increase the period when the flux of food is too low to replace what is being removed. It should be possible to define the temporal changes in activity that are associated with a good site.

During some seasons, animals have very little food available. If animals have not been feeding recently, they may not deal well with the stresses of handling and/or shipping. Rather than guess when that season might be (based on experience over a number of seasons), one may be able to simply observe feeding behaviour. Thus the MarineCanary™ could be useful for quality assurance by predicting how well animals will withstand the stress of harvesting and shipping. No doubt other management uses will be recognised once the system is commonly in use.

Thanks to the National Research Council's Institute of Marine Biosciences, and IRAP who provided technical and financial support for field trials. Indian Point Marine Farms in Mahone Bay, Nova Scotia, provided the site for the field trials and assistance with deployments. Thanks are also due to the sponsors of the Production Capacity Workshop: Atlantic Canada Opportunities Agency (ACOA), Canada/Newfoundland Agreement on Economic Renewal - Aquaculture Component (ACERA) and the Canadian Centre for Fisheries Innovation.

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Managing Seeding Density at Mussel Farms in Maine (USA) using the Mussel Growth Model MUSMOD© along with a Consideration of Seston Depletion at Site-specific Inshore Farm Locations

Carter R. Newell

Investigations of current speed, the supply and demand of particulate food by bottom-cultured mussels, and growth vs density relationships were used at a commercial mussel lease site to develop a mussel growth model. The model is based on field data of water temperature, depth, current speed, food concentration, mussel density, seed size, time of year seeded, and mortality. A two-dimensional finite difference model was used to calculate currents at each 3-hectare lease plot, and food quality was followed as both the live phytoplankton and detritus components. Food assimilation was modelled as a function of food quality, where seasonal changes in the quantity of live phytoplankton (mostly diatoms) and the quality of detritus had significant effects on mussel growth trajectories. Predicted depletion contours above indi-

Bottom lease site at Mud Cove, Deer Isle, Maine. The area is about 2 meters deep with a 4-meter tidal amplitude, approximately 20 hectares in area, and produces about 230,000 kilograms of mussels annually.

vidual mussel patches or thinly seeded beds were also used to adjust mussel densities to improve growth rates and final meat yields of mussels at three commercial lease sites. Application of MUSMOD© to suspension culture was achieved by making all of the particulate food available to the mussels instead of just the fraction mixed into the benthic boundary layer. Growth trajectories of mussels from Lunenburg, Nova Scotia, gave a reasonable first order fit to field data when input data from the site were used. Current research is focusing on mussel feeding behavior in response to current speed, particle concentration, and in-situ fluxes of particulate food in Maine.

Introduction

When suspension-feeding bivalves are placed on a bottom lease, there is a maximum biomass (in grams of dry tissue weight/m^2) which can develop as the animals grow to market size.[6,7] This asymptotic biomass is an upper limit to the production potential of a site. For example, if the maximum biomass of a bed of mussels in June at a particular site is 500 g/m^2 and if the density is 500 mussels/m^2, each mussel will have a tissue weight of 1 gram. If the density is 250/m^2, the tissue weight will be 2 grams. Thus, seeding densities

