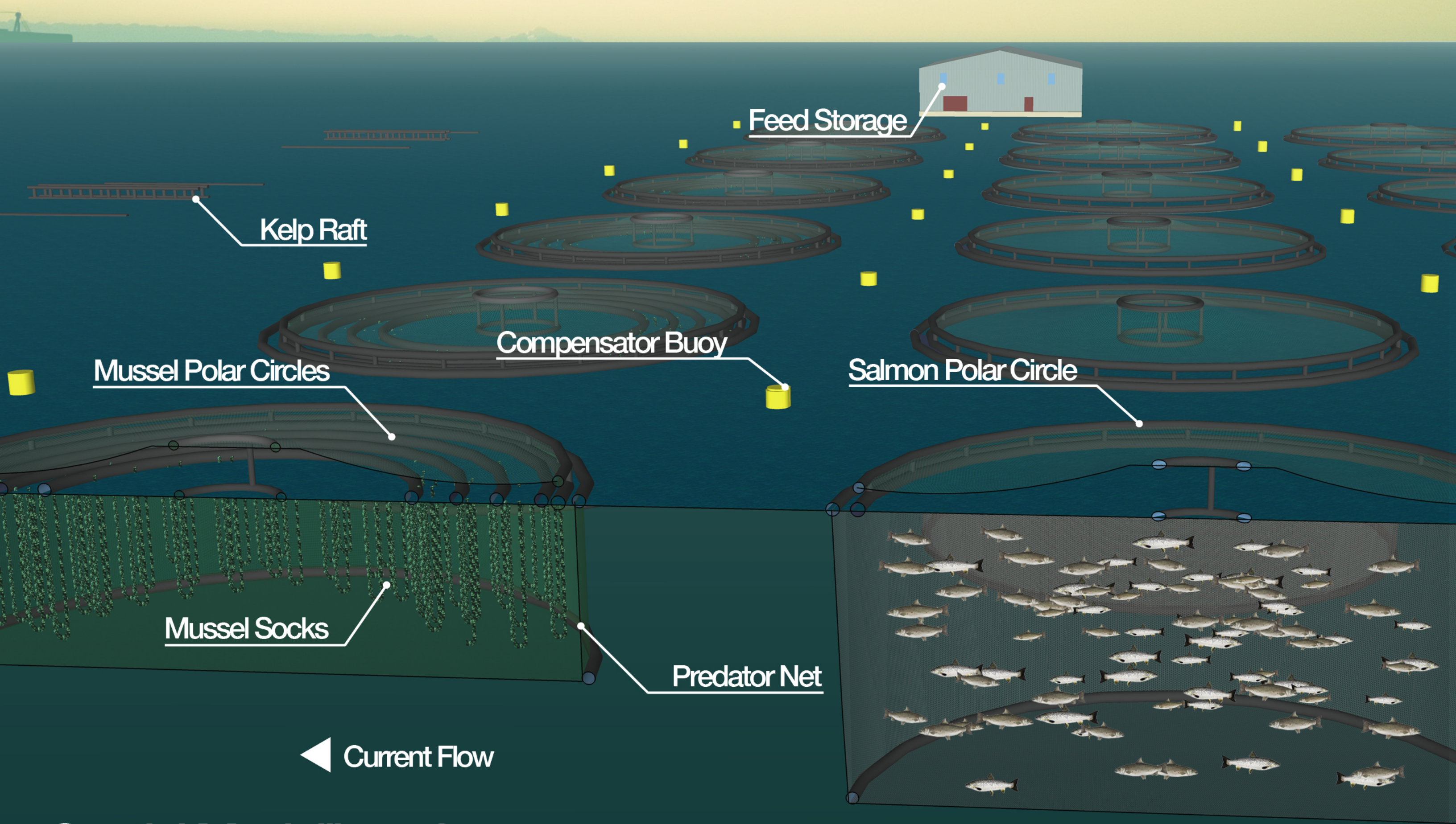
Bulletin

of the Aquaculture Association of Canada



Spatial Modelling of
Integrated Multi-Trophic Aquaculture (IMTA) Shellfish

109-2 (2011)

Bulletin
de l'Association aquacole du Canada
109-2

Vous pouvez recevoir le *Bulletin* en vous y abonnant pour la somme de 60$ 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, St-Andrews (Nouveau-Brunswick), Can ada E5B 3T6 [tél.: 506 529-4766; téléc.: 506 529-4609; courriél.: aac@dfo-mpo.gc.ca; site Internet: http://www. aquacultureassociation.ca]. La cotisation s'élève à 60$ par personne (40 $ pour les étudiants et les retraités) et 95$ 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° 40065445. 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.

ISSN 0840-5417
Imprimé par Taylor Printing Group Inc., Fredericton, N-B

Bulletin
of the Aquaculture Association of Canada
109-2

The *Bulletin* is available through subscription ($60 per year) or as a benefit of membership in the Aquaculture Association of Canada, a nonprofit charitable organization. For membership information contact: Aquaculture Association of Canada, 16 Lobster Lane, St. Andrews, N.B., Canada E5B 3T6 [telephone 506 529-4766; fax 506 529-4609; e-mail aac@dfo-mpo.gc.ca; website http://www.aquacultureassociation.ca]. Annual dues are $60 for individuals ($40 for students and seniors) and $95 for companies; 25 per cent of dues is designated for *Bulletin* subscription. The *Bulletin* is indexed in Aquatic Sciences and Fisheries Abstracts (ASFA) and the Zoological Record. Mailed under Canada Post Publications Mail Commercial Sales Agreement No. 40065445. Change of address notices and undelivered copies should be mailed to AAC. Return postage guaranteed.

ISSN 0840-5417
Printed by Taylor Printing Group Inc., Fredericton, NB

Cover: A Canadian east coast IMTA site schematic, emphasizing the shellfish and fish components. Developed in Google SketchUp by Paul 'Robson' Robertson and Gregor K. Reid

NSERC Canadian Integrated Multi-Trophic Aquaculture Network
Réseau canadien d'aquaculture multitrophique intégrée du CRSNG

Introductory Comments: The CIMTAN Technical Workshop "Spatial Modelling of Integrated Multi-Trophic Aquaculture (IMTA) Shellfish"

T. Chopin

It is my pleasure, as Scientific Director of the Canadian Integrated Multi-Trophic Aquaculture Network (CIMTAN), to provide a few introductory comments for the technical workshop on Spatial Modelling of IMTA Shellfish, held September 19-22, 2011, at the Riverside Resort and Conference Centre in Mactaquac, New Brunswick.

CIMTAN is a Strategic Network funded by the Natural Sciences and Engineering Research Council of Canada (NSERC), Fisheries and Oceans Canada (DFO), the University of New Brunswick (UNB) and its industrial partners Cooke Aquaculture Inc., Marine Harvest Canada Ltd. and Kyuquot SEAfoods Ltd. One of the Network objectives is to provide relevant workshops for CIMTAN researchers, students and partners.

This particular workshop arose from the need to combine network expertise with a multi-disciplinary approach necessary to develop an ecosystem-type shellfish model for open-water IMTA systems. CIMTAN researchers and partners came to explore strategies specific to IMTA systems on both the Pacific and Atlantic coasts. The workshop was fortunate enough to be able to bring in some external expertise, which included Ramón Filgueira, as the model facilitator, and Pedro Duarte, from the University Fernando Pessoa, Porto, Portugal, as a guest presenter.

I am very pleased to have taken part in our first technical workshop. It was very instructive and in cordial atmosphere, conducive to many fruitful exchanges among participants, all under the very able guidance of Dr. Gregor Reid, who led the workshop efficiently and successfully.

Shellfish production is an important contributor to aquaculture and coastal communities in Canada and worldwide. Inclusion of shellfish production, as part of Integrated Multi-Trophic Aquaculture (IMTA) systems, is a fairly recent development in the western world. Spatial modelling of shellfish within IMTA systems and their environment is needed to determine filtration rates of fish farm particles, augmented growth and, consequently, metrics for environmental, economic and societal sustainability. Such models can be complex and necessitate a variety of expertise and collaboration. Our CIMTAN workshop series has been designed to be one of the tools to facilitate such collaboration at the interfaces of disciplines.

While the theme of this technical workshop was directed towards resolving research and development issues in IMTA, you will find that much of the enclosed material is directly applicable to shellfish and finfish aquaculture in general. I encourage you to peruse this publication with that in mind, and invite you to read about our workshop discussion and progress in this latest issue of the Bulletin of the Aquaculture Association of Canada.

Contents

Spatial Modelling of Integrated Multi-Trophic Aquaculture (IMTA) Shellfish

A CIMTAN Technical Workshop

Mactaquac, NB, 19-22 September 2011

Introduction

Invited Papers

Open-water Integrated Multi-Trophic Aquaculture (IMTA): Modelling the Shellfish Component

Gregor K. Reid

G.K. Reid, P. J. Cranford, S.M.C. Robinson, R. Filgueira and T. Guyondet

Modelling shellfish production and particle uptake from fish cages in open-water IMTA presents some unique challenges. The following text reviews shellfish production in the context of open-water IMTA and discusses modelling challenges in detail as a premise for using an ecophysiological model to describe shellfish growth and interactions with their environment. Some of the more pressing issues that need to be addressed during model development include: determination of the relative proportions of natural vs. IMTA diets consumed by the shellfish, quantification of the natural size distribution of fish farm particulates and the capacity of shellfish to capture and ingest the full range of particle sizes, and how to utilize empirical data on shellfish growth at farm and reference sites for model validation given known problems with reference site selection.

Background

Integrated Multi-Trophic Aquaculture (IMTA) is the intensive culture of trophically compatible species proximally connected by nutrient transfer through water. This aquaculture practice typically aims for the nutrient waste of one species to supply wholly, or partially, the nutritional inputs for another. In this manner, a diet introduced to a fed species (*e.g.* fish) that is partially egested as faeces or excreted as soluble nutrients, may have another opportunity for capture by co-cultured species, thereby improving the efficiency of the overall system. This has the potential to reduce possible negative environmental effects of finfish culture that stem from organic and inorganic nutrient enrichment. An additional criteria for optimizing IMTA, is to ensure that more than one trophic level is represented so different categories of 'nutrient streams' have a greater potential to be targeted and captured. In these respects, IMTA is different from the age-old practice of polyculture, where species are grown as extensive culture (low densities) with minimal interactions and may contain only species from the same trophic level.

IMTA species groups can be classified according to the type of 'nutrient stream' targeted, similar to the niche concept in ecology. For example, finfish culture will excrete soluble inorganic nutrients (*e.g.* ammonium, phosphate), generate fine suspended organic particles (faeces and feed 'fines') that settle slowly, as well as larger, rapidly settling, organic material (waste feed pellets and faeces). Consequently, inorganic extractive species such as seaweeds can target the soluble nutrients. Organic extractive species such as shellfish will primarily target fine suspended particulates and deposit feeders (comprised of various species of invertebrates and fish) can target the larger particles.

While organic matter and dissolved inorganic waste mitigation is often cited as the initial rationale for an IMTA approach, there may in fact be several other objectives for practicing open-water IMTA. These are as follows:

1. Waste recovery or transformation
2. Augmented or accelerated growth of co-cultured species
3. Mitigation of pathogens
4. Improved use of coastal area
5. Increased economic diversity and site profitability
6. Improved social acceptance

The Canadian Integrated Multi-Trophic Aquaculture Network (CIMTAN) currently has several research projects, related to most of these objectives. Arguably however, one of the most pressing objectives is determining the degree of excess material recovery (waste extraction benefit) and augmented growth (economic benefit) of co-cultured species. Given the complex nature of all the ecological interactions involved in an aquaculture site, the leaky nature of open-water IMTA operations and the limited capacity to assess system efficiency using water quality measures, some level of system modelling is necessary to quantify these two objectives.

"The primary division of IMTA types, is between open-water and land-based systems. It is much easier to influence nutrient capture efficiency in land-based systems where there is an opportunity to manage multiple-water passes for nutrient extraction"

Variants of open-water IMTA

Aquaculture, in general, has many different manifestations. For example, catfish culture in land-based ponds of southeast United Sates is very different from the mariculture of kelps in China's coastal waters. Likewise, there are several different manifestations of IMTA and the variant will influence production and environmental performance.

The primary division of IMTA types, is between open-water and land-based systems. It is much easier to influence nutrient capture efficiency in land-based systems where there is an opportunity to manage multiple-water passes for nutrient extraction such that co-cultured species may have more than one chance to target a given 'waste stream'. Water flow is also more easily controlled enabling manipulation of the concentration of nutrients through the adjustment of flushing rates. System efficiency can be readily assessed by measuring the concentration differences between tank inflows and outflows. Initiatively, land-based IMTA systems can be more efficient at recycling nutrients than open-water systems, although there may be some environmental 'trade-offs' with the energy resources required to move water and handle wastes. Due to the significant differences between these two IMTA systems, measures of efficiencies from one system can not be reliably extrapolated to the other. Until very recently, the vast majority of scientific literature on the efficiency of IMTA systems has been land-based. There have also been some recent advancements with the development of closed containment aquaculture in marine systems and there may present some additional opportunities for IMTA. To our knowledge however, IMTA is not being practised in such systems at present.

It is useful to categorize the development of open-water IMTA into three types:

1. Addition of co-cultured species to an existing full scale commercial aquaculture farm
2. Custom designed sites specifically developed for IMTA
3. Incidental IMTA through the proximate location of different farms

The first two types of IMTA are practiced in Canada. On the east coast in the Passamaquoddy Bay region (New Brunswick) of the Bay of Fundy, Cooke Aquaculture Inc. has several IMTA sites with blue mussels (*Mytilus edulis* and *trossulus*) and kelps (*Alaria esculenta*, *Saccharina latissima*) cultured adjacent to commercial salmon cages. On the West coast, in Kyuquot Sound off northwest Vancouver Island, Kyuquot SEAFoods Ltd. has custom designed an IMTA site around the culture of sablefish (*Anoplopoma fimbria*), with a dozen species eligible for culture on their site licence. The co-cultured species at this site presently include kelp (*Saccharina latissima*), blue mussels, Japanese scallops (*Patinopecten yessoensis*), sea urchins *(Strongylocentrotus franciscanus, Strongylocentrotus droebachiensis)* and sea-cucumbers (*Parastichopus californicus)*. Both Cooke Aquaculture Inc. and Kyuquot SEAFoods Ltd. are industry partners within CIMTAN.

With an add-on IMTA approach to an existing commercial operation, it is important to note that the site has been selected for optimizing the growth and the operational logistics of the predominant fish culture species. In the case of salmon culture, large sites benefit from placement in accessible areas with high current exchange to reduce accumulation of organics on the sea floor, ensure adequate oxygen supply and recently, to reduce the attachment potential for some external parasites such as sea lice. Consequently, the addition of co-cultured species needs to accommodate these current regimens and associated fish cage configurations. Based on the scale of fish production there will be a specific load of excess organic matter and nutrients available and the IMTA objective to maximize that waste recovery, requires co-cultured species production must be brought up to match this surplus. Husbandry practices (*e.g.* co-cultured species densities, growing structures and locations) also need to be designed in a way to maximize nutrient uptake across the different trophic levels under culture. With a custom designed IMTA site there is greater opportunity to adjust the production ratio between the fed trophic level and extractive species, and arguably more possibilities for locating the site in areas with reduced current flow, to concentrate and deliver waste streams to extractive species. Consequently, there may be a greater potential for site efficiency at the farm-level with a custom designed IMTA site. However, since most finfish production, in general, is supplied through large mono-culture sites, an add-on approach is necessary if IMTA is to be applied to any significant portion of commercial fish production at the present time. Ultimately, this may have some implications for larger scale coastal management.

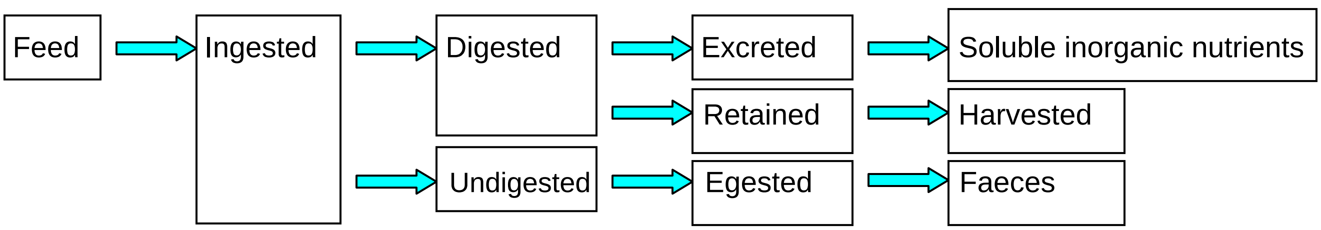
" … since most finfish production, in general, is supplied through large mono-culture sites, an add-on approach is necessary if IMTA is to be applied to any significant portion of commercial fish production … "

Modelling of IMTA systems

Approaches to modelling nutrient recovery may vary depending in the niche or species group. However the first logical step to modelling an IMTA system is to determine the load from the fed or upper trophic level(s). In the case of fish culture nutritional mass balance approaches are reasonably well developed[1, 2]. Nutrients, nutritional categories (*e.g.* protein, lipids) and the energy associated with them can be partitioned along pathways in the production process as illustrated in Figure 1.

Modelling the nutrient recovery potential of the inorganic extractive niche, such as kelps can be relatively straight forward. This is because the concept of nutrient equivalents can be reasonably applied. Soluble inorganic nutrients excreted from fish, will mix in the water column and manifest as a concentration relative to the volumes in which they were dissolved. Removal of a dissolved nutrient from the localized culture area will potentially be reflected in a change of concentration regardless of the nutrient source. This means that nutrient uptake from kelps will have a similar mitigative effect regardless of whether a nutrient molecule specifically came from any fish farm or other source, assuming the excreted nutrient species (NH_4^+) are readily useable by the inorganic extractive niche. This enables a simple comparison with the amount of nutrients removed in harvested kelps with the amount of nutrients excreted by cultured fish. A few studies have used this approach with kelps to estimate nitrogen mitigation potential for open-water IMTA systems[3-6]. This is not to suggest there is no need for a fundamental understanding of when and where nutrient uptake occurs by IMTA kelps. Salmon growth rates and excretion will vary substantially over the seasons and consequently the seasonal grow-out times of candidate kelp or, other seaweed species should be considered in this context. There may also be spatial considerations for kelp deployment in the presence of inorganic nutrient gradients around fish cages, or whether nuisance species may colonize and strip nutrient portions 'destined' for IMTA kelps. Nevertheless, application of nutrient removal equivalents does provide a useful and easily obtained first step for determination of system effectiveness.

Figure 1: Partition of nutrients in fish production. Feed that is ingested but not digested will become faeces. Digested feed will be either retained in the tissue or metabolized and excreted. Carbon that is digested and not retained is respired as carbon dioxide while nitrogen will be excreted as ammonium.



Particulate nutrient removal by shellfish and deposit-feeder IMTA components requires that they specifically target the removal of excess feed and undigested organic matter as it is this material that can be potentially responsible for organic enrichment under fish cages. Environmental impact of finfish farms in Canada are regulated on the basis of their potential to create a harmful alteration, disruption or destruction (HADD) of fish habitat. Currently, the focus is primarily on benthic conditions in close proximity to aquaculture sites and the quality of the oxic conditions. Metabolic processes for microbial decomposition of organic material requires oxygen for electron receptors. If the rate of oxygen demand exceeds the supply, nitrate will be used, then followed by sulphate reduction which generates hydrogen sulphide[7]. Benthic HADD potential at fish farms is determined through measures of hydrogen sulphides as a proxy for impact potential. Consequently, it is presently the actual farm organics that must be targeted in IMTA to reduce impact potential, not nutrient equivalents as is applicable for inorganic extractive species. Determining the nutrient uptake of settleable organics by extractive species can be achieved using a variant of the mass balance approach applied along the pathway in Figure 1. However, this approach can only be practically implemented if it can be assumed that farm organics make up the entire diet (as may be the case with co-cultured deposit feeders), or if we know what percentage of the diet was supplied by outside sources. With knowledge of the digestibility of farm organics (absorption efficiency) and the proportion retained (production efficiency) under typical metabolic conditions and activity, it is possible to estimate the theoretical amount of organics consumed and removed from the system based on harvest biomass.

Challenges measuring and modelling IMTA shellfish

Modelling augmented growth and uptake of fish farm organics by shellfish in open-water IMTA systems present some unique challenges. This is largely because shellfish adjacent to fish cages will consume natural seston (organic particles, phytoplankton and zooplankton) in addition to the potential consumption of fish farm particulates. Consequently, teasing out the proportion of fish farm organics filtered, transformed or removed in harvest biomass relative to natural food sources can be problematic. A link may also exist between the dissolved inorganic nutrients excreted from fish and the potential to enhance planktonic primary production; indirectly influencing shellfish growth(8). This feedback effect may be more likely in warmer climates and areas of slow currents and is less likely to be important in Canadian waters. In the Passamaquoddy Bay area, increases in chlorophyll concentrations at fish farming locations are no different than elsewhere in the Bay(9). Nevertheless, the potential for multiple-routes to augment shellfish growth at fish cages does illustrate some of the complexities and diversity of mechanisms involved in the IMTA shellfish component.

In laboratory studies, it is clear that some shellfish can readily filter, digest and retain fish faeces(10-12). However, evidence of the perceived growth benefit to shellfish in open-water IMTA systems is contradictory. Several studies report augmented shellfish growth or evidence of farm organic uptake in open-water IMTA systems(13-18), while other studies reported no effect(19-21). This implies a substantial influence of site specific factors that affect the concentrations and spatial distribution of finfish wastes through differences in nutrient supply (husbandry) and dilution (advection and dispersion) processes. Together, these studies suggest that the application of general model parameters may be difficult and significant site specific data inputs may be required.

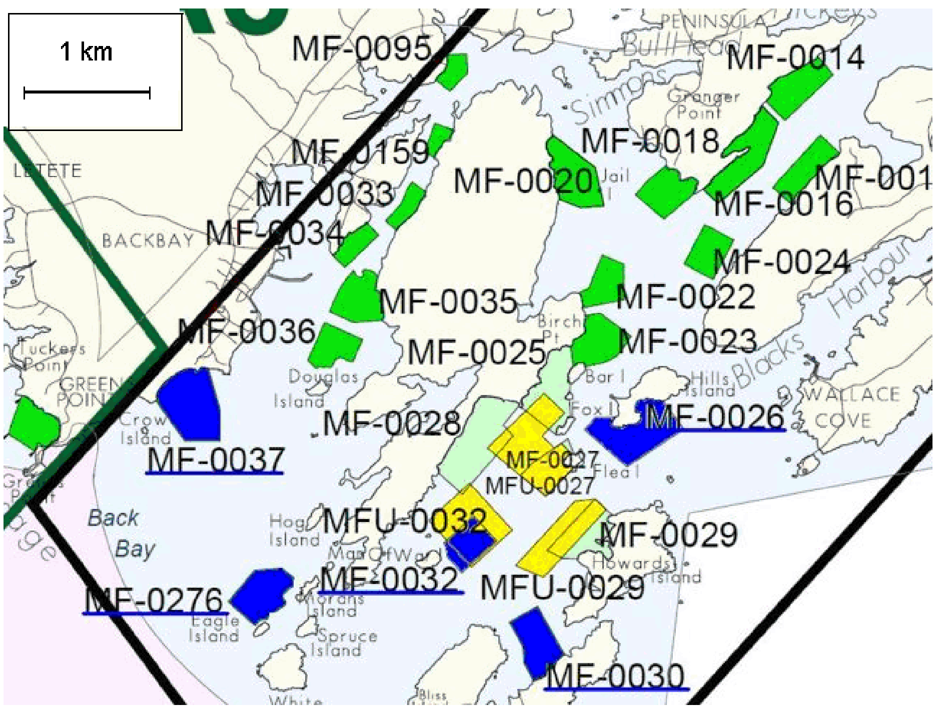
"In laboratory studies, it is clear that some shellfish can readily filter, digest and retain fish faeces. However, evidence of the perceived growth benefit to shellfish in open-water IMTA systems is contradictory."

Given that one of the objectives of shellfish-finfish co-culture is to target fish farm organics, relevant metrics of IMTA efficiency or effectiveness should be determined relative to the organic load from the farm. The shellfish component of IMTA only targets the portion of farm organics within their filtering size range so IMTA efficiency has to be addressed by considering the contributions of all IMTA species. Blue mussels can filter particles between 3 μm(22) and 1000 μm(23, 24). If only 10% of the biomass of farm organics fall within this range, the mussels are incapable of filtering the remaining organic material and the remainder needs to be targeted by additional organic extractive species. Unfortunately, very little is known about the proportion of fish farm organics that lie within the shellfish filtering size range at any given time. In culture systems such as land-based raceways or tank culture, suspended solids (fine particles) in some systems may comprise up to a third of the total organic load(25). Land-based fish culture occurs in a high abrasion environment, with walls, aeration, drains, pipes and the potential for higher stocking densities. It is difficult to extrapolate data on particle size of semi-flocculent material such as fish faeces in such an environment to cage culture scenarios. While it is possible to empirically measure particle size and concentrations in parcels of water at fish cages, this will not provide information on relative proportions of particles from fish faeces, waste feed and natural seston. Organic particle sizes at fish farms are also a function of dietary ingredients and fish size(1). Ingredients may change frequently depending on availability and price. Proportions of ingredients may also change depending on the size of the fish (*e.g.* variation in protein requirements). Different feed companies may source their aqua-feed ingredients differently. As such, there may be no consistency between organic particles from different farms unless the same feed is fed to the same cohorts.

Other limitations on the efficiency of excess nutrient extraction by shellfish include the maximum biomass of shellfish that can be incorporated without leading to additional seabed organic enrichment impacts from shellfish biodeposits. Organic matter in shellfish faeces contains a large proportion of fine natural particles, which will deposit much more rapidly after incorporation into faecal pellets. The IMTA goal of highly efficient nutrient extraction must be balanced against the increase in organic matter flux to the seabed and the associated risks to benthic communities. Nutrient extraction efficiency is also limited by the time the shellfish have to capture the nutrients[26]. While dense shellfish populations have a remarkable ability to filter large quantities of water, there are severe limitations on how much a fixed population can remove from a moving water body.

The second IMTA objective of enhanced shellfish performance may be documented at open-water IMTA sites by comparing shellfish growth at a fish farm with that of growth at a suitable reference site. This allows calculation of the augmented growth potential from IMTA. Unfortunately, there are a number of difficulties with this approach. The first is finding appropriate reference sites. Ideally a reference site should be far enough from the farm to negate potential influences from the farm itself, but close enough to ensure exposure to the same local water quality and hydrodynamics. Complex bay structure, bathymetry and multiple uses of shoreline, may result in significant different in flushing and nutrient loading rates within the scale of hundreds of meters. Location of farm sites can also be problematic. Recent CIMTAN research has shown large spatial variations in particulate material around fish cages. Arbitrarily placing shellfish at a particular location or depth is unlikely to be representative of optimal or average IMTA growth conditions. The second challenge is the potential of unknown influences from localized fish farms in the overall general area. Most east coast IMTA sites are located in high density aquaculture areas (Fig. 2) with the potential for suspended aquaculture particles to travel throughout the bay management area, including to possible reference sites. If this is the case multi-trophic aquaculture may be occurring at a reference site, without the 'integrated' aspect. This is unlikely to be an issue at relatively isolated sites. The third challenge with reference sites, is the difficulty culturing mussels at the same scale or densities they are cultured at on the IMTA sites.

Figure 2: Marine Farm (MF) lease areas (as of 2010) in the Back Bay - Black's Harbour area of Passamaquoddy Bay, on the New Brunswick side of the Bay of Fundy. Green indicates approved leases; yellow sites are proposed; and blue sites are approved for IMTA. Solid lines indicate the borders of Bay Management Areas (BMAs), which are partitioned based on water circulation areas as one method to manage risk of disease transfer.



(New Brunswick Department of Agriculture, Aquaculture and Fisheries, *with permission*)

Shellfish growth differences between IMTA and reference sites may be a reflection of density differences that confound the interpretation of results. On the east coast, Cooke Aquaculture presently uses continuous socking of mussels hanging from concentric polar circles (see cover image). Deploying one of these at a reference site would require an additional aquaculture site licence. The expense is difficult to justify from a business perspective and the collection of truly representative growth data may not even be possible, in locations with limited room for new aquaculture lease areas.

The challenges identified with the collection of empirical data and the filtration of multiple food sources have prompted CIMTAN researchers to explore the option of modifying an ecosystem model, for application to open-water IMTA systems consisting of caged fish, suspended shellfish and kelp components. Models of shellfish culture are well developed and spatial application of such models within a larger ecosystem type model may be one mechanism to address at least some of the aforementioned issues. An advantage to this approach is that since these shellfish models have been well validated with general shellfish culture (correctly reproducing shellfish growth in non-IMTA scenarios). Such models can be run with natural diet as well as with a combined diet, as a means to help ‘tease out’ contribution of farm particulates contributing to growth. A validated shellfish model at a given IMTA site (accounting for both natural seston and fish farm waste) can be used to derive 'virtual' reference conditions by allowing removing the fish farm waste input and predicting the resulting shellfish growth. This can develop predictions of the growth increase potential that could be related to an additional food uptake on fish farm waste. Two of the most common shellfish models that have been used in aquaculture settings are application of the Scope For Growth model[27] and Dynamic Energy Model[28]. Recent work has shown that both models return comparable results[29]. These are described elsewhere in this issue with emphasis on the SFG as a candidate for the spatial modelling of IMTA shellfish.

“The concept of IMTA prompts a robust ecophysiological model describing shellfish growth as well as the interactions of the bivalves with their environment. Ecosystem models can help explain these environmental interactions within complex manipulated ecosystems. ”

Ecosystem modelling as a management tool

Shellfish production models were first developed in the 1970s[30] and variants of these models eventually evolved for inclusion into carrying capacity models. Most development has occurred with *production* carrying capacity and *ecological* carrying capacity[31]. There are several examples of complex, production carrying capacity models. These typically couple the biophysical and geochemical environment, and include physical forcing functions (*e.g.* temperature, food supply, current, tidal exchange, structural drag), compartments (*e.g.* particulate organic matter (POM) in boundary layers, mussel biomass and quantity, shell volume) which are coupled though a series of pathways (*e.g.* POM flux, assimilation, respiration, growth and mortality)[32, 33]. Work on *ecological* carrying capacity models in recent years has focused on the effects of nutrient cycling[34, 35], phytoplankton biomass[36] or both[37]. In the context of aquaculture impacts, biodeposition from mussel culture can cause classical organic deposition impacts[38, 39] and some biodeposition models for shellfish culture have also been recently developed [*e.g.* 40].

The concept of IMTA prompts a robust ecophysiological model describing shellfish growth as well as the interactions of the bivalves with their environment. Ecosystem models can help explain these environmental interactions within complex manipulated ecosystems. The possibility of running different hypothetical scenarios allows an objective exploration of different situations (*e.g.* IMTA configuration or optimal farm location). Such scenario building can be crucial for an effective integration of science and management, allowing the study and evaluation of alternatives and facilitating the decision-making process. In addition, ecosystem models can be complemented with optimization tools, that is, outcome-oriented tools used to make rational and transparent decisions about a well-defined problem, making a system as efficient as possible. Optimization can constitute an ideal and objective way to maximize production of an IMTA site and minimize ecosystem impacts. Together, ecosystem modelling, scenario building, and optimization processes are the ideal group of tools for exploring management strategies in IMTA sites. Ultimately, providing insight into the most challenging objectives related to IMTA performance, determining the degree of nutrient recovery and augmented growth of co-cultured species.