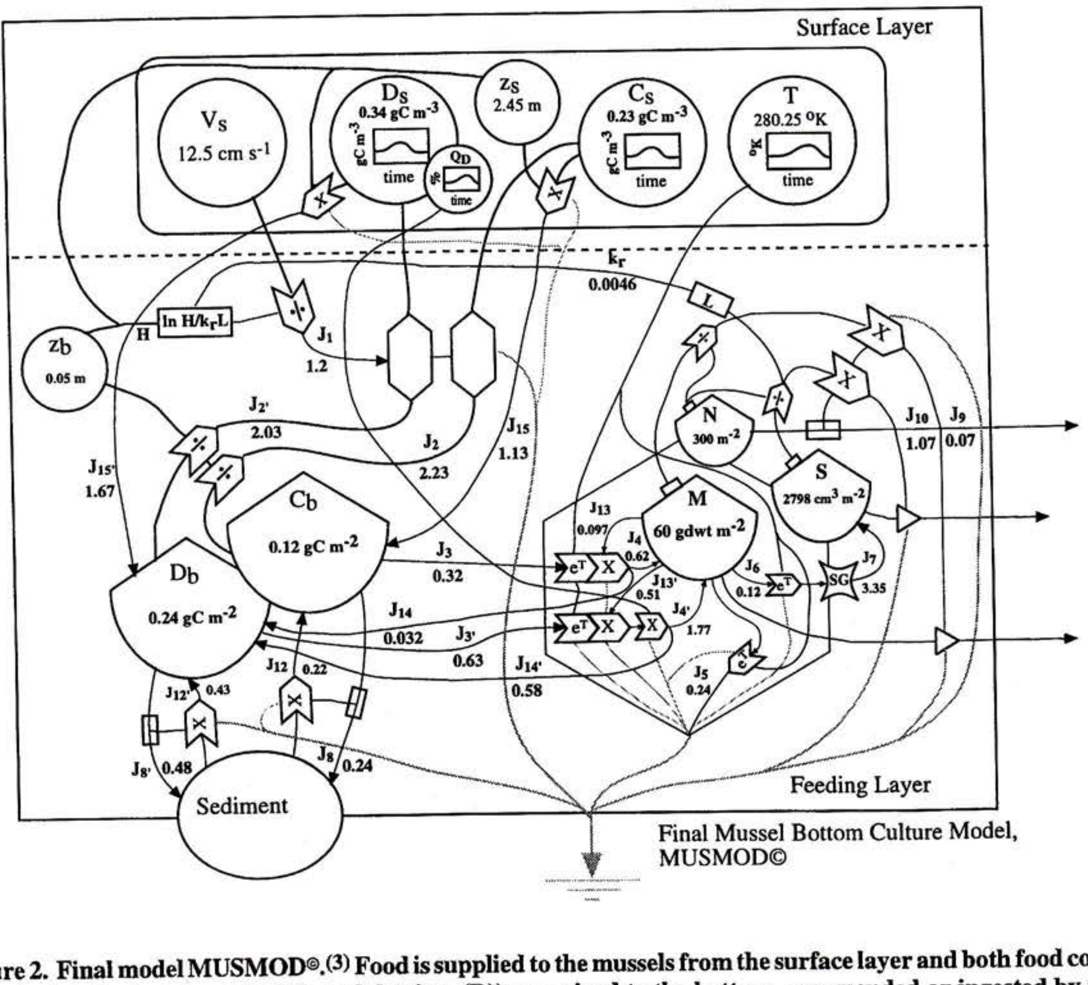

Figure 2. Final model MUSMOD©.(3) Food is supplied to the mussels from the surface layer and both food components (phytoplankton cells (C) and detritus (D)) are mixed to the bottom, resuspended or ingested by the mussels (M). For a given density N (300 m^2), current speed (V) and food supply, mussels will grow as a percentage of the food available at the edge of the lease site.

have a direct bearing on final meat weight of the shellfish on an aquaculture lease and determine not only the growth rate but also the final maximum tissue weight.

Earlier work[11] established the effects of mussel density and position in bottom patches on growth rates. Slow growth was observed especially in low current areas in the middle of mussel patches over 1 meter in diameter. Once we developed a seed spreader which resulted in small individual clumps on the bottom, minimizing individual patch size, we were faced with the problem of determining optimal seeding densities within the entire lease site. There was a need to develop a more mechanistic model of the growth of shellfish as a function of food supply and

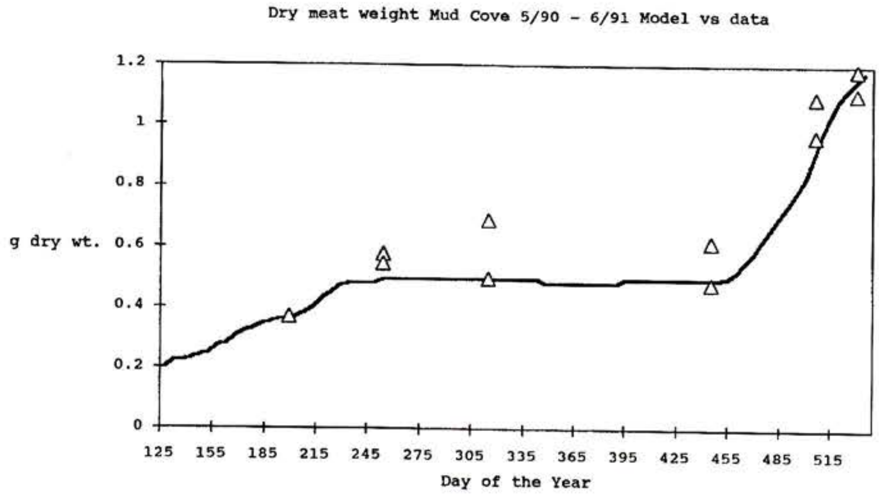

Figure 3. Model predictions versus actual dry meat weight of mussels at Mud Cove (May 1990 to June 1991).

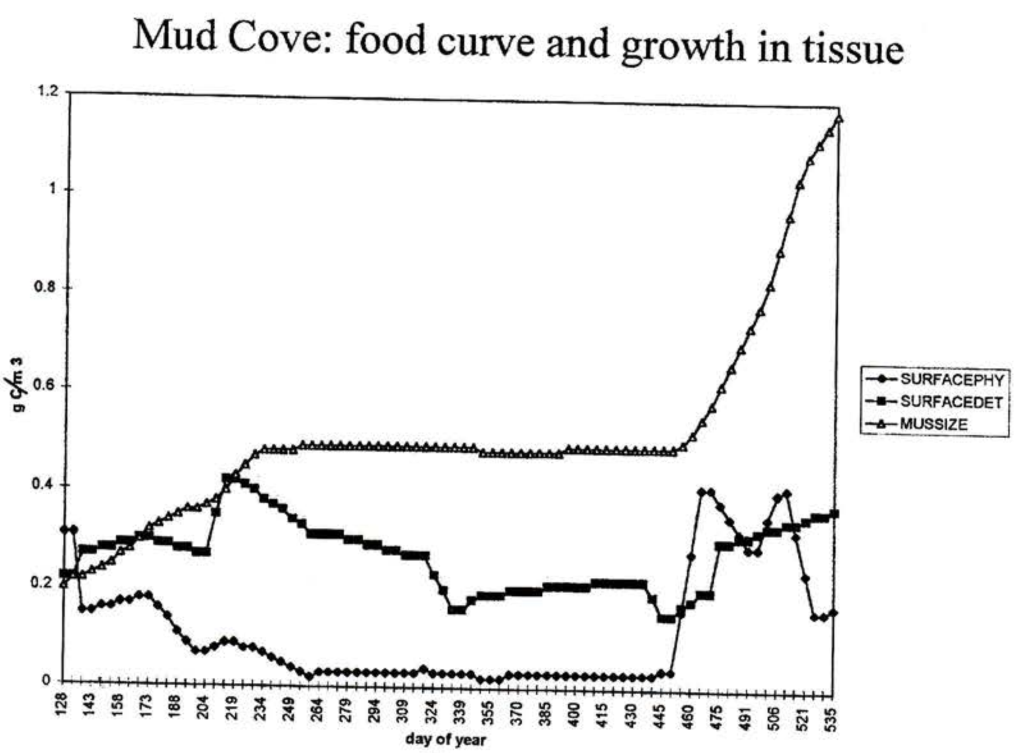

Figure 4. Food curve and growth from MUSMOD® simulations in Mud Cove (note rapid growth in second spring during declining phytoplankton and rising detritus). Units for mussels size (triangles) are in grams of dry tissue weight. Food concentration units in grams carbon/m^3.

demand such that individual lease sites could be managed for maximum yields. This work resulted in the development of the model Musmod©[3] based on field work performed at commercial mussel bottom leases along the coast of Maine.[10,12]

When we first started to model mussel growth, a sensitivity analysis of various factors demonstrated the importance of food concentration, food quality, food assimilation rates, and current speed on the growth rates of mussels. As we built the model, we followed mussel growth trajectories at the Mud Cove lease site in Deer Isle, Maine (Fig. 1) while also monitoring the concentration and quality of suspended particles (seston). The results give growth of mussel meat and shucked meat yield as a function of seeding densities, and allowed us to decrease growth periods and increase harvest to seed yields at the three study sites.

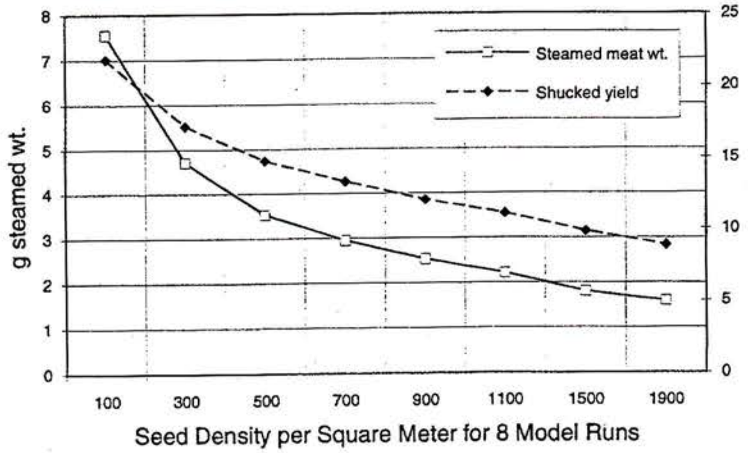

Figure 5. Mussel growth over one year in steamed meat weight or shucked meat yield (1 bushel = 35 liters) as a function of density at Mud Cove, Maine.

MUSMOD©: basic components

The mussel model MUSMOD© (Fig. 2), which is basically an energy flow diagram based on units of carbon, requires entering the food concentration and quality in the surface waters and the temperature curve from each site

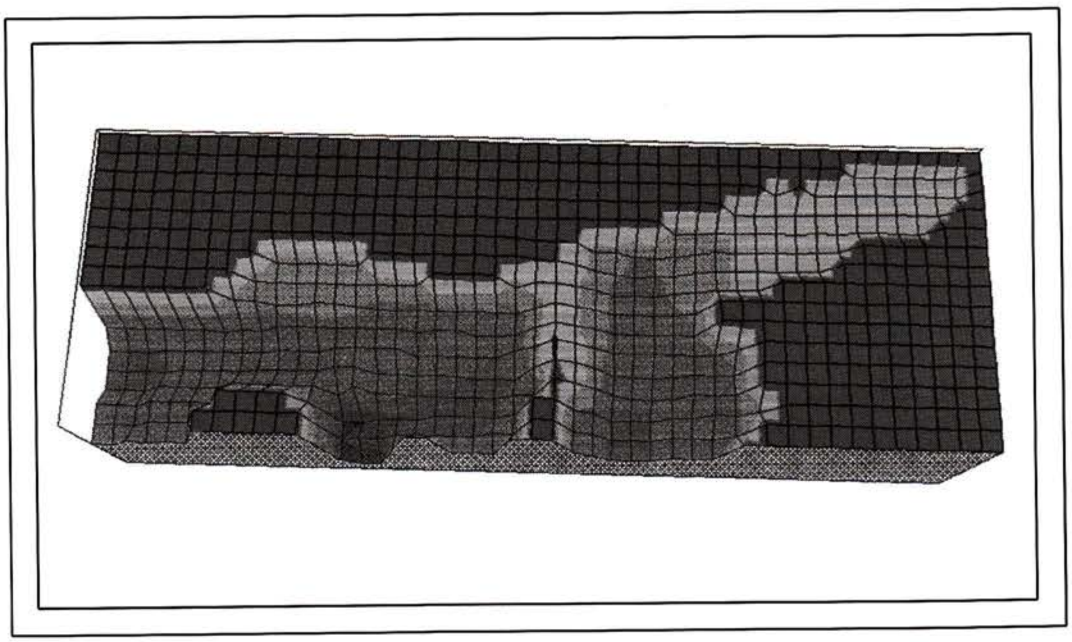

Figure 6. Mud Cove bathymetry in meters.