References

1. Reid GK, Liutkus M, Robinson SMC, Chopin T, Blair T, Lander T, Mullen J, Page F, Moccia RD. 2009. A review of the biophysical properties of salmonid faeces: implications for aquaculture waste dispersal models and integrated multi-trophic aquaculture. *Aquac Res.* 40(3):257-273.
2. Papatryphon E, Petit J, Werf H, Sadasivam K, Claver K. 2005. Nutrient-balance modeling as a tool for environmental management in aquaculture: the case of trout farming in France. *Environ Manage.* 35(2):161-174.
3. Broch O and Slagstad D. *in press.* Modelling seasonal growth and composition of the kelp *Saccharina latissima*. *J Appl Phycol*. DOI: 10.1007/s10811-011-9695-y
4. Petrell RJ, Alie SY. 1996. Integrated cultivation of salmonids and seaweeds in open systems. *Hydrobiologia.* 326-327(1):67-73.
5. Abreu MH, Varela DA, Henríquez L, Villarroel A, Yarish C, Sousa-Pinto I, Buschmann AH. 2009. Traditional vs. Integrated Multi-Trophic Aquaculture of *Gracilaria chilensis* C. J. Bird, J. McLachlan & E. C. Oliveira: productivity and physiological performance. *Aquaculture.* 293(3-4):211-220.
6. Troell M, Ronnback P, Halling C, Kautsky N, Buschmann A. 1999. Ecological engineering in aquaculture: use of seaweeds for removing nutrients from intensive mariculture. *J Appl Phycol.* 11(1):89-97.
7. Poole NJ, Wildish DJ. 1979. Polysaccharide degradation in estuaries. In, *Microbial polysaccharides and their degradation* (RC Berkley, DC Ellwood, GW Gooday, eds.), p. 339-416, Academic Press, London.
8. Sarà G, Reid GK, Rinaldi A, Palmeri V, Troell M, and Kooijman SALM. *in press.* Growth and reproductive simulation of candidate shellfish species at fish cages in the southern Mediterranean: Dynamic energy budget (DEB) modelling for integrated multi-trophic aquaculture. *Aquaculture*. DOI: 10.1016/j.aquaculture.2011.10.042
9. Martin LL, LeGresley MM, Strain PM. 2006. Plankton monitoring in the Western Isles region of the Bay of Fundy during 1999-2000. Fisheries and Oceans Canada. *Can. Tech. Rep. Fish. Aquat. Sci.* 2629.
10. Reid GK, Liutkus M, Bennett A, Robinson SMC, MacDonald B, Page F. 2010. Absorption efficiency of blue mussels (*Mytilus edulis* and *M. trossulus*) feeding on Atlantic salmon (Salmo salar) feed and fecal particulates: Implications for integrated multi-trophic aquaculture. *Aquaculture.* 299(1-4):165-169.
11. Redmond KJ, Magnesen T, Hansen PK, Strand Ï, Meier S. 2010. Stable isotopes and fatty acids as tracers of the assimilation of salmon fish feed in blue mussels (*Mytilus edulis*). *Aquaculture.* 298(3-4):202-210.
12. Lefebvre S, Barillé L, Clerc M. 2000. Pacific oyster (*Crassostrea gigas*) feeding responses to a fish-farm effluent. *Aquaculture.* 187(1-2):185-198.
13. Wallace JC. 1980. Growth rates of different populations of the edible mussel, Mytilus edulis, in north Norway. *Aquaculture.* 19(4):303-311.
14. Gao QF, Shin PKS, Lin GH, Chen SP, Cheung SG. 2006. Stable isotope and fatty acid evidence for uptake of organic waste by green-lipped mussels *Perna viridis* in a polyculture fish farm system. *Mar Ecol Prog Ser.* 317:273-283.
15. Taylor BE, Jamieson G, Carefoot TH. 1992. Mussel culture in British Columbia: the influence of salmon farms on growth of *Mytilus edulis*. *Aquaculture.* 108(1-2):51-66.

16. Jones TO, Iwama GK. 1991. Polyculture of the Pacific oyster, *Crassostrea gigas* (Thunberg), with chinook salmon, *Oncorhynchus tshawytscha*. *Aquaculture.* 92:313-322.

17. Lander T, Barrington K, Robinson S, MacDonald B, Martin J. 2004. Dynamics of the blue mussel as an extractive organism in an integrated multi-trophic system. *Bull Aquac Assoc Can.* 104(3):19-28.

18. Sarà G, Zenone A, Tomasello A. 2009. Growth of *Mytilus galloprovincialis* (mollusca, bivalvia) close to fish farms: a case of integrated multi-trophic aquaculture within the Tyrrhenian Sea. *Hydrobiologia.* 636(1):129-136.

19. Cheshuk BW, Purser GJ, Quintana R. 2003. Integrated open-water mussel (*Mytilus planulatus*) and Atlantic salmon (*Salmo salar*) culture in Tasmania, Australia. *Aquaculture.* 218(1-4):357-378.

20. Parsons GJ, Shumway SE, Kuenstner S, Gryska A. 2002. Polyculture of sea scallops (*Placopecten magellanicus*) suspended from salmon cages. *Aquac Int.* 10(1):65-77.

21. Navarrete-Mier F, Sanz-Lázaro C, Marín A. 2010. Does bivalve mollusc polyculture reduce marine fin fish farming environmental impact? *Aquaculture.* 306(1-4):101-107.

22. Møhlenberg F, Riisgård HU. 1979. Filtration rate, using a new indirect technique, in thirteen species of suspension-feeding bivalves. *Mar Biol.* 54:143-148.

23. Newell CR, Shumway SE, Cucci TL, Selvin R. 1989. The effects of natural seston particle size and type on feeding rates, feeding selectivity and food resource availability for the mussel *Mytilus edulis* Linnaeus, 1758 at bottom culture sites in Maine. *J Shellfish Res.* 8(1):187-196.

24. Davenport J, Smith RJJW, Packer M. 2000. Mussels *Mytilus edulis*: significant consumers and destroyers of mesozooplankton. *Mar Ecol Prog Ser.* 198:131-137.

25. Wong KB, Piedrahita RH. 2000. Settling velocity characterization of aquacultural solids. *Aquacult Eng.* 21(4):233-246.

26. Troell M, Norberg J. 1998. Modelling output and retention of suspended solids in an integrated salmon-mussel culture. *Ecol Model.* 110(1):65-77.

27. Winberg GG. 1960. Rate of metabolism and food requirements of fishes. *Transl Ser Fish Res Board Can.* 194:1-202.

28. Kooijman SALM. 1986. Energy budgets can explain body size relations. *J Theor Biol.* 121(3):269-282.

29. Filgueira R, Rosland R, and Grant J. 2011. A comparison of scope for growth (SFG) and dynamic energy budget (DEB) models applied to the blue mussel (*Mytilus edulis*). *J Sea Res.* 66(4):403-410

30. Bayne BL. 1976. Marine Mussels: Their Ecology and Physiology. In, *International Biological Program Part 10* (BL Bayne, eds.), p. 506-511, Cambridge University Press, Cambridge.

31. McKindsey CW, Thetmeyer H, Landry T, Silvert W. 2006. Review of recent carrying capacity models for bivalve culture and recommendations for research and management. *Aquaculture.* 261(2):451-462.

32. Campbell DE, Newell CR. 1998. MUSMOD®, a production model for bottom culture of the blue mussel, *Mytilus edulis* L. *J Exp Mar Biol Ecol.* 219(1-2):171-203.

33. Duarte P, Labarta U, Fernández-Reiriz MJ. 2008. Modelling local food depletion effects in mussel rafts of Galician Rias. *Aquaculture.* 274(2-4):300-312.

34. Guyondet T, Roy S, Koutitonsky VG, Grant J, Tita G. 2010. Integrating multiple spatial scales in the carrying capacity assessment of a coastal ecosystem for bivalve aquaculture. *J Sea Res.* 64(3):341-359.

35. Grant J, Curran KJ, Guyondet TL, Tita G, Bacher C, Koutitonsky V, Dowd M. 2007. A box model of carrying capacity for suspended mussel aquaculture in Lagune de la Grande-Entrée, Iles-de-la-Madeleine, Québec. *Ecol Modell.* 200(1/2):193-206.

36. Grant J, Bacher C, Cranford PJ, Guyondet T, Carreau M. 2008. A spatially explicit ecosystem model of seston depletion in dense mussel culture. *J Mar Syst.* 73(1-2):155-168.

37. Grangere K, Lefebvre S, Bacher C, Cugier P, Menesguen A. 2010. Modelling the spatial heterogeneity of ecological processes in an intertidal estuarine bay: dynamic interactions between bivalves and phytoplankton. *Mar Ecol Prog Ser.* 415:141-158.

38. Cranford PJ, Hargrave BT, Doucette LI. 2009. Benthic organic enrichment from suspended mussel (*Mytilus edulis*) culture in Prince Edward Island, Canada. *Aquaculture.* 292(3-4):189-196.
39. McKindsey CW, Archambault P, Callier MD, Olivier F. 2011. Influence of suspended and off-bottom mussel culture on the sea bottom and benthic habitats: a review. *Can J Zool.* 89(7):622-646.
40. Weise AM, Cromey CJ, Callier MD, Archambault P, Chamberlain J, McKindsey CW. 2009. Shell fish-DEPOMOD: modelling the biodeposition from suspended shellfish aquaculture and assessing benthic effects. *Aquaculture.* 288(3-4):239-253.

Authors

Gregor Reid is with the Canadian Integrated Multi-Trophic Aquaculture Network (greid@unb.ca), working out of the St. Andrews Biological Station (SABS), St. Andrews, NB. Peter Cranford is with Fisheries and Oceans Canada (DFO), Bedford Institute of Oceanography, Dartmouth, NS. Shawn Robinson is with DFO, SABS. Ramón Filgueira is affiliated with the Department of Oceanography, Dalhousie University, Halifax, NS. Thomas Guyondet is with DFO, Gulf Fisheries Centre, Moncton, NB.

Modelling Shellfish Growth Using a Scope For Growth (SFG) Approach

R. Filgueira

Growth models of species with economic value have been directly applied to management aquaculture production and combined with broader ecosystem models to study the implications of aquaculture activity on the ecosystem. One of the most common techniques for modelling shellfish growth is based on the Scope For Growth (SFG) approach. This paper presents the fundamental aspects related to SFG, the different applications of this technique as well as a summary of datasets that are required to construct a model for a specific site.

SFG model

Prediction of shellfish growth has been widely studied over the years due to its direct implications for aquaculture management. More recently, due to the increase in computer power and the development of sophisticated ecosystem models, shellfish growth models have become crucial components for studies: evaluating the effects of aquaculture on the ecosystem[*e.g.* 1, 2], determining the carrying capacity of aquaculture sites[*e.g.* 3, 4], optimizing the profitability of existing farms[*e.g.* 5, 6], and evaluating the potentiality of new cultivation areas[*e.g.* 7, 8]. The need to make accurate growth predictions has promoted the development of individual bivalve growth models, which can be based on empirical, mechanistic or mixed approaches. Two main approaches have been applied to model shellfish growth: Scope For Growth[9] (SFG) and Dynamic Energy Budget[10] (DEB). The SFG approach is based on the measurement of an energetic balance between the energy absorbed from the food and the energy lost in respiration and excretion:

"Two main approaches have been applied to model shellfish growth: Scope For Growth (SFG) and Dynamic Energy Budget (DEB) ... The main difference between them is that DEB is based on theoretical assumptions, while SFG is based on empirical measurements."

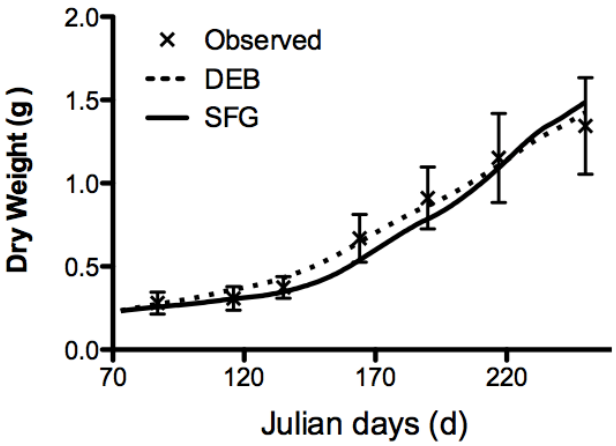
$$P = A - (R + U)$$

Where P, production, is the energy available for growth and reproduction, A is the energy absorbed from the food, R is the respiratory energy expenditure and U is the energy lost as excreta. If this balance is positive, the organism has energy available for growth and reproduction that is manifested as an increase in body weight. In contrast, a negative balance will result in a decrease in body weight as a consequence of the utilization of reserves.

DEB theory describes the energy flow through organisms from assimilation, to allocation, growth and reproduction and maintenance using a mechanistic approach. The main difference between these two modelling approaches is that DEB is based on theoretical assumptions, while SFG is based on empirical measurements. This is a direct consequence of the simplification adopted in SFG modelling. SFG studies organism physiology through the empirical measurement of processes that are relatively easy to measure, and not through the general mechanistic principles in which these processes are based on, in contrast to the DEB approach.

Figure 1

Modelled (dashed and continuous lines for DEB and SFG, respectively) and observed (crosses with bars showing standard deviation) dry flesh mass (mg C) for a mussel population in Pertuis Breton (France).



However, the study of general principles utilized by DEB requires value estimation of several parameters, which can be challenging. Consequently, both model approaches present advantages and disadvantages, and have both been successfully applied to individual shellfish growth models (SFG: Brigolin *et al.*[11]; DEB: Rosland *et al.*[12]). Recently, Filgueira *et al.*[13] compared both models to the same datasets and obtained a similar performance, suggesting that although the basis of SFG and DEB model construction differs, both can successfully reproduce the observed growth of *Mytilus edulis* (Fig. 1).

SFG may be utilized for two main objectives, to determine the energetic status or to provide insight into the growth process of a population. The former provides a rapid and quantitative assessment of the energy status of a population at a given time, which is a direct indicator of the performance of the population in the ecosystem. This indicates for example, if the population is suffering stress or accumulating reserves. Such application of the SFG approach requires experimental measurements of the following physiological data: (1) feeding rate, (2) food absorption efficiency, (3) respiration rate and (4) nitrogen excretion. However, given the changing conditions of the environment these discrete measurements cannot provide a long-term projection of shellfish growth. Therefore, functional relationships of these physiological rates with a broad range of environmental conditions are needed to use SFG models for insight into the population growth process. Given that it may be methodologically costly to establish these functional relationships each time a new aquaculture site is studied, ecological models are usually based on generic equations that are calibrated for each specific site.

General SFG models[*e.g.* 14] for *Mytilus edulis* can be used as a starting point for modelling other populations worldwide. The calibration required for a specific location requires the following time series:

1. Chlorophyll-a, as a proxy for phytoplankton abundance (primary source)
2. Detrital organic matter (secondary food source)
3. Temperature (forcing function on biological processes)

These generic models can be easily modified for different species by modifying physiological parameters and these are frequently available in the scientific literature.

Final remarks

Although SFG and DEB models can be successfully applied in shellfish modelling, the simplification adopted in SFG, arguably facilitates its implementation in ecosystem-level models in cases where the objective of the study focuses more on the ecosystem and not specifically shellfish physiology. Such a generic approach with SFG can be easily exported and calibrated for different locations and species, constituting a powerful tool for predicting shellfish growth.

References

1. Grangere K, Lefebvre S, Bacher C, Cugier P, Menesguen A. 2010. Modelling the spatial heterogeneity of ecological processes in an intertidal estuarine bay: dynamic interactions between bivalves and phytoplankton. *Mar Ecol: Prog Ser*. 415:141-158.
2. Byron C, Link J, Costa-Pierce B, Bengtson D. 2011. Modeling ecological carrying capacity of shellfish aquaculture in highly flushed temperate lagoons. *Aquaculture* 314(1-4):87-99.
3. Ferreira JG, Hawkins AJS, Monteiro P, Moore H, Service M, Pascoe PL, Ramos L, Sequeira A. 2008. Integrated assessment of ecosystem-scale carrying capacity in shellfish growing areas. *Aquaculture* 275(1-4):138-151.
4. Filgueira R, Grant J. 2009. A box model for ecosystem-level management of mussel culture carrying capacity in a coastal bay. *Ecosystems* 12(7):1222-1233.
5. Héral M. 1993. Why carrying capacity models are useful tools for management of bivalve molluscs culture. In, *Bivalve filter feeders in estuarine and coastal ecosystem processes* (RF Dame, eds.), p. 455-477, Springer-Verlag, Heidelberg.
6. Ferreira JG, Sequeira A, Hawkins AJS, Newton A, Nickell TD, Pastres R, Forte J, Bodoy A, Bricker SB. 2009. Analysis of coastal and offshore aquaculture: application of the FARM model to multiple systems and shellfish species. *Aquaculture* 289(1-2):32-41.
7. Brigolin D, Davydov A, Pastres R. 2006. Site Selection Criteria for Off-Shore Mussel Cultivation Use: A Modelling Approach. International Institute for Applied Systems Analysis. Interim Report IR-06-042.
8. Filgueira R, Grant J, Strand Ø, Asplin L, Aure J. 2010. A simulation model of carrying capacity for mussel culture in a Norwegian fjord: role of induced upwelling. *Aquaculture* 308(1-2):20-27.
9. Winberg GG. 1960. Rate of metabolism and food requirements of fishes. *Transl Ser Fish Res Board Can*. 194:1-202.
10. Kooijman SALM. 1986. Energy budgets can explain body size relations. *J Theo Bio* 121(3):269-282.
11. Brigolin D, Maschio GD, Rampazzo F, Giani M, Pastres R. 2009. An individual-based population dynamic model for estimating biomass yield and nutrient fluxes through an off-shore mussel (*Mytilus galloprovincialis*) farm. *Estuarine, Coastal Shelf Sci*. 82(3):365-376
12. Rosland R, Strand Ø, Alunno-Bruscia M, Bacher C, Strohmeier T. 2009. Applying Dynamic Energy Budget (DEB) theory to simulate growth and bio-energetics of blue mussels under low seston conditions. *J Sea Res*. 62(2-3):49-61.
13. Filgueira R, Rosland R, Grant J. 2011. A comparison of scope for growth (SFG) and dynamic energy budget (DEB) models applied to the blue mussel (*Mytilus edulis*). *J Sea Res*. 66(4):403-410
14. Grant J, Curran KJ, Guyondet TL, Tita G, Bacher C, Koutitonsky V, Dowd M. 2007. A box model of carrying capacity for suspended mussel aquaculture in Lagune de la Grande-Entree, Iles-de-la-Madeleine, Quebec. *Ecol Modell*. 200(1-2):193-206.

Author

Ramón Filgueira is affiliated with the Department of Oceanography, Dalhousie University, Halifax, NS. ramonf@dal.ca

Influence of Scale on Estimates of Carrying Capacity: Implications for Modelling Integrated Multi-Trophic Aquaculture (IMTA) Systems

P. Duarte

This report addresses some current challenges to modelling aquaculture systems for Production and Ecological Carrying Capacity (CC) estimation, related to the integration of different spatial scales and the choice of the right spatial resolution. Some possible approaches to these problems are presented and discussed, including criteria to prevent biasing CC.

Introduction

Aquaculture is a rapidly growing industry, contributing more than 40% to the Global consumption of aquatic organisms. The general approach of modern aquaculture is similar to those of industrial agriculture and husbandry, with large energy investment and the usage of chemicals in, predominantly, monoculture systems, with the potential for a large ecological footprint[1]. One approach to improve aquaculture sustainability is the re-use of energy and material that would otherwise be lost in monoculture systems, to improve production while reducing negative environmental impacts. Integrated Multi-trophic Aquaculture (IMTA) systems are designed with these purposes in mind and aim improved aquaculture sustainability.

The concept of sustainability has been used and "abused" over the last two decades. If this concept is to have some practical usage, it is important to establish criteria for its quantification. Alternatively, some proxy to the concept that is more prone to quantification may be used. Carrying capacity (CC) seems to be one such proxy. However, there are several CC categories, regarding coastal aquaculture development, as defined by Inglis et al.[2] and adopted by McKindsey et al.[3]:

"The concept of sustainability has been used and "abused" over the last two decades. If this concept is to have some practical usage, it is important to establish criteria for its quantification."

- (i) Physical CC: the total area of marine farms that can be accommodated in the available physical space
- (ii) Production CC: the stocking density at which harvests are maximized
- (iii) Ecological CC: the stocking or farm density which causes unacceptable ecological impacts
- (iv) Social CC: the level of farm development that causes unacceptable social impacts

A parabolic relationship of yield with investment has been demonstrated for Production CC[4] (Fig. 1). Yield is maximized at the level of investment corresponding to Production CC. The cited authors used as a proxy for investment the number of recruits in bivalve production systems.

Different approaches are required to estimate the CC categories described above such as Geographic Information Systems (GIS), for physical CC, market studies, queries and workshops with stakeholders, for economic and social CC, and models, for Production and Ecological CC (Fig. 2). Decision Support Systems (DSS) using multi-criteria methods may be used to achieve the best compromise among different categories.

The main objective of this report is to emphasize some of the current challenges to modelling aquaculture systems for Production and Ecological CC estimation. Some of the aforementioned challenges are related to the hierarchical nature of these systems, as discussed by the Fréchette[5] bivalve culture example. Consequently, the following questions arise:

(i) What are the relevant spatial scales for aquaculture modelling and CC estimation?

(ii) What is the right resolution for aquaculture modelling and CC estimation?

The modelling methods used for CC estimation depend largely on the answers to these questions. Ecosystem type models typically partition distinct state variables (*e.g.* bivalve biomass, phytoplankton biomass). Flows of energy or material between state variables are quantified as biological fluxes (*e.g.* grazing), which are regulated by external forcing functions (*e.g.* light intensity). Fluxes are normally represented by a series of differential equations that define internal processes. To account for spatial heterogeneity, the ecosystem may be divided in boxes or cells. The size of each box determines the spatial resolution of the model. For a description of the general structure of an ecosystem box model with bivalve suspension-feeders, see Herman[6] and Dowd[7]. Over the last decades there has been an increasing tendency to couple ecological with hydrodynamic models to account for physical and biogeochemical feedbacks[8]. These models compute simultaneously the current velocity field as well as local sinks and source terms for each model cell. These are integrated into the transport equation to calculate concentration changes.

Figure 1

Relationship between yield and investment for Production CC.

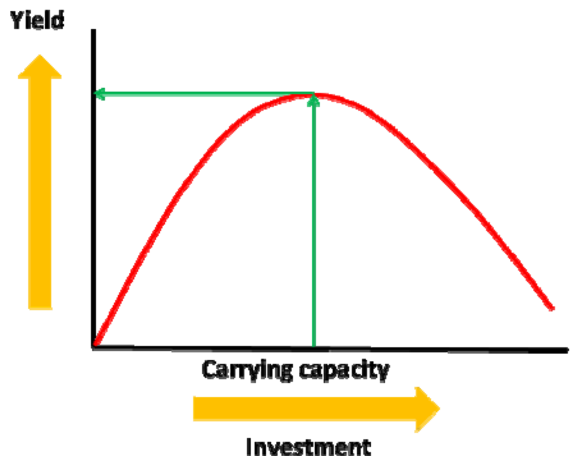
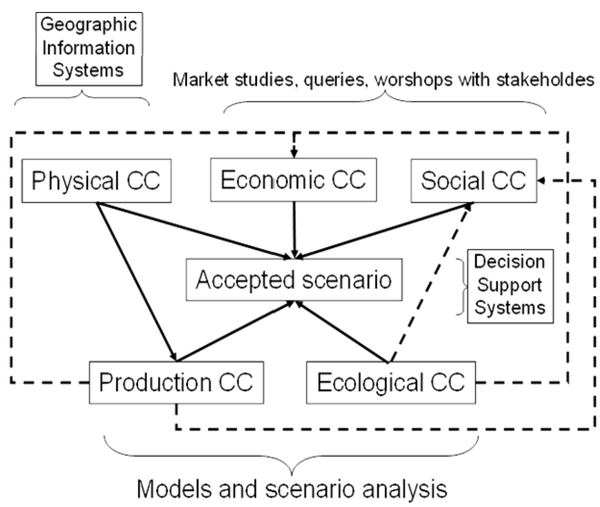


Figure 2

Approaches to quantify different CC categories. Decision Support Systems may be useful to find the best compromise among different categories [1].



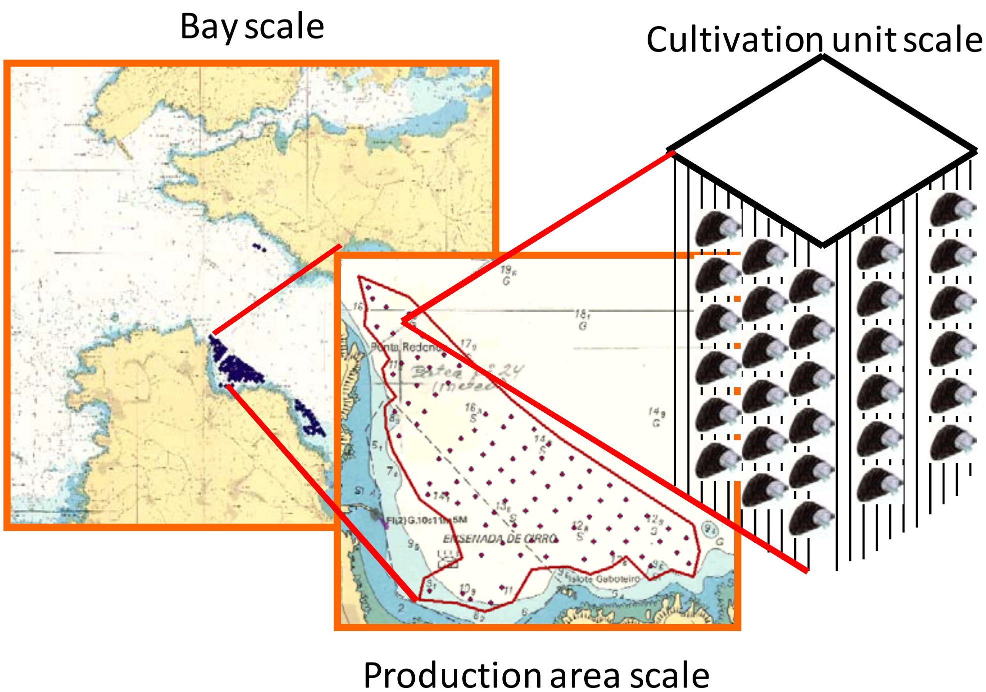
Rationale

An example of the hierarchical nature of aquaculture systems is illustrated in Figure 3, with suspended shellfish culture. At different levels in the hierarchy, physical and biogeochemical processes may have roles of varying importance in defining CC. For example, at the bay scale, biogeochemical processes may play an important role providing food for cultivated bivalves, since the time it takes for phytoplankton to double its biomass is, typically, of a few days which may compare with water residence time. However, at the cultivation unit scale, water renewal is much faster than phytoplankton growth and, therefore, more important in providing food for suspension-feeders. Furthermore, there are feedbacks across the hierarchical levels. For example, water leaving a cultivation area may be food depleted, reducing energy input to organisms located downstream. This complexity suggests that models should integrate different spatial scales to properly estimate CC. A similar reasoning may be applied to other forms of aquaculture. In the case of finfish, natural food depletion is not a problem since organisms depend on artificial diets. However, biogeochemical and physical processes are of utmost importance in removing metabolites and replenishing oxygen in fish cages. Coupling these processes raise the question of how different spatial scales may be integrated in models, such as those depicted in Figure 3? This may be achieved by increasing model resolution to the smallest "relevant" scale[9, 10]. Frequently however, this would involve unaffordable computational costs. Challenges defining the smallest "relevant' scale or appropriate resolution, will be discussed first.

Using the example of bivalve suspension feeding culture, Duarte *et al.*[11] proposed several criteria to define adequate spatial resolution of Production CC models. In Figure 4, water residence time (RT), primary production rate, as reflected by cell doubling time (PT) and the time taken by bivalves to clear a specific volume of water (CT)[12] are plotted against a spatial scale. These results were partly obtained from a model described in Duarte *et al.*[9]. PT is relatively independent of the spatial scale considered. RT is proportional to the spatial scale. CT is more or less independent of the spatial scale within the cultivation units, where bivalve densities are homogeneous, but it tends to increase at larger scales, when bivalve cultivation does not occupy all available space.

Figure 3

The hierarchical structure of aquaculture systems, exemplified with a Galician Ria, from the bay to the cultivation unit scale/raft.



If a model has a spatial resolution coarser (greater) than c.a. 3000 m, it will tend to overestimate local CT (Fig. 4), underestimating food depletion and leading to a probable Production CC overestimation. This bias may be prevented by choosing a spatial resolution better than 3000 m, where RT tends to be smaller than CT. If such a resolution is not possible to achieve, the system can be considered to be beyond its Production CC[11].

The above reasoning applies to a specific CC category and to a specific cultivation type. However, a similar approach may be attempted to other CC categories and aquaculture systems with proper adaptations. Another important advantage of choosing an appropriate high resolution is to guarantee that RT is smaller than other processes in order to fulfill the usual assumption of homogeneity in water properties within the cells or boxes of model grids used for CC estimation.

As mentioned previously, the selection of adequate spatial resolution may lead to unaffordable computational costs in some instances. This may result not only from the larger number of cells on the computational grid, but also due to the smaller time steps required to fulfill the stability criteria of the numerical computations defined by the Courant condition (Fig. 5). There are some alternatives that can be considered to resolve this problem.

One possible alternative to increasing grid resolution in the overall model domain (Fig. 5), may be to use nested grids or variable size grids. In the previous case, it is possible to have a highly detailed model running within the grid of a coarser model as is a usual practice in oceanography models[13] (Fig. 6). The larger scale model may provide the hydrodynamic forcing for the smaller scale one and two way feedbacks may be computed with respect to water quality variables.

Another alternative is to integrate processes at smaller spatial scales within larger scales in such a way as to avoid the bias discussed above. Let's consider again the mussel raft culture example. The size of mussel rafts is of the order of tens of meters. For example, in Galician Rías they are c.a. 25x20 m. Let's assume that, due to computational overhead, it is not practical to use a resolution smaller than c.a. 100 m, as shown in Figure 7. Consequently, bivalve densities within each cell will be a function of the number of rafts located within that cell and the enclosed water volume. Since this volume is larger than the volume occupied by mussel rafts, it follows that bivalve densities in the model are "diluted" and local food depletion effects may be underestimated, as discussed above. One possible way to solve this problem is to compute food depletion within the raft as a function of raft size, current velocity and mussel raft density. If this may be done analytically, there is no need to increase grid resolution. In this particular case, the approach described in Duarte *et. al.*[14] may be followed assuming that clearance rate is constant across the raft, that food particle decay follows a first order kinetics and that the front of the raft turns towards the current:

Figure 4

Selection of the adequate resolution for bivalve Production Carrying Capacity (adapted from Duarte *et al.*[11]). Arrow on lower left corner depicts appropriate spatial scale/resolution for Production CC estimation (see text).