into an Excel spreadsheet. The program is run in QuickBasic. Data on the mean current speed, water depth, mussel size, mussel meat weight, culture density and mortality rates are also entered as initial conditions. Storages include feeding zone phytoplankton, feeding zone detritus, mussel biomass, mussel volume and mussel density. Details on the various physiological coefficients and other parameters in the model are given by Campbell and Newell.[3]

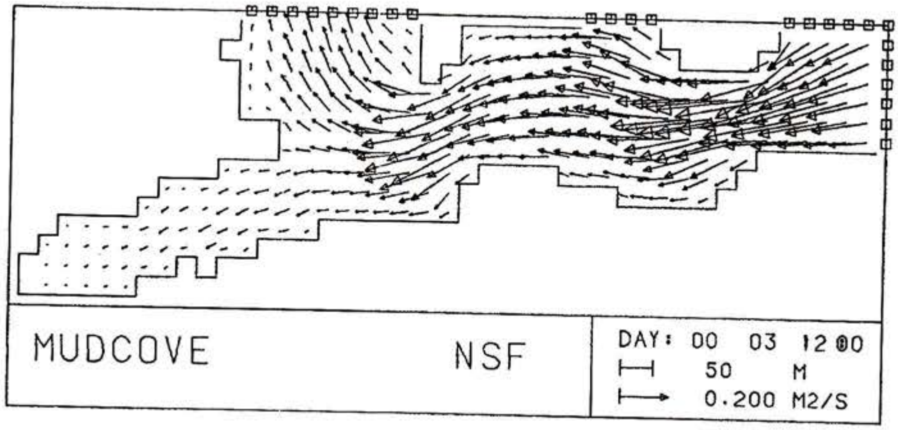

Figure 7. Current vectors at Mud Cove (output from flow model DUCHESS).

When following mussel growth trajectories, we noticed very rapid growth rates in late spring (May and June) which could not be successfully represented in earlier versions of the model. We split the food into two basic elements:

- live phytoplankton (over 95% diatoms) which was assimilated at a high rate (85%) by the mussels and resulted in rapid growth.
- detritus which had variable quality over the year and was assimilated at rates varying from 25% to 65% (depending on the quality of the detritus which was modelled as the N/C (nitrogen to carbon) ratio).

We were then able to estimate food quality by doing the following:

a. Measure total carbon and nitrogen in the seston using a GFC filter.

b. Determine phytoplankton carbon using an inverted micro-

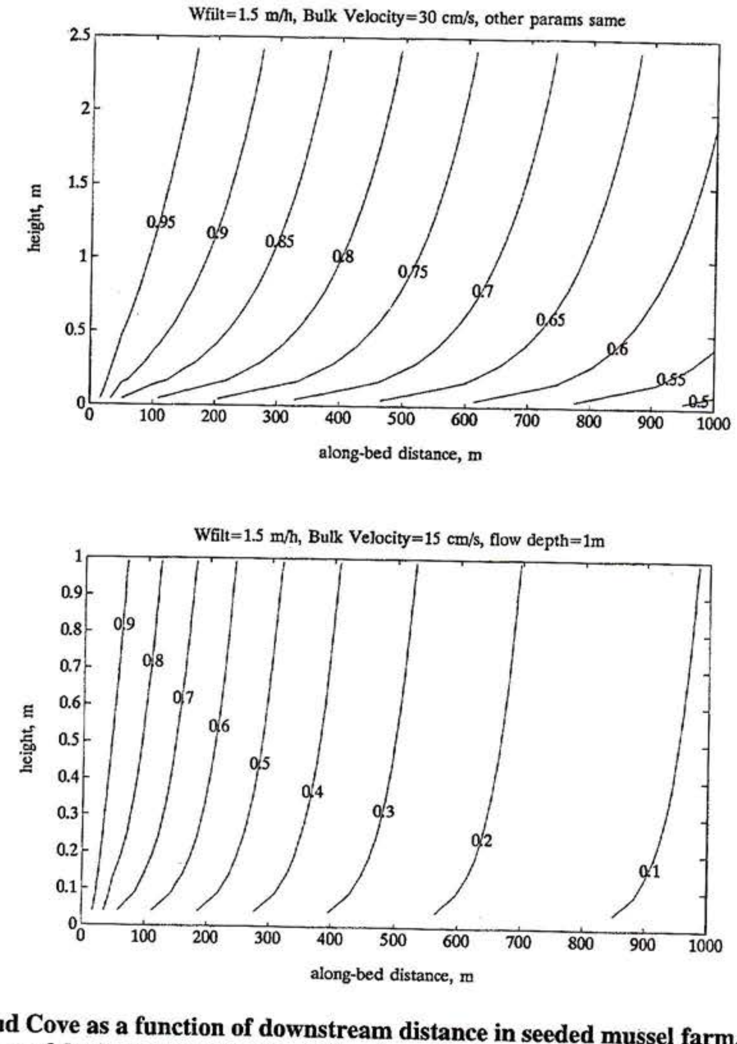

Figure 8. Depletion contours above Mud Cove as a function of downstream distance in seeded mussel farm. Output of particle contours as a percentage of the food concentration at the edge of the lease site with a bulk current velocity of 30 cm per second, filtration velocity 1.5 m per hour, field values of bottom roughness and ingestion height.(12)