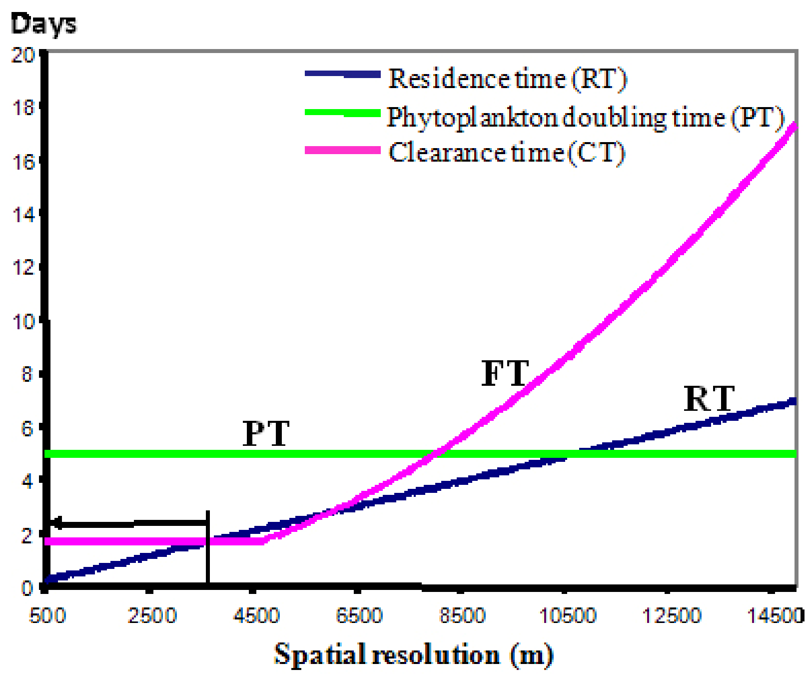
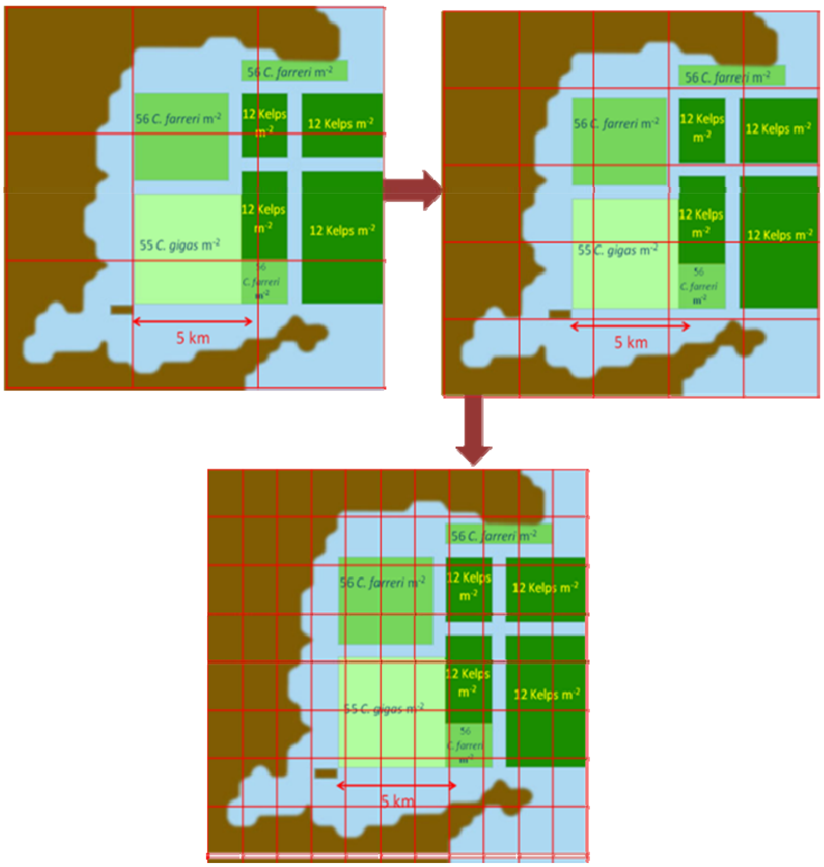


Figure 5

Increasing spatial resolution implies a larger number of computational cells and a smaller time step leading to an increasingly larger computational overhead.



(1)

$$C_x = C_0 \cdot \exp\left(-\frac{CR.N.x}{Q}\right)$$

(2)

$$FR_x = CR.C_0 \cdot \exp\left(-\frac{CR.N.x}{Q}\right)$$

Where C_0 and C_x (equation 1) are food concentrations before water enters the mussel raft and at a distance x within the raft, respectively, Q is water flow, CR is mussel individual clearance rate and N is the mussel number per unit of length. Integrating equation 2 across raft length allows calculating an average filtration rate (equation 3):

(3)

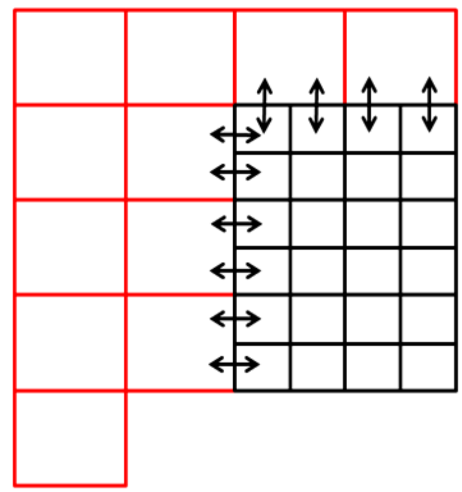
$$\overline{FR} = \frac{CR.C_0 \cdot \int_{x0}^{x1} \exp\left(-\frac{CR.N.x}{Q}\right) dx}{\Delta x} \Leftrightarrow \frac{C_0 \cdot Q\left[-\exp\left(-\frac{x1.CR.N}{Q}\right) + \exp\left(-\frac{x0.CR.N}{Q}\right)\right]}{N.\Delta x}$$

From the average FR and the total number of mussels in the rafts located in each cell, a sink may be calculated and used in the transport equation. Using this method, local food depletion is addressed without any "dilution" effect. The feeding function is affected not by the concentration of feeding particles in the model cell but by their concentration across the mussel raft and the final concentration within the cell will be reduced as a function of depletion within the raft.

This approach may be generalized to any other process within cultivation units, in models that do not resolve them spatially. If an analytical approach is not possible due to the complexity of functions involved it is always possible to use a numerical approach that will slow down the model but, almost certainly, much less than using a finer grid.

Figure 6

Nested grids (see text).



Final remarks

Apart from challenges with appropriate resolution, there are a number of additional scientific and technical challenges relating to which processes and variables should be included in CC models; in addition to which modelling approaches are more adequate to simulate growth and production of cultivated species. The model used will in part be a preference of the user. In the case of shellfish for example, some researchers may prefer the Scope for Growth paradigm whereas others will prefer the Dynamic Energy Budget paradigm.

Furthermore, apart from physiologic paradigms, in some cases it may be necessary to simulate some species as structured populations, including population dynamics in models when, for example, it is important to quantify the part of the population that has economic importance (for an example see Ferreira *et al.*[(15)]).

Given the diversity of aquaculture systems, species and areas, it is difficult to achieve a common modelling approach. However, the development of guidelines for minimum model requirements of Production and Ecological CC would benefit from the inclusion of some common approaches to simulate the different processes. Such guidelines would help determine best approaches for the following:

(i) Coupling physical and biogeochemical processes

(ii) Physical detail of model grids

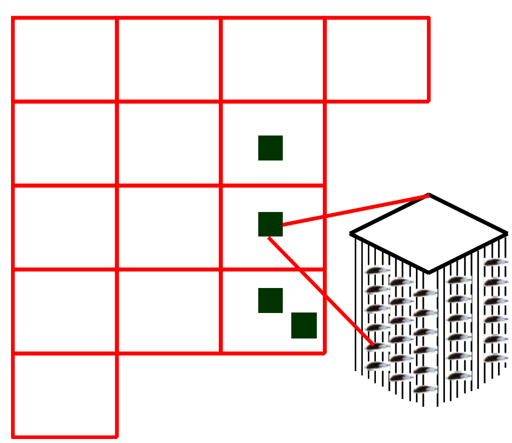
(iii) Inclusion of functional groups

(iv) Determination of physiologic approaches

(v) Species as unstructured or structured populations

Figure 7

Part of a model grid (red quadrates) and some mussel rafts (green quadrates) (see text).



It is clear there are a number of issues requiring resolution in the context of CC modelling. This report emphasized resolution problems and proposed some solutions for a specific aquaculture type. In the case of IMTA however, these problems must be analyzed for all cultivated species and this may introduce another layer of complexity. Nevertheless, despite some of the aforementioned challenges, the approaches presented here should provide a good foundation for expanded efforts in IMTA modelling.

References

1. Serpa D, Duarte P. 2008. Impacts of aquaculture and mitigation measures. In, *Aquaculture 1. Dynamic Biochemistry, Process Biotechnology and Molecular Biology 2 (Special Issue 1)* (R Ruso, eds.), p. 1-20, Global Science Books.
2. Inglis GJ, Hayden BJ, Ross AH. 2000. An Overview of Factors Affecting the Carrying Capacity of Coastal Embayments for Mussel Culture. NIWA. *Client Report CHCOO/69*.
3. McKindsey CW, Thetmeyer H, Landry T, Silvert W. 2006. Review of recent carrying capacity models for bivalve culture and recommendations for research and management. *Aquaculture*. 261(2):451-462.
4. Bacher C, Duarte P, Ferreira JG, Héral M, Raillard O. 1997. Assessment and comparison of the Marennes-Oléron Bay (France) and Carlingford Lough (Ireland) carrying capacity with ecosystem models. *Aquat Ecol.* 31(4):379-394.
5. Fréchette M. 2010. Hierarchical structure of bivalve culture systems and optimal stocking density. *Aquac Int.* 18(1):99-114.
6. Herman MJ. 1992. A set of models to investigate the role of benthic suspension feeders in estuarine ecosystems. In, *Bivalve Filter Feeders in Estuarine and Coastal Ecosystem Processes* (RF Dame, eds.), p. 421-454, Springer-Verlag, Heidelberg.
7. Dowd M. 1997. On predicting the growth of cultured bivalves. *Ecol Modell.* 104(2-3):113-131.
8. Pereira A, Duarte P, Norro A. 2006. Different modelling tools of aquatic ecosystems: A proposal for a unified approach. *Ecol Inform.* 1(4):407-421.
9. Duarte P, Meneses R, Hawkins AJS, Zhu M, Fang J, Grant J. 2003. Mathematical modelling to assess the carrying capacity for multi-species culture within coastal waters. *Ecol Modell.* 168(1-2):109-143.
10. Duarte P, Azevedo B, Ribeiro C, Pereira A, Falcão M, Serpa D, Bandeira R, Reia J. 2007. Management oriented mathematical modelling of Ria Formosa (South Portugal). *Transition Water Monographs.* 1:13-51.
11. Duarte P, Hawkins AJS, Pereira A. 2005. How does estimation of environmental carrying capacity for bivalve culture depend upon spatial and temporal scales? In, *Proceedings of the NATO Advanced Research Workshop*, Comparative Roles of Suspension-Feeders in Ecosystems. 121-135. Springer, Dordrecht, The Netherlands.
12. Dame R, Prins T. 1997. Bivalve carrying capacity in coastal ecosystems. *Aquat Ecol.* 31(4):409-421.
13. Dyke PPG. 2001. Coastal and Shelf Sea Modelling. Kluwer Academic, Boston.
14. Duarte P, Labarta U, Fernández-Reiriz MJ. 2008. Modelling local food depletion effects in mussel rafts of Galician Rias. *Aquaculture.* 274(2-4):300-312.
15. Ferreira J, Duarte P, Ball B. 1997. Trophic capacity of Carlingford Lough for oyster culture: analysis by ecological modelling. *Aquat Ecol.* 31(4):361-378.

Acknowledgments

The author wishes to thank the Canadian Integrated Multi-Trophic Aquaculture Network (CIMTAN) for the kind invitation to participate in the workshop, Spatial Modelling of IMTA Shellfish, in Fredericton (Mactaquac), Canada, between the 19th and the 21st of September 2011.

Author

Pedro Duarte is from the University Fernando Pessoa CIAGEB (349 Praça 9 de Abril, 4249-004 Porto, Portugal, pduarte@ufp.pt, TL: +351225071300) with the Interdisciplinary Centre for Marine and Environmental Research – CIIMAR (Rua dos Bragas, 289, 4050-123 Porto, Portugal)

The Role of Three Dimensional Habitats in the Establishment of Integrated Multi-Trophic Aquaculture (IMTA) Systems

Shawn Robinson

S.M.C. Robinson, J.D. Martin, J.A. Cooper, T.R. Lander, G.K. Reid, F. Powell, R. Griffin

In order for co-cultured species in IMTA systems to assimilate the scale of settling particulate material from commercial fish production in cages, simple two dimensional structures on the bottom are unlikely to be sufficient, and utilization of three dimensional space will instead be necessary. At an Atlantic salmon (*Salmo salar*) farm, a 2.5 m x 2.5 m x 5 m artificial benthic reef, containing green sea urchins (*Strongylocentrotus droebachiensis*) and giant sea scallops (*Placopecten magellanicus*), was deployed next to salmon cages. One year after deployment, both species were flourishing in addition to some feral species that populated the structure. Both feral and cultured species appeared to benefit from the combination of an appropriate substrate and the flux of organic material originating from fish cages. We conclude from this initial study that organisms are able to successfully exist in high enrichment areas as long as suitable habitat and environmental conditions can be maintained. Further studies on the biological interactions are planned.

Introduction

The underlying concept of Integrated Multi-Trophic Aquaculture (IMTA) is directly related to the intentional recapture and recycling of waste food nutrients (*i.e.* energy) through various trophic levels. The degree to which these species interactions are successful will determine how successful the IMTA operation will be. This recycling of waste nutrient philosophy is in tune with the industry's requirements for more efficient and cost-effective production methods, and society's demands for greater ecological sustainability and higher levels of social acceptability.

The salmon aquaculture industry worldwide grows fish at large industrial scales, following the modern agricultural model of growing food in large volumes with substantial amounts of automation. As would be expected, when animals exist in large concentrations, large amounts of food are consumed and correspondingly large amounts of metabolic by-products are also produced and deposited within relatively small spatial areas. As a result, surplus nutrient loading around fed aquaculture sites can be quite large and therefore, because of the volumes and dispersion, the solutions to deal with this nutrient surplus will have to be both practical and efficient. In all likelihood, there will need to be multiple solutions available to a farmer since there is a high probability of differences among habitats and species involved.

Developing the concept

In order to understand how to design successful IMTA systems that can exist within the current aquaculture industry, it is important to understand some of the physical forces that are at work and that will have an effect on the delivery of food to the target organisms.

One of these forces is the effect that the sea bottom has on the flow of water traveling over it. As the water moves across the bottom, friction is created with the result that the water slows down as it gets closer and closer to the bottom to the point where the velocity is zero right at the surface. The region where the water velocity is affected by the bottom friction is known as the Benthic Boundary Layer (BBL). Depending on where you are in the ocean, the BBL may range from a few cm to 100 m[1]. Since many benthic organisms receive their food via transport on water currents, a slowdown in the current speed results in a lower flux rate of food being brought to them. As a result, many organisms position themselves higher up in the water column on various structures in order to optimize the amount of food available to them.

Therefore, the amount of food available to an organism could be described as:

$$\text{Food available} = \text{concentration } x \text{ delivery rate} \qquad (1)$$

"The biomass capable of being grown in an aquaculture situation is directly proportional to the surface area available for habitation or colonization and subsequent growth."

where concentration is measured in biomass per unit volume (*e.g.* mg L^{-1}) and is determined by the amount of excess feed and waste delivered from a fed system. The delivery rate is measured as volume per unit time (*e.g.* L min^{-1}) and is determined by the flow of water. Food availability relates directly to the size of the fed component of the IMTA operation and the physics of food delivery which may modify the particle size during its delivery. This is an inherent characteristic of the feeding system and is not something that can be easily modified since the original food is targeted for another organism.

If we were interested in the amount of nutrients being removed from the system as a measure of the efficiency of the IMTA operation, we could describe this as:

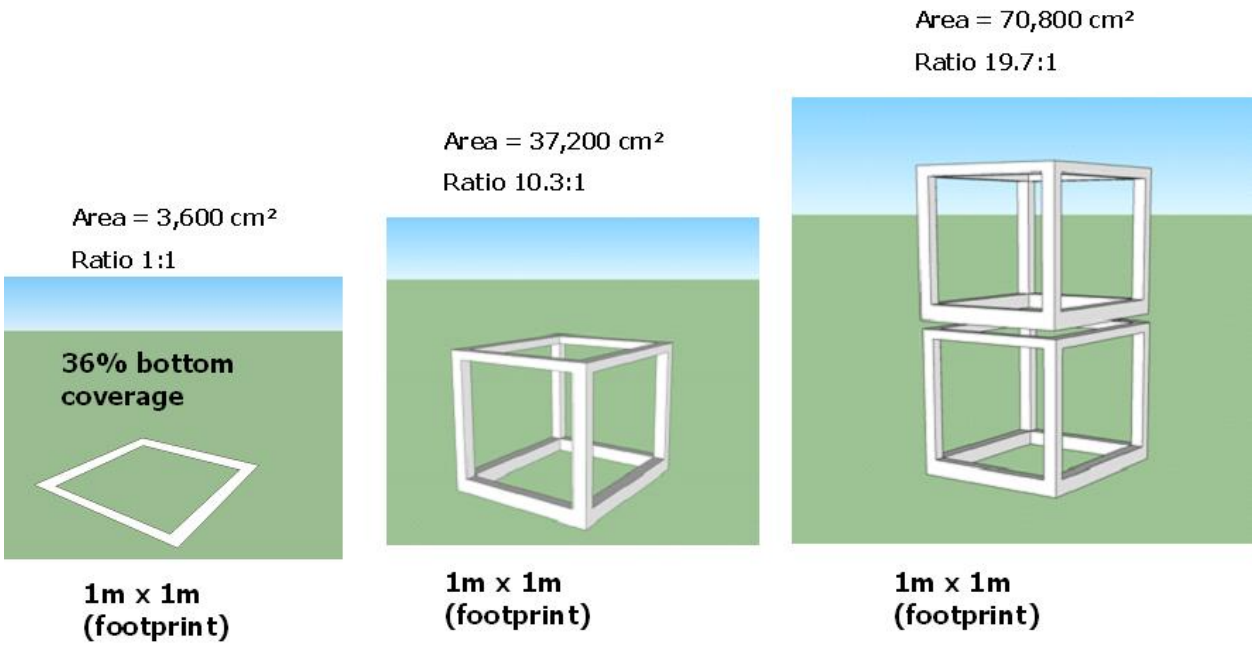
$$\text{Nutrients removed} = \text{capture efficiency } x \text{ food available } x \text{ biomass available} \qquad (2)$$

where the nutrients removed represent the total biomass of nutrients sequestered. The capture efficiency is an inherent characteristic of the organism and how it exploits a certain niche within the ecosystem. It is represented as the percentage of the food available that the organism is able to successfully capture and assimilate. The food availability is described above. The biomass available is user-defined and can be modified by the IMTA farmer choosing which species and how many are to be integrated into the system in order to optimize the total amount of nutrients captured.

The biomass capable of being grown in an aquaculture situation is directly proportional to the surface area available for habitation or colonization and subsequent growth. A simple example demonstrates this. Assume we have a simple, flat 1 m^2 square quadrat with a frame width of 10 cm and place this on the sea bottom (Fig. 1). This square frame would have an area of 3,600 cm^2 and cover 36% of the sea bottom within that 1 m square. However, if we convert that 2-dimensional 1 m^2 frame into a three-dimensional cube (a simple reef), the surface area of all the surfaces available for colonisation increases by an order of magnitude while still maintaining the same relative benthic footprint of 3,600 cm^2. If we add a second cube on top of the first one, then the surface area available for colonisation increases by a factor of almost 20 over the original two-dimensional footprint (Fig. 1). Therefore, this simple example indicates that the construction of three dimensional surfaces within an IMTA site will be one of the key components in increasing the biomass available to assimilate nutrients coming from the fed components because it provides the support for the addition of surface area above the benthic boundary layer which improves both food availability (equation 1) and structure to increase available biomass (equation 2). Obviously, the scales of commercial configurations to deal with the large nutrient sources coming from industrial aquaculture could be even greater with more complex shapes that are incorporated into the construction of a reef.

Figure 1

Schematic diagram of a conceptual footprint and surface area of 3-dimensional shapes that could be used as an artificial reef. The area represents the surface area of the structure in cm^2. The frame width is 10 cm, with an inner square diameter of 80 cm. The ratio represents the surface area of the 3-dimensional structure divided by the area of the original 2-dimensional frame (3,600 cm^2).



Objectives

We chose to investigate the feasibility of this concept in 2009 by testing the efficacy of a subtidal reef/cage on one of the IMTA sites in southwestern New Brunswick, Bay of Fundy. The objectives of this study were to:

1. Evaluate the construction, transportation and installation of reef structure within an IMTA aquaculture site. Look at feasibility in relation to interactions with industry operation, interactions with physical environment, the ability to introduce species and monitor changes.
2. Evaluate the performance of two potential IMTA species, the green sea urchin (*Strongylocentrotus droebachiensis*) and the giant sea scallop, (*Placopecten magellanicus*) that might be incorporated into future trophic modules of an IMTA site based on their growth responses to the conditions encountered within the raft as a result of the nutrient plumes coming from the large-sized organic particulates of the salmon cage.
3. Observe the behavioural interactions of some of the local species to the introduction of the reef.

Figure 2

Photographs of the artificial reef at the Crow Island site, while under construction (top) and the reef deployment (bottom).

Materials and methods

A reef was constructed at the fabrication facilities of the industrial partner Cooke Aquaculture Inc. out of black plastic pipe (12 inch (30.5 cm) diameter high density polyethylene) with a dimension of 2.5 m high *x* 2.5 m wide *x* 5 m long (Fig. 2). It was deployed using a barge next to a salmon cage at the Crow Island site (MF-0037) in 15 m depth (mean low water) on a bottom of soft mud in January 2009. The reef was a series of eight double 3-dimensional cubes, similar to the shape in Figure 1. The bottom series of cubes were left open in order to facilitate water flow, while the top ones held wire or nylon mesh cages in which various species could be placed for growth performance trials.

In January 2009, 200 green sea urchins (*Strongylocentrotus droebachiensis*) were measured and placed into two plastic coated wire mesh (50 mm mesh size) cages with plastic snow fencing inserts in order to allow the sea urchins to climb and maintain their position in the cage. The cages were deployed by diver and secured in the reef with the use of rubber straps. The cages were left with no further interventions for a year except for occasional observational dives.

In addition, 400 sea scallops (*Placopecten magellanicus*) were measured; a square notch was made in the edge of the shell with an electric Dremel™ tool with a round cutting wheel and placed in four 5-tier Japanese-style lantern nets. Both species were left to grow for an entire year and were sampled again in March 2010 where they were re-measured to the nearest 0.1 mm with callipers.

Traditional experimental controls for species performance were not possible with this experiment as it was logistically impossible to place a similar reef in a reference site where there was no salmon aquaculture due to the costs associated with installing another reef and the lengthy and costly process to obtain the marine permits required for a new aquaculture site. Growth on either wild or cultured species found in the area was derived from previously published studies[2-9].

Results

The logistics of deploying the artificial reef were very simple and problem free. The raft was delivered by truck where it was unloaded at the high tide mark on a sand beach close to the aquaculture site. At high tide, the barge attached lines to the reef and slowly pulled it into the water where it was attached to the side of the vessel and towed to the aquaculture site. Weights were attached to the bottom corners of the reef and it was slowly lowered to the bottom by a bridle and a line with a surface float attached. Manipulating the cages in the reef underwater by a pair of divers was fairly easy.

The sea urchins adapted readily to the captivity of the cages. They used both the vertical surfaces of the wire sides of the cage as well as the snow fence partitions. They were regularly seen hanging from the top of the cage by their tube feet where the oral side of the sea urchin was facing up, often eating food particles that had fallen down and landed on the cage surface.

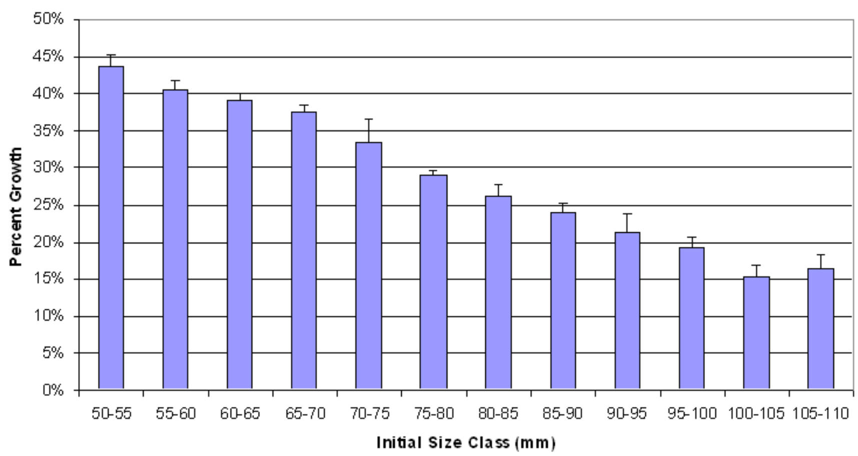
The sea urchins in the cages in the underwater reef grew significantly larger (t-test, $p<0.001$) over the course of the year they were in captivity from a mean size of 52.6 mm (± 5.9 mm SD) in 2009 to 56.4 mm (± 5.2 mm SD) in 2010 representing a 7% increase in test diameter. The daily growth rate in test diameter was calculated to be 0.008 mm per day. There was a 34% loss of sea urchins from the cages which was likely a combination of both mortality and escape as some of the urchins appeared to have squeezed out between the openings in the cage judging by their rapid appearance on the black plastic pipe surfaces after initial deployment. The experimental urchins were not tagged in any fashion so they were indistinguishable from any wild sea urchins that also gradually moved in to colonize the reef.

The sea scallops also adapted to the conditions in the lantern nets in the nutrient plume of the salmon cage. The animals maintained an even distribution within the net layers and there was no sign of disturbance where the animals would "bite" or "knife" each other as a result of flight behaviour from some negative stimulus eliciting escape responses through swimming. Visual observations by the divers indicated that the animals were open and generally feeding normally. Biofouling on the shell surfaces appeared to be minimal.

The sea scallops grew significantly larger from a mean size of 72.6 mm (± 15.9 mm SD) in 2009 to 107.9 mm (± 10.4 mm SD) in 2010 (t-test, $p<0.001$). The average daily growth rate in shell height was calculated to be 0.072 mm per day. The average percent increase in shell height varied by size class (Fig.3), but the overall size increment for all size classes was 33%. Mortality in the lantern nets of the scallops was 13%.

Figure 3

Percent increase in shell height of scallops grown in lantern nets over 1 year on the artificial reef based on individual measurements from the notches on the shell.



Discussion

From an industrial point of view, the construction, transport and deployment of the artificial reef presented no major logistic problems. Building the reef used very similar skills and approaches that the cage builders use to construct salmon cages so the learning curve was minimal. The size and weight of the reef was easily managed by the mechanical infrastructure that existed in the industry, so no special accommodations had to be made to handle the structure.

Observations by the divers on the contents of the artificial reef indicated that the condition of the animals appeared to be very high. They seemed to be behaving normally and were successfully acquiring food as evidenced by their increase in growth. The colonization on the reef was initially slow and most of the material on the reef in the early period looked to be a brown organic fine mud-like layer. Some of the earlier colonizers were sea cucumbers (*Cucumaria frondosa*), longhorn sculpin (*Myoxocephalus octodecemspinosus*), winter flounder (*Pseudopleuronectes americanus*), rock gunnel (*Pholis gunnelis*), lumpfish (*Cyclopterus lumpus*), sea stars (*Asterias vulgaris*), green crab (*Carcinus maenas*), rock crab (*Cancer irroratus*), toad crab (*Hyas coarctatus*), common northern whelk (*Buccinum undatum*), hydroids, tunicates and schools of mysid shrimp (*Mysis spp., Praunus flexuosus*) and caprellid amphipods (*Caprella mutica*) that used the reef for both habitat and likely shelter from predators.

The sea urchins used in this experiment were commercial sized (*e.g.* greater than 50 mm) to start the trials. While sea urchins of this size class begin to slow their growth rate dramatically[(8)], the animals in this study still showed an increased in test diameter growing at a rate of 0.008 mm per day. This is consistent with the growth rates of wild animals in the field from the Bay of Fundy[(6)] and sea urchins farther south in the Gulf of Maine[(7,8)]. We would conclude from these observations that there were no negative effects on the growth of the sea urchins caused by the salmon aquaculture operations and that the animals grew normally in the reef.

"…organisms are able to successfully exist in high enrichment areas as long as suitable habitat can be maintained."

The growth of the sea scallops was also unaffected in the cages from the operations of the salmon farm. The observed growth rates of 0.07 mm per day were in close agreement with other studies on cage culture of scallops in the Bay of Fundy[(2,9)] who found growth rates of 0.07 and 0.08 mm per day respectively. The growth was also higher than the growth from wild populations of scallops locally (0.05 mm per day[(5)]) and further out in the Gulf of Maine on Georges Bank (0.06- 0.07 mm per day)[(3)]. The size class specific growth rates were typical of those found in other studies on this species[(3)] and would suggest that all size classes of the scallops studied were able to utilize the nutritional resources available.

It is worth noting that there were no other scallops found in the general area by the divers. The bottom substrate was depositional in nature and far too soft for scallops to exist, based on past observations. Thus, we would conclude that it was the substrate available for the scallops and not the organic loading originating from the salmon cages that resulted in no wild animals being found in the area. This does not imply that the salmon farming operation was not responsible for any changes to the benthic environment by changing the sedimentation rate, but rather that the loading itself is not necessarily detrimental to the well-being of scallops providing that they have a suitable habitat in which to live; in this case lantern nets.

The conclusions of the study are that the organisms are able to successfully exist in high enrichment areas as long as suitable habitat can be maintained. The concept of putting a structure with a large surface area around an aquaculture site appears to be practical, providing that the future engineering component of the design phase is successful in maximizing the efficiency and reducing the cost of the structure.

We would emphasize that there is a biological interaction effect between the artificial reef and wild species in the general area. Because of the increased surface area and vertical height of the reef that interacts with the natural environment, many of the wild species in the near vicinity will utilize the structure. In the future, we may wish to encourage or discourage these interactions, depending on whether they are judged to be beneficial by using various ecological engineering techniques. These will have to be evaluated in further studies as work on the three-dimensional benthic component of IMTA continues

References

1. Boudreau BP, Jørgensen BB. 2001. The Benthic Boundary Layer: Transport Processes and Biogeochemistry. Oxford University Press Inc., New York.
2. Dadswell MJ, Parsons J. 1991. Potential for aquaculture of the giant scallop, *Placopecten magellanicus* (Gmelin, 1791), in the Canadian maritimes using naturally produced spat. In, *World aquaculture workshops, No. 1, An international compendium of scallop biology and culture* (SE Shumway, PA Sandifer, eds.), p. 330-207, World Aquaculture Society, Baton Rouge.
3. Harris BP, Stokesbury KDE. 2006. Shell growth of sea scallops (*Placopecten magellanicus*) in the southern and northern Great South Channel, USA. *ICES J. Mar. Sci.* 63(5):811-821.
4. Parsons GJ, Dadswell MJ. 1994. Evaluation of intermediate culture techniques, growth, and survival of the giant scallop, *Placopecten magellanicus*, in Passamaquoddy Bay, New Brunswick. *Can Tech Rep Fish Aquat Sci* 2012.
5. Robinson SMC. 1993. A review of the biological information associated with enhancing scallop production. *World Aquacult.* 24(2):61-67.
6. Robinson SMC, MacIntyre AD. 1997. Aging and growth of the green sea urchin. *Bull Aquac Assoc Can.* 97(1):56-60.
7. Russell MP. 2001. Spatial and temporal variation in growth of the green sea urchin, *Strongylocentrotus droebachiensis*, in the Gulf of Maine, USA. Proceedings of the 10th International Echinoderm Conference, Echinoderms 2000. 533-538. A.A. Balkema, Rotterdam.
8. Russell MP, Ebert TA, Petraitis PS. 1998. Field estimates of growth and mortality of the green sea urchin, *Strongylocentrotus droebachiensis*. *Ophelia.* 48(2):137-153.
9. Wildish DJ, Wilson AJ, Young-Lai W, Decoste AM, Aiken DE, Martin JD. 1988. Biological and Economic Feasibility of Four Grow-Out Methods for the Culture of Giant Scallops in the Bay of Fundy Canada. *Can Tech Rep Fish Aquat Sci* (1658):i-21.