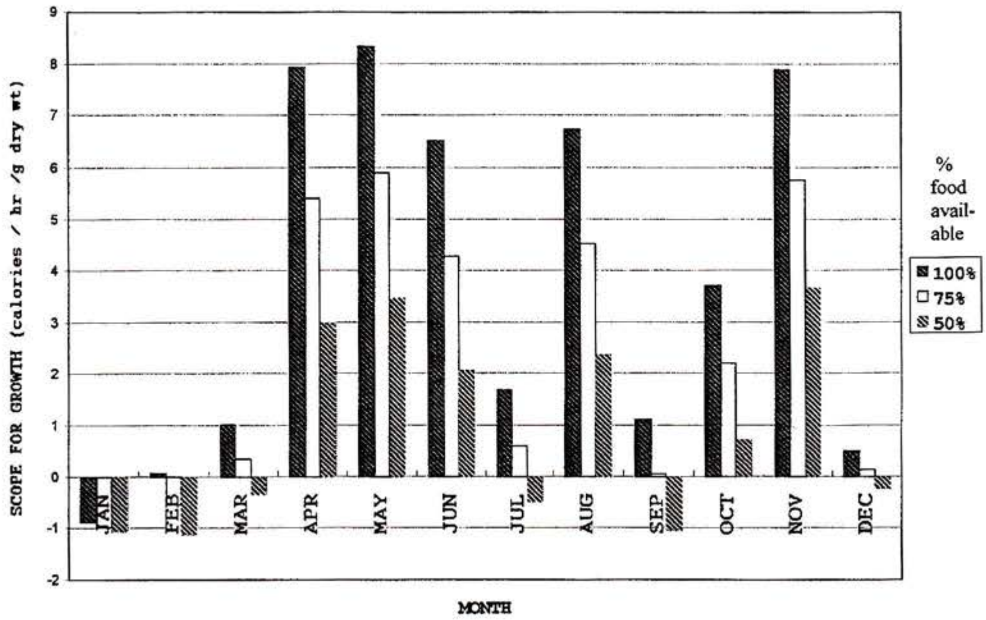

Figure 9. Scope for growth (energy available for growth) for mussels as a function of depletion (downstream distance, see Figure 8).[10]

scope based on cell volumes and appropriate carbon conversions for the diatoms, dinoflagellates and ciliates in the samples by species.

c. Subtract phytoplankton carbon from total carbon to give detrital carbon.

d. Using phytoplankton C/N ratios, do the same thing for nitrogen.

e. An easier estimate of phytoplankton carbon can be obtained using chlorophyll-*a* if regressions to (b) above are obtained throughout the year.

When we input the food concentration in the above manner, the mussel growth fit very well with the model (Fig. 3). In the spring in Maine, rapid growth is initially due to a high level of phytoplankton carbon. In late spring, the growth continues due to the increasing concentration and high quality of detritus (Fig. 4). Later in the summer, as the detritus gets colonized by bacteria, there may also be improved growth rates. The final result was mussel growth as a function of density (Fig. 5).

Estimating current speed and particulate fluxes

We have had great success using the model DUCHESS[2] for building flow models with 50 m resolution at our culture sites. First, the bathymetry is entered on a grid (Fig. 6). Then, an Interocean S4 current meter is placed at the model boundaries. The model is forced either by tidal height or current speed. It also accommodates flooding and drying, and wind forcing. Once a model is up and running, it is tuned using data from within the model domain by putting the S4 in the site for a week or so. The result is current vectors of the site at each stage of the tidal cycle (Fig. 7), as well as mean values for each lot within the lease site on flood and ebb tides, and for spring and neap tides. Mixing to the mussels in the bottom was deter-

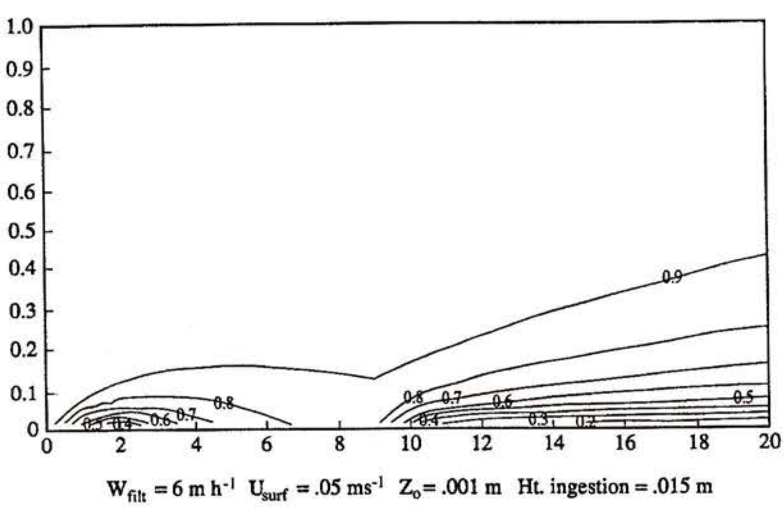

Figure 10. Depletion of seston over a densely seeded mussel patch.[12]

mined from boundary layer theory[3,12] in an explicit representation of shear velocity, U*. We simplified the water column into two regions, the feeding zone (0 to 5 cm off the bottom) and the surface water (the rest of the water column to the surface), based on field studies of the consumption rates of mussel beds and gradients of seston upstream and over a mussel bed in Maine.[8] Finally, we added the settling flux and resuspension of seston, feces and pseudofeces to the food vertically mixed to the feeding zone for accurate representation of mussel growth rates. The greatest uncertainty in modelling food availability is the *in situ* settling rates of natural particulates, including flocs, at the lease sites.

Finite difference models of seston depletion

Fréchette et al.[4] used a finite-difference model to determine depletion contours above mussel beds, as a function of current speed, water depth and consumption rates by the mussels. Simulations of the Mud Cove lease site showed that with seeding densities of about 250/ m^2 there would be about 50% of the food available at the end of the lease site over 1 km (Fig. 8), and there would be much more depletion of food in the bottom waters than at the surface. This model prediction was verified by field work which showed depletion of POM in bottom waters in the downstream direction on both flood and ebb tides[12] as well as samples taken by the flow cytometer which showed grazing of phytoplankton in the bottom waters vs. the surface.[9,10] Using various values of depletion, it was possible to determine what the energy available for growth (scope for growth) would be as a function of the mussel's position at the lease site (Fig. 9).

Due to the high density of individual mussel patches, rapid depletion would be expected in the space of meters (Fig. 10). Since the vertical mixing of food can be represented by the bottom shear velocity, U*, and the filtration of water by the mussels on the bottom can be estimated as m^3/ m^2 /hour (simplified as "filtration velocity", W_{filt} in units meters per hour), a dimensionless coefficient called W_{filt} / U* can be determined which gives a feeling for the depletion contours in the downstream direction at a mussel farm (Fig. 11). Thus, it can easily be seen that the greater the demand by the mussels, the greater the depletion. Mussels seeded at a small size on the farm can rapidly grow into a larger biomass which will result in seston depletion later in the year. Therefore, it becomes critical to estimate food consumption rates by the mussels in order to accurately model the effects of biomass on food availability within a lease area.

Uncertainties in mussel consumption rates

While there are many published studies on mussel feeding rates, very few have been performed in the field with natural particulates. Our studies[10] have demonstrated that mussels do not filter at maximum rates all the time, but have a periodicity in pumping rates with low rates during low particulate concentrations (below about 5 million particles over 3 microns diameter per liter) and higher rates when food availability is at its maximum. Therefore, in order to estimate particulate consumption at a site, field work is necessary. Direct effects of current speed on mussel feeding have also been noted by Wildish and Miyares.[13] Recent experiments by CR Newell, B MacDonald and D Wildish in a recirculating flume at the Biological Station, St. Andrews, New Brunswick, Canada, have confirmed the importance of both seston concentration and current speed on mussel feeding behavior. Especially important is the ability of mussels to go from active to passive respiration, reducing energy losses, when there is little food available. In Maine estuaries, mussels maximize their energy gain by the control of pumping rate via the shell gape response. There is promise in the development of a remote video system recording variations in exhalent siphon area and shell gape (distance between valves) to better represent daily averages of mussel

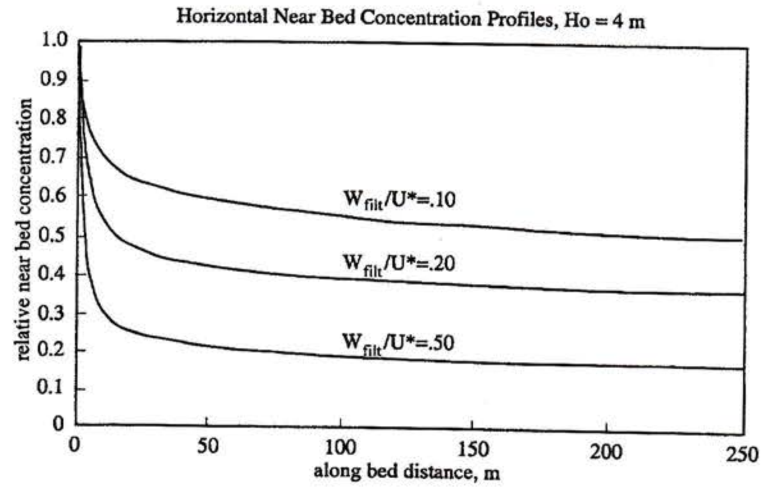

Figure 11. Percent of seston depletion as a function of supply (U*) and demand (W_{filt}) (see also Newell and Shumway[12]).

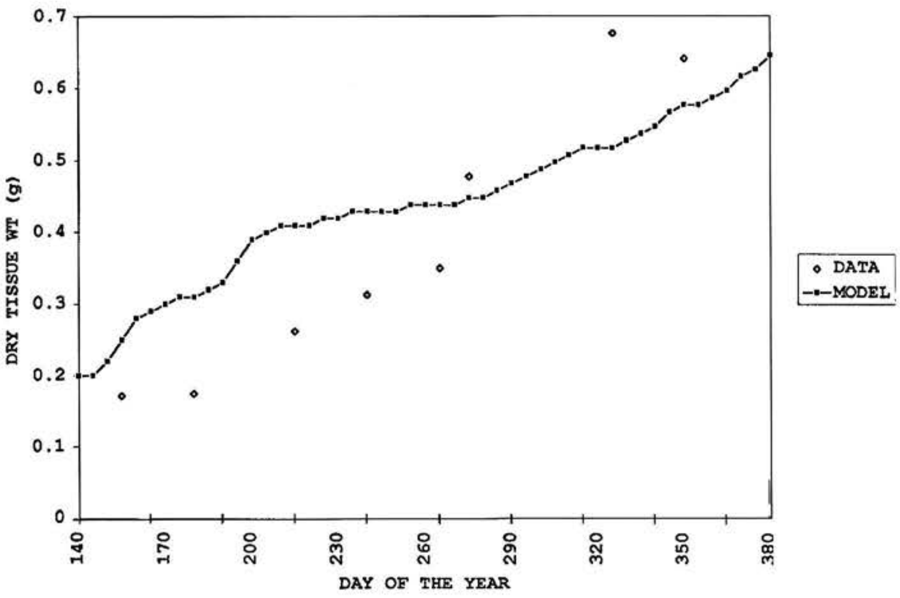

Figure 12. Bottom phytoplankton, bottom detritus and mussel growth from Lunenburg, Nova Scotia, using the mussel model MUSMOD and having all the food available to the mussels in suspension culture. Data points are observed tissue weights supplied by Grant and Bacher,[4] at the Plymouth TROPHEE Workshop in September, 1996. Phytoplankton carbon was estimated from a chlorophyll to carbon regression from Mud Cove, Maine[9] (Table 4).

feeding rates, and these will result in more accurate estimates of seston depletion and carrying capacity at site-specific locations where mussel cultivation is occurring.