Acknowledgements

We would like to thank the crew from the CCGS Pandalus III and the CCGCS Viola Davidson (Wayne Miner, Perry Smith, Danny Loveless and Will Johnston), and Lennie Totten and the crew from the Cooke Aquaculture barge. Craig Smith, Nathaniel Feindel and Paul Robertson helped with the sampling. This research was partially funded by the Atlantic Canada Opportunities Agency AIF program, through the University of New Brunswick.

Authors

Shawn Robinson is a research scientist with Fisheries and Oceans Canada (DFO), St. Andrews Biological Station (SABS), St. Andrews, NB, and an adjunct professor at the University of New Brunswick Saint John, Saint John, NB (shawn.robinson@dfo-mpo.gc.ca). Jim Martin is a retired biologist from SABS. Andrew Cooper is a research scientist at SABS. Terralynn Lander is a biologist at SABS. Gregor Reid is with the Canadian Integrated Multi-Trophic Aquaculture Network (CIMTAN) working out of SABS. Frank Powel and Randy Griffin are managers with Cooke Aquaculture Inc.

Hydrodynamic Considerations for Spatial Modelling of Integrated Multi-Trophic Aquaculture (IMTA)

G.K. Reid, S. Haigh, T. Jeans, and M. Foreman

Aquaculture models that aim to predict nutrient dispersal or deposition require hydrodynamic data. The need for high resolution current flow data in open-water Integrated Multi-Trophic Aquaculture (IMTA) systems is particularly acute as nutrient transport to co-cultured species is often at the scale of dozens of meters. This is smaller than the typical scale of oceanographic models, although this gap is narrowing. The potentially complex array of farm structures and the small scales necessitating flow–field description have prompted an examination of Computational Fluid Dynamics (CFD) as one option to address these issues in IMTA systems. Modelling shellfish in an open-water system most likely requires inclusion within a larger ecosystem model. Consequently, in addition to resolving smaller scale hydrodynamics at the cage scale, linkages may be required with a larger oceanographic model to define appropriate boundary conditions. The Unstructured Grid Finite Volume Coastal Ocean Model (FVCOM) is the predominant oceanographic model used by Fisheries and Oceans Canada and has been used on east and west coasts to support aquaculture management decisions. Consequently, FVCOM is a logical choice as the oceanographic component for an ecosystem type model that includes IMTA shellfish. CFD and FVCOM functionally are described below and implications for the modelling of shellfish in IMTA systems are discussed.

Introduction

Over the last few decades, there has been a great deal of Aquaculture modelling focused on understanding or predicting nutrient waste dispersal, deposition or fate[*e.g.* 1-15]. A commonality with all of these models is the need for hydrodynamic data; the scale, frequency and data format, a function of a particular model's objectives. Many of these existing models or approaches should be intuitively applicable to nutrient delivery in IMTA systems. However, several of the hydrodynamic sub-modules in these models can be quite complex and significant consideration is warranted prior to potential implementation in open-water IMTA systems. Some of these models [*e.g.* 5, 16, 17] are variants of hydrodynamic models that employ finite element techniques (a defined series of connected spaces) to solve the Navier–Stokes equations and produce flow velocities in adjacent areas (the element component in the model). While it is possible to apply this approach to the scale of meters it has typically been applied to the 100 of meters (or greater) scale[*e.g.* 18]. These models are useful for tracking the potential of pathogen transfer between fish farms, or the medium-term (*e.g.* days) fate of nutrients to determine where phytoplankton response may occur[19]. Hydrodynamic finite element models are sometimes embodied in larger models to determine aquaculture carrying capacity at bay-wide scales. In China for example, incidental IMTA can occur throughout entire bays with culture rafts of a variety of species and several models have aimed to quantify these effects [*e.g.* 20, 21].

Challenges quantifying near-field flows

At the farm scale, knowledge of mean current directions and speeds exiting from fish cages are crucial for predictions of nutrient and particle densities. Ideally, this could be measured empirically or modelled analytically. Either approach is not without difficulty. Near-field dynamics of water flow through net panels in and around cages can be extremely complex. Drag is produced as water flows through the cage netting and around cage structures(22), thereby reducing the flow velocity and increasing turbulence in adjacent waters. Drag and turbulence are affected by: the ratio of net thread to space, referred to as solidity(22) or porosity(23), flexibility of the cage(24), angle of attack(22, 23), number of net panel crossings(22), lift(25), space between cages(22), the drag coefficient (or roughness) of the individual net threads (22), and current velocity(26). Wakes can be generated at multiple scales, ranging from individual net threads(22) to vortical flow generated by the general obstruction of water flow caused by the cages(23); the amount is of spread a function of the distance traveled (22). These parameters are seldom constant. Fouling of the mesh can alter the thread drag coefficients and change the porosity. The affect of potentially hundreds of tonnes of fish on flow-fields appears to be largely unknown.

"There are few published aquaculture studies that aim to model near-field current dynamics or concentrations, and even fewer relating to open-water IMTA."

Current flow through cages is necessary to determine volumetric exchange which in turn provides the denominator for estimates of nutrient concentrations. Some initial work by Løland(22) successfully developed analytical methods for modelling current reduction and wake spread as water passes through net panels. However, the data required for model inputs is arguably more labour intensive than empirical data collection of current and nutrient concentrations throughout a farm. There has been some success circumventing a number of these data requirements using simplifying assumptions(27), but this has occurred in fairly simple systems with data integrated as daily averages, at a set distance.

There has only been one study to our knowledge that has attempted to model near-field concentrations in the context of open-water IMTA. Petrell *et al.*(28) initially used a diffusion model to determine placement of the kelp *Laminaria* for ammonium uptake at salmon cages, but found the model invalid within the vicinity of the cage structure due to the unsteady and complicated flow patterns associated with the structure. They suggested that significant mixing occurred between 10 to 40 m from the sea cages at their study site, and consequently higher concentrations can be measured beyond 10 m than within 10 m. There was some success using a dilution model between 10 and 40 m.

Observations of increased concentrations a short distance away from cages, as opposed to right at cage edges, are supported by Sanderson *et al.*(29). Ammonium was extensively sampled (4 m depth) around salmon cages to understand spatial patterns of nutrients for the development of co-cultured kelps. In general, ammonium concentrations were elevated typically within 50 m of the down current direction (although sometimes effects were detected up to 200-300 m from cages), not right at the cages.

Given the complexities of modelling near-field flows around cages and farm structures, this may beg the question of why not pursue alterative approaches? For example, there is some merit using "biocollectors" as a proxy to determine current flow and spatial distribution of nutrients(30). While this can be done at an existing farm it does not necessarily help with predictive capacity for new site proposals. Empirical data collection of current may also be an option, but high intensive data collection may be required. Recent work observing the release of dye inside polar circles (as a proxy for tracking therapeutants added to cages), demonstrated that several current meters may be required to accurately map near-field nutrient plumes exiting just one cage[31] at full scale salmon farms in the Bay of Fundy environment.

Another question may be how precise does the location of co-culture species need to be? In uncomplicated culture conditions, a high degree of spatial resolution may not be warranted as a general understanding of up-current and down-current direction may be all that is required. However, if decisions are required to determine optimal filtration rates (relative to farm particulates available), nutrient concentrations and associated scale, detailed flow data may still be required.

Computational fluid dynamics

"One option for exploring detailed 3D flow-fields at small scales is through the use of computational fluid dynamics (CFD). In recent years there has been some experimentation applying CFD to aquaculture related problems."

One option for exploring detailed 3D flow-fields at small scales is through the use of computational fluid dynamics (CFD). In recent years there has been some experimentation applying CFD to aquaculture related problems. CFD simulations have been used to describe: water flow and solids removal in land-based aquaculture systems[32, 33], the effect of mussel socks on flow dynamics[34], the effect of oyster tables on flow[35], flow through net panels[36, 37], mixing behind aquaculture cages[23], and to assist in the design of fish cages for high-energy sites[38]. Some of this work has used commercially available software packages such as, FLOW-3D[34], FLUENT[36] or Ansys Fluent™ [35]. Given some of the aforementioned challenges of near-field spatial modelling around open-water cages and structures in an open-water IMTA settings; CFD may have some appeal.

As with the oceanographic type hydrodynamic models, CFD also solves the steady or unsteady Navier-Stokes equations, ensuring the conservation of mass, momentum, and energy throughout the fluid flow. The three main elements of the CFD procedure are pre-processing, solver solution, and post-processing[39]. The computational domain, including fluid properties, geometry, and boundary conditions, are defined in the pre-processing step and an appropriate CFD grid is generated. CFD grid generation is the process of dividing the domain into smaller control volumes or cells. In general, as the grid density increases, so too does the accuracy of the CFD solution. However, the necessary computer hardware and calculation time also increases with increasing grid density, and the optimal solution is often a non-uniform grid with increased cell density in regions where flow field gradients are largest. Solver solution consists of discretizing the governing equations into a system of algebraic equations and solving this system of equations using an iterative method. The governing equations can be discretized using the finite volume, finite difference, finite element, or spectral methods; finite volume being the most common for well-established commercial CFD codes such as Ansys® CFX®, Ansys Fluent™, and STAR-CD. Post-processing involves quantifying the errors in the CFD solution through verification, validation and extracting the flow field variables of interest. Once the CFD solution has been verified and validated it provides details of the local flow features[40] at a level that are difficult to obtain from laboratory scale experiments or field measurements (*e.g.*, Fig. 1).

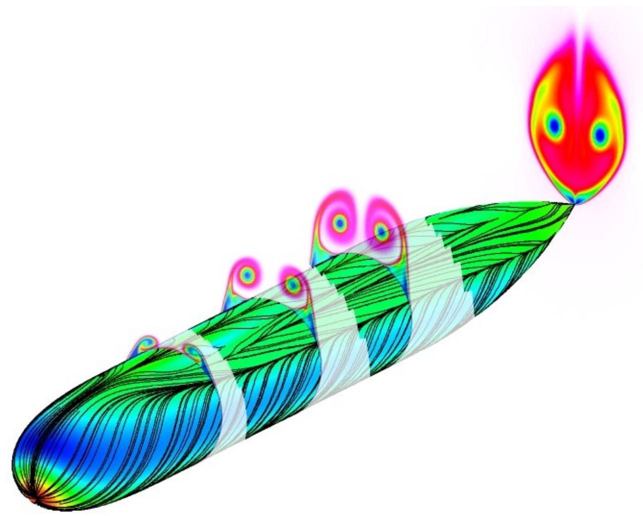
Most practical high Reynolds number turbulent flow simulations must implement turbulence models because the range of length scales are too vast to be properly resolved with practical grid densities[39]. The most commonly employed turbulence models are based on the time-averaged Navier-Stokes equations, known as the Reynolds-averaged Navier-Stokes (RANS) equations. The time-averaging results in six additional unknowns that must be modelled to close the system of mean flow equations. Large eddy simulation (LES) is another approach being increasingly employed that is based on the spatially filtered unsteady Navier-Stokes equations.

Using this approach, the largest most important, turbulent scales are resolved and the smallest scales are modelled using a sub-grid scale model. However, the grid resolution required for many high Reynolds number flows is still impractical. Delayed eddy simulation is a hybrid approach where the entire boundary layer is treated using a RANS model and highly separated regions are treated using LES. This results in a numerically feasible approach that combines the most favourable elements of each method.

Open-water aquaculture invariably involves the use of nets, and this is one of the primary challenges in the application of CFD to aquaculture. While it is theoretically possible to model flow in and around mesh in nets using a CFD approach, the computing power needed to model this at the scale of a farm is exorbitant. Netting can be approximated by small cylinders but the number of cylinders required to model the net area in a cage is very large - more than 10 million in a single salmon farming cage, thus it is computationally expensive to model the exact geometry(36). This has lead to the development of a porous media approach with application to flow through and around net panels(37). While this approach has proven successful, resistance coefficients are required for each individual net modelled and finding the coefficients is nontrivial. Nevertheless, given some of the recent applications of CFD to aquaculture, it was felt that options for CFD for open-water IMTA should be explored at the workshop.

Figure 1

An example of a contour of surface-pressure and skin-friction lines for a submarine hull (DRDC-STR) geometry at *Re* = 23 x 10^6 and α = 30 deg using the BSL-RSM turbulence model(40).



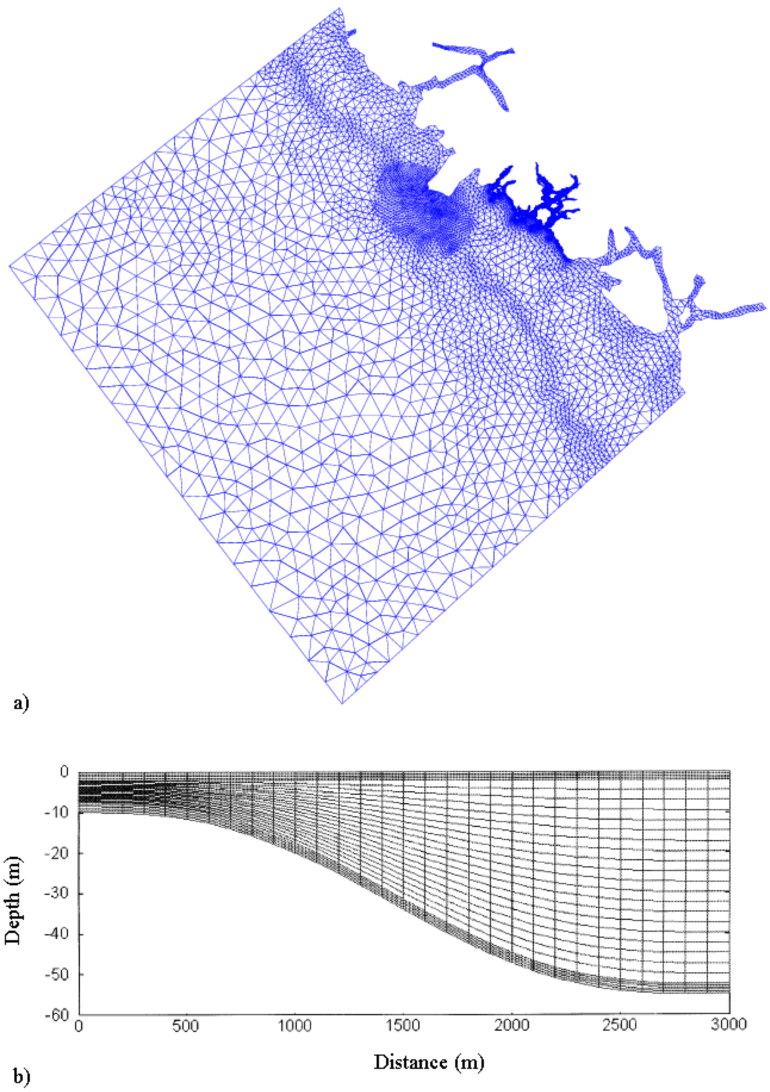
The unstructured grid Finite Volume Coastal Ocean Model (FVCOM)

Coastal zone management of aquaculture in Canada has often utilized the support of oceanographic modelling by Fisheries and Oceans Canada (DFO). On Canada's east coast, in the fish farm dense waters around Passamaquoddy Bay, Maces Bay and Grand Manan, water circulation models were initially used to estimate the potential for water exchange between farms and to assist in the management of Infectious Salmon Anaemia (ISA)(41). A customized finite element model by Greenberg *et al.*(42) was used for estimates of the areal extent of one tidal excursion around existing fish farms. This work ultimately helped to revise the Bay Management Areas (BMAs)(43), and in combination with a mandatory one year site fallowing requirement, was largely successful at thwarting ISA in the region.