Using MUSMOD with suspension culture data: Plymouth workshop

During the Plymouth, England TROPHEE workshop in 1996,[1] a series of mussel models from the United Kingdom, Canada, France, and the Netherlands (including MUSMOD) were tested using independent data on food supply and mussel growth rates at a longline culture operation in Lunenburg, Nova Scotia.[5] When MUSMOD was initially run, there was not enough food mixed to the bottom for the mussels to grow as fast as was observed. When the entire food supply was made available (in suspension culture), mussel growth in tissue weight was a good first-order approximation to the observed growth rates in Lunenburg (Fig. 12).

I thank ACERA, ACOA and CCFI for support to attend the conference in Newfoundland. In addition, Dr. Dan Campbell, Mr. Sam Sankar, and Dr. Vijay Panchang contributed to the flow and mussel modelling, and support was obtained from Great Eastern Mussel Farms, Inc. Thanks to the Ennis Sisters for the nice music at the banquet.

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Calendar

• **52nd Annual Meeting of the Gulf and Caribbean Fisheries Institute,** 1 – 5 November 1999, Key West, Florida, USA. Topics: recent advances in Caribbean aquaculture, management of marine parks and reserves, impacts of anthropogenic activities on marine and freshwater fisheries, marine habitat assessment, recreational fisheries, and the socioeconomics of fisheries management. Information: LeRoy Creswell (e-mail creswell@hboi.edu).

• **FISH RIGHTS '99 Conference, Use of Property Rights in Fisheries Management,** 11 – 19 November 1999, Freemantle, Western Australia. Conference will explore the strategic, political, and operational issues of different forms of rights-based fisheries management worldwide. Information: Secretariat Office, Petrie International, PO Box 568, Kalamunda, Western Australia 6076 (tel (61) 08 9257 2088, fax (61) 08 9257 2099, e-mail petrcon@iinet.net.au).

• **Marketing and Shipping Live Aquatic Products '99, 2nd International Conference and Exhibition,** 14 – 17 November 1999. DoubleTree Hotel, SeaTac Airport, Seattle, Washington, USA. Focus on ornamentals, baits, finfish, shellfish, plants and aquatic foods. Agenda: improved handling technologies, resource management, regulatory concerns, unwanted introductions of non-indigenous species, economics, and animal welfare issues. Information: JB Peters, 5815 NE Baker Hill Road, Bainbridge Island, WA 98110 (fax 360 394-3760, e-mail JohnBPeters@compuserve.com, website http://www.alaska.net).

• **Aquaculture Venezuela '99 and 2nd South American Aquaculture Congress,** 17 – 20 November 1999, Puerto La Cruz, Venezuela. Sponsored by the Latin American Chapter of the World Aquaculture Society. Contact: John Cooksey, 21710 7th Place West, Bothell, Washington, USA (fax 425 483-6319, e-mail worldaqua@aol. com).

• **Aquaculture America 2000,** 2 – 5 February 2000, New Orleans Marriott, New Orleans, Louisiana, USA. Annual meetings of the US Chapter of the World Aquaculture Society, the American Tilapia Association, Striped Bass Growers Association, AFS Fish Culture Section, and the Lousiana Aquaculture Association. Sessions: freshwater crustacean, tilapia, red drum, marine shrimp, tropical fish, reptile, amphibian, salmonid, molluscan, and striped bass culture; water quality; aquaculture regulations; ploidy manipulaiton and sex reversal; recirculating systems; computers and aquaculture; nutritional requirements and diet formulation for shrimp and fish; and aquaculture as a teaching tool. Information: John Cooksey, Conference Manager, 21710 7th Place West, Bothell, Washington, USA (telephone 425 485-6682, fax 425 483-6319, e-mail worldaqua@aol. com).

• **International Conference on Risk Analysis in Aquatic Animal Health,** 8–10 February 2000, Paris, France. Sessions: the need for risk analysis; risk analysis methodology; areas of application to aquatic animal health including problems, research needs and environmental concerns, case histories and field studies; and recommendations and future prospects. Information: Dr. K. Sugiura, Office International des Epizooties, 12 Rue de Prony, 75107, Paris, France (tel 33 (0)1 44 15 18 88, fax 33 (0)1 42 76 09 87, website http://www.oie.int).

• **Conference on Aquaculture in the Third Millennium and Aquaculture and Seafood Fair 2000,** 21 – 25 February 2000, Bangkok, Thailand. Sessions: integrating aquaculture into rural and coastal development; aquaculture and poverty alleviation; involving stakeholders in policy making, planning and management; promoting sustainable aquaculture with economic incentives; building the information base for policy making; establishing legal, institutional and regulatory frameworks; aquaculture production systems; genetics, health management and disease control; nutrition and feeding; culture-based fisheries and enhancement; systems approach to aquaculture management. Exhibitions will be held on aquaculture nutrition and health, seafood and cold storage, and ornamental fish. Conference information: e-mail naca@inet. co.th; website http://naca.fisheries.go.th.

• **National Shellfisheries Association,** 92th annual meeting, 19 – 23 March 2000, Crown Plaza Hotel, Seattle, Washington, USA. Information: Dr. Chris Langdon (tel 541 867-0231, fax 541 867-0105, e-mail chris. langdon@hmsc.orst.edu) or check the National Shellfisheries Association website at http://www. shellfish.org.

• **AQUA 2000,** 2 – 6 May 2000, Acropolis Convention Centre, Nice, France. Annual meetings of the World Aquaculture Society and the European Aquaculture Society. A special thematic session running the full length of the conference will focus on responsible aquaculture — can it accomplished? Information: John Cooksey, Conference Manager, 21710 7th Place West, Bothell, Washington, USA (tel 425 485-6682, fax 425 483-6319, e-mail worldaqua@ aol.com). For program information check the WAS and EAS websites: http://www.was.org and www.easonline.org.

• **Annual Meeting of the Canadian Society of Zoologists,** 3 – 6 May 2000, Algonquin Hotel, St. Andrews, NB. Information: Dr. M. Burt, Huntsman Marine Science Centre, St. Andrews, NB (tel 506 529-1222, fax 506 529-1212, e-mail mburt@nbnet.nb.ca).

• **9th International Symposium on Nutrition and Feeding in Fish**, 21 – 25 May 2000, Miyazaki, Japan. Topics include: Challenges and strategies for aquafeed development in the 2000s, nutrient requirements and availability, nutrient metabolism and its control, alternative protein sources, fish health with reference to fish feed, larval and broodstock nutrition, and nutritional strategies and management of aquaculture waste. Information: Prof. T. Takeuchi, Tokyo University of Fisheries, Konan 4, Minato, Tokyo 108-8477 (tel +81-3-5463-0545, fax +81-3-5463-0553, e-mail take@tokyo-u-fish.ac.jp, website http://www.tokyo-u-fish.ac.jp/fish-nutrition).

• **Aquaculture Canada 2000,** 28 – 31 May 2000, Hotel Beausejour, Moncton, NB. 17th annual meeting of the Aquaculture Association of Canada. This millenial conference and exposition will cover a broad spectrum of aquaculture topics. It will focus on industry and science and will attract growers, suppliers, scientists, administrators, educators and students. Information: Dr. Andrew Boghen, Dept. Biologie, Université de Moncton, Moncton, NB E1A 3E9 (tel 506 858-4321, fax 506 858-4541, e-mail aac2000@umoncton.ca, website http://www.aac2000.org).

• **Fishery 2000 Guang-zhou, The International Fishery Exhibition**, 30 May – 1 June 2000, Chinese Export Commodities Fairground, Guangzhou, P.R. China. Exhibition of seafood, commercial fishing, fish farming and fish processing equipment and technology, seafood transportation systems, refrigeration equipment and technology, and seafood packaging. Information: Top Repute Co., Ltd., Room 2403, Fu Fai Commercial Centre, 27 Hillier Street, Sheung Wan, Hong Kong, P.R. China (tel 852 2851 8603, fax 852 2851 8637, e-mail topreput@hkabc.net).

• **3rd International Conference on Shellfish Safety,** 19– 24 June 2000, Southhampton College, Long Island University, New York. As with previous symposia in this series, presentations will be given dealing with shellfish biology and ecology, chemical and microbiological contamination and assessment, impacts of harmful and toxic algae, depuration technology, monitoring and management, aquaculture and harvesting sites, health and sanitation, and quality assurance programs and regulatory controls. Information: Dr. Sandra Shumway, Natural Science Division, Southampton College, 239 Montauk Highway, Southampton, NY 11968 USA (fax 516 287-8419, e-mail sshumway@southampton.liunet.edu).

• **International Congress on the Biology of Fish**, 23 – 26 July 2000, Abderdeen, Scotland. Information on the meeting is available at the website http://www.fishbiologycongress.org. Plans for symposia are underway. If you have suggestions or would like to be involved in organizing a session, contact Don MacKinlay (tel 604 666-3520, fax 604 666-6894, e-mail mackinlayd@pac.dfo-mpo.gc.ca).

• **Coastal Zone Canada 2000**, 17 – 22 September 2000, Trade and Convention Centre, Saint John, NB. Theme: Coastal Stewardship — Lessons Learned and the Paths Ahead. The conference will focus on four related subthemes: Aboriginal Practices, Community-based Actions, Coastal Health and Oceans Governance. Information: Coastal Zone Canada 2000 Secretariat, Department of Fisheries and Aquaculture, P.O. Box 6000, Fredericton, NB E3B 5H1 (tel 506 453-2253, fax 506 453-5210, e-mail czczcc2000@ gov.nb.ca, website http://www.gov.nb.ca/dfa/czc-zcc2000.htm.

• **Third World Fisheries Congress,** 31 October - 3 November 2000, Beijing, P.R. China. Topics: effect of sustainable fisheries on optmizing food composition and improving human health, scientific management, reasonable exploitation and protection of fisheries, fisheries technologies, machinery and instruments, healthy aquaculture and ecosystems, biotechnology, processing, biodiversity, fishery policies and sustainable development, and application of information technology. Secretariat: China Society of Fisheries, Bldg 22, Maizidian Street, Chadyang District 100026, Beijing, P.R. China (tel 86 10 64194233, fax 86 10 64194231, e-mail csfish@agri.gov.cn).