Over the last few years, DFO under the auspices of the Centre for Ocean Model Development for the Application Centre of Excellence, has adopted FVCOM for its near shore modelling. FVCOM is an open source model developed at the Marine Ecosystem Dynamic Modeling Laboratory, School for Marine Science and Technology, University of Massachusetts-Dartmouth (http://fvcom.smast.umassd.edu/FVCOM/index.html) and has a large active user community. The underlying mathematics solved by FVCOM are the primitive equations governing the fluid flow: conservations of momentum, mass, temperature and salinity and the equation of state(44, 45). The model outputs include temporally-varying two-dimensional sea surface elevation fields and three-dimensional temperature, salinity and velocity fields. These equations are solved numerically using the finite volume method. In the horizontal, the model domain is represented by nonoverlapping triangles of non-uniform sizes (Fig. 2a) known as an unstructured grid. As opposed to the rectangular grids that are used with finite difference methods, unstructured grids are particularly well-suited for modelling coastal oceans. They allow realistic representation of the coastline. Additionally, they permit variations in the grid size enabling a more refined grid (*i.e.* smaller triangles) in coastal areas or areas of particular interest. Other areas (for example off-shore) can be represented by a coarser grid (*i.e.* larger triangles) offering a significant computational advantage. In the vertical, sigma-coordinates, or terrain following coordinates, which accurately represent the depth, are used (Fig. 2b). FVCOM can be run on parallel multi-processor platforms which can greatly reduce the model run-time.

Figure 2

a) Horizontal triangular grid for Kyuquot Sound, BC. This grid has 55270 nodes and 98144 triangles with resolution down to 10m. b) Vertical distribution of sigma layers.



In applying FVCOM to a given region, much effort is spent setting up the model's domain and boundary conditions. For the model grid, a coastline and bathymetric data of the area of interest are required. For inter-tidal regions, the coastline must cover the maximum flooding area so that the region can be properly modelled using FVCOM's wetting and drying capabilities. The horizontal triangular grid is generated using one of many mesh generating programs that are available. The model is driven by various forcing fields which are defined along the boundaries. There are two types of lateral boundaries: closed and open. Closed boundaries are characterized by a no flow-through condition and include coastlines and islands. Open boundaries, on the other hand, are not bounded by land and require specification of the tides, mean sea surface elevation and vertically varying temperature and salinity fields along these boundaries. These temporally varying fields can be obtained either from observations or from output of another model with a larger domain. At the sea surface the effects of wind, heat flux, and net salt flux (evaporation minus precipitation) may be included. These fields can be time-dependent and spatially varying and are obtained from either observations or a meteorological model. Along the closed lateral boundaries, river flows can be specified and require the river's discharge rate, temperature and salinity which are usually obtained from observations. Finally, evaluation of the model results is an important step in the development of any model. Typically this is done by comparing model results with time series of observed fields such as sea surface elevations, currents, temperatures and salinities.

On Canada's west coast, finite element and finite volume circulation models[46] have been developed and coupled to customized particle tracking models to simulate the behaviour, dispersion, and growth/decay of parasites and disease. In the Broughton Archipelago, this approach has been used to study the dispersion and life-cycle development of sea lice eggs originating on salmon farms[47]. Output concentration fields have been compared against field observations and the lice 'footprints' associated with individual farms have been used to devise management plans that minimize sea lice infections on outward migrating wild juvenile salmon. A similar coupled model has been developed for the Discovery Islands where in the past, transmission of the Infectious Hematopoietic Necrosis (IHN) virus between salmon farms has been a problem with costly consequences. In this case, viral shedding rates from an infective farm, virus stability in water, and minimum infective dosage information have been incorporated into the viral particle tracking component of the coupled model.

FVCOM has historically been applied to scales of 2.5 km to 40 m[45], suggesting some potential challenges with near-field application to an open-water IMTA at the farm level (near-field), where effects are often recognized at scales of meters. There are however, some possible solutions to address this. For example, there have been recent advancements coupling FVCOM, with a CFD model that resolves small-scale flows; to achieve a combined resolution from centimetres to hundreds of kilometres[48].

Given the wider adoption of FVCOM by DFO for aquaculture management, FVCOM is the logical choice for modelling hydrodynamics at open-water IMTA sites. A number of DFO oceanographers using FVCOM are directly involved with CIMTAN projects and it makes sense to pursue FVCOM from an expertise, resource and logistical perspective.

Summary

A presentation and discussion on the challenges of tracking and predicting water movement, through and between cages for the purposes of modelling shellfish growth and nutrient uptake, occurred at the workshop. Specifically, the potential use of FVCOM, CFD and like strategies for implementation, were explored. Different strategies were pursued with respect to the different IMTA systems on the west and east coast of Canada, where necessary. These system differences are discussed elsewhere in this issue.

References

1. Cromey CJ, Nickell TD, Black KD, Provost PG, Griffiths CR. 2002. Validation of a fish farm waste resuspension model by use of a particulate tracer discharged from a point source in a coastal environment. *Estuaries.* 25(5):916-929.
2. Silvert W, Sowles J. 1996. Modelling environmental impacts of marine finfish aquaculture. *J Appl Ichthyol.* 12(2):75-81.
3. Kishi MJ, Uchiyama M, Iwata Y. 1994. Numerical simulation model for quantitative management of aquaculture. *Ecol Modell.* 72(1-2):21-40.
4. Hevia M, Rosenthal H, Gowen RJ. 1996. Modelling benthic deposition under fish cages. *J Appl Ichthyol.* 12(2):71-74.
5. Panchang V, Cheng G, Newell C. 1997. Modeling hydrodynamics and aquaculture waste transport in coastal Maine. *Estuaries.* 20(1):14-41.
6. Dudley RW, Panchang VG, Newell CR. 2000. Application of a comprehensive modeling strategy for the management of net-pen aquaculture waste transport. *Aquaculture.* 187(3-4):319-349.

7. Cromey CJ, Nickell TD, Treasurer J, Black KD, Inall M. 2009. Modelling the impact of cod (Gadus morhua L) farming in the marine environment-CODMOD. *Aquaculture.* 289(1-2):42-53.
8. Carroll ML, Cochrane S, Fieler R, Velvin R, White P. 2003. Organic enrichment of sediments from salmon farming in Norway: environmental factors, management practices, and monitoring techniques. *Aquaculture.* 226(1-4):165-180.
9. Doglioli AM, Magaldi MG, Vezzulli L, Tucci S. 2004. Development of a numerical model to study the dispersion of wastes coming from a marine fish farm in the Ligurian Sea (Western Mediterranean). *Aquaculture.* 231(1-4):215-235.
10. Campbell DE, Newell CR. 1998. MUSMOD®, a production model for bottom culture of the blue mussel, *Mytilus edulis* L. *J Exp Mar Biol Ecol.* 219(1-2):171-203.
11. Chamberlain J, Stucchi D. 2007. Simulating the effects of parameter uncertainty on waste model predictions of marine finfish aquaculture. *Aquaculture.* 272(1-4):296-311.
12. Corner RA, Brooker AJ, Telfer TC, Ross LG. 2006. A fully integrated GIS-based model of particulate waste distribution from marine fish-cage sites. *Aquaculture.* 258(1-4):299-311.
13. Jusup M, Klanjscek J, Petricioli D, Legovic T. 2009. Predicting aquaculture-derived benthic organic enrichment: Model validation. *Ecol Modell.* 220(19):2407-2414.
14. Jusup M, Geček S, Legovič T. 2007. Impact of aquacultures on the marine ecosystem: Modelling benthic carbon loading over variable depth. *Ecol Modell.* 200(3-4):459-466.
15. Cromey CJ, Nickell TD, Black KD. 2002. DEPOMOD - modelling the deposition and biological effects of waste solids from marine cage farms. *Aquaculture.* 214(1-4):211-239.
16. Falconer RA, Hartnett M. 1993. Mathematical-modeling of flow, pesticide and nutrient transport for fish-farm planning and management. *Ocean Coast Manag.* 19(1):37-57.
17. Panchang VG, Cheng G, Newell CR. 1993. Application of Mathematical Models in the Environmental Regulation of Net-Pen Aquaculture. National Marine Fisheries Service (NOAA). MSG-TR-93-1
18. Grangere K, Lefebvre S, Bacher C, Cugier P, Menesguen A. 2010. Modelling the spatial heterogeneity of ecological processes in an intertidal estuarine bay: dynamic interactions between bivalves and phytoplankton. *Mar Ecol Prog Ser.* 415:141-158.
19. Olsen Y. 2007. Impacts on pelagic ecosystems. In, *Nutrient Impacts of Farmed Atlantic Salmon (Salmo salar) on Pelagic Ecosystems and Implications for Carrying Capacity* (B Costa-Pierce, eds.), p. 23-39, World Wildlife Fund.
20. Duarte P, Meneses R, Hawkins AJS, Zhu M, Fang J, Grant J. 2003. Mathematical modelling to assess the carrying capacity for multi-species culture within coastal waters. *Ecol Modell.* 168(1-2):109-143.
21. Shi J, Wei H, Zhao L, Yuan Y, Fang J, Zhang J. 2011. A physical–biological coupled aquaculture model for a suspended aquaculture area of China. *Aquaculture.* 318(3-4):412-424.
22. Løland G. 1993. Water-flow through and around net pens. In, *Fish Farming Technology* (H Reinertsen, LA Dahle, L Jorgensen, K Tvineereim, eds.), p. 177-183, AA Balkema, Rotterdam.
23. Helsley CE, Kim JW. 2005. Mixing downstream of a submerged fish cage: A numerical study. *IEEE Journal of Oceanic Engineering.* 30(1):12-19.
24. Lader PF, Olsen A, Jensen A, Sveen JK, Fredheim A, Enerhaug B. 2007. Experimental investigation of the interaction between waves and net structures--Damping mechanism. *Aquacult Eng.* 37(2):100-114.
25. Le Bris F, Marichal D. 1999. Numerical and experimental study of submerged flexible nets: Applications to fish farms. *Proceedings of the Ninth (1999) International Offshore and Polar Engineering Conference.* III:749-755.
26. Fu EB, Sato O, Nashimoto K, Yamamoto K. 1989. Fluid force on simplified models of aquaculture net cage. *Nippon Suisan Gakkaishi.* 55(7):1211-1216.
27. Reid GK, Moccia RD. 2007. Estimating aquatic phosphorus concentrations 30 metres down-current from a rainbow trout cage array. *J Environ Monit.* 9(8):814-821.

28. Petrell R, Tabrizi K, Harrison P, Druehl L. 1993. Mathematical model of *Laminaria* production near a British Columbian salmon sea cage farm. *J Appl Phycol.* 5(1):1-14.

29. Sanderson JC, Cromey CJ, Dring MJ, Kelly MS. 2008. Distribution of nutrients for seaweed cultivation around salmon cages at farm sites in north-west Scotland. *Aquaculture.* 278(1-4):60-68.

30. García-Sanz T, Ruiz-Fernández JM, Ruiz M, Garcìa R, González MN, Pérez M. 2010. An evaluation of a macroalgal bioassay tool for assessing the spatial extent of nutrient release from offshore fish farms. *Mar Environ Res.* 70(2):189-200.

31. Page F. 2011. Fisheries and Oceans Canada, personal communication.

32. Huggins DL, Piedrahita RH, Rumsey T. 2005. Use of computational fluid dynamics (CFD) for aquaculture raceway design to increase settling effectiveness. *Aquacult Eng.* 33(3):167-180.

33. Huggins DL, Piedrahita RH, Rumsey T. 2004. Analysis of sediment transport modeling using computational fluid dynamics (CFD) for aquaculture raceways. *Aquacult Eng.* 31(3-4):277-293.

34. Waterman PJ. 2009. Modeling commercial aquaculture systems emnploying FLOW 3D. *Desktop Engineering Elements of Analysis.* November:30-33.

35. Gaurier B, Germain G, Kervella Y, Davourie J, Cayocca F, Lesueur P. 2009. Experimental and numerical characterization of an oyster farm impact on the flow. *European Journal of Mechanics - B/Fluids.* 30(5):513-525.

36. Patursson ØE, Swift MR, Baldwin K, Tsukrov I, Simonsen K. 18-9-2006. Modeling flow through and around a net panel using computational fluid dynamics. In, *OCEANS 2006*, OCEANS 2006. 1-5.

37. Patursson ØE, Swift MR, Tsukrov I, Simonsen K, Baldwin K, Fredriksson DW, Celikkol B. 2010. Development of a porous media model with application to flow through and around a net panel. *Ocean Engineering.* 37(2-3):314-324.

38. Celikkol B, Decew J, Baldwin K, Boduch S, Chambers M, Fredriksson DW, Irish J, Patursson O, Rice G, Swift MR, Tsukrov I, Turmelle CA. 18-9-2006. Engineering overview of the University of New Hampshire's open ocean aquaculture project. In, *Proceedings of the MTS/IEEE OCEANS 2006 Boston Conference and Exhibition*, OCEANS 2006. 1-7.

39. Versteeg HK, Malalaseka W. 2007. An Introduction to Computational Fluid Dynamics: The Finite Volume Method. Pearson Education Limited, Toronto.

40. Jeans TL, Watt GD, Gerber AG, Holloway AGL, Baker CR. 2009. High-resolution reynolds-averaged navier-stokes flow predictions over axisymmetric bodies with tapered tails. *AIAA.* 47(1):19-32.

41. Chang BD, Page F, Losier RJ, Greenberg DA, Chaffey JDMEP. 2005. Water circulation and management of infectious salmon anemia in the salmon aquaculture industry of Letete Passage, Back Bay, Bliss Harbour, and Lime Kiln Bay in Southwestern New Brunswick. Fisheries and Oceans Canada. *Can Tech Rep Fish Aquat Sci.* 2599.

42. Greenberg DA, Shore JA, Page FH, Dowd M. 2005. A finite element circulation model for embayments with drying intertidal areas and its application to the Quoddy region of the Bay of Fundy. *Ocean Modelling.* 10(1-2):211-231.

43. Chang BD, Page FH, Losier RJ, Lawton P, Singh R, Greenberg DA. 2007. Evaluation of Bay Management Area Scenarios for the Southwestern New Brunswick Salmon Aquaculture Industry: Aquaculture Collaborative Research and Development Program Final Project Report. St. Andrews Biological Station, Fisheries and Oceans Canada. *Can Tech Rep Fish Aquat Sci. 2722*.

44. Chen C, Liu H, Beardsley RC. 2003. An unstructured grid, finite-volume, three-dimensional, primitive equations ocean model: application to coastal ocean and estuaries. *J. Atmos. Oceanic Technol.* 20(1):159-186.

45. Chen C, Beardsley RC, Cowles G. 2006. An unstructured grid, finite-volume coastal ocean model (FVCOM) system. *Oceonography.* 19(1):78-89.

46. Foreman MGG, Czajko P, Stucchi DJ, Guo M. 2009. A finite volume model simulation for the Broughton Archipelago, Canada. *Ocean Modelling.* 30(1):29-47.

47. Stucchi DJ, Guo M, Foreman MGG, Czajko P, Galbraith M, Mackas D, Gillibrand P. 2011. Modelling sea lice production and concentrations in the Broughton Archipelago, British Columbia. In, *Salmon Lice: An Integrated Approach to Understanding Parasite Abundance and Distribution* (S Jones, R Beamish, eds.), p. 117-150, Wiley.

48. Wu Xg, Tang Hs. 2010. Coupling of CFD model and FVCOM to predict small-scale coastal flows. *Journal of Hydrodynamics, Ser. B.* 22(5, Supplement 1):284-289.

Authors

Gregor Reid is with the Canadian Integrated Multi-Trophic Aquaculture Network (greid@unb.ca), working out of St. Andrews Biological Station (SABS), St. Andrews, NB. Susan Haigh is with Fisheries and Oceans Canada (DFO), SABS/Fredericton. Tiger Jeans is with the Department of Engineering, University of New Brunswick Fredericton, Fredericton, NB. Mike Foreman is with DFO at the Institute of Ocean Sciences, Sidney, BC.

Spatial Modelling of Integrated Multi-Trophic Aquaculture (IMTA) Shellfish: Workshop Discussions and Developments

G.K. Reid and T. Chopin

Challenges modelling near-field hydrodynamics around aquaculture cages, in conjunction with shellfish production and nutrient mitigation potential, prompted a workshop for Canadian Integrated Multi-Trophic Aquaculture Network (CIMTAN) researchers and partners. Issues and approaches were explored over two full days of discussion with respect to both east and west coast IMTA systems. Computational Fluid Dynamics (CFD) at its present level of development was deemed impractical for flows around highly complex structures at IMTA sites, but may have merit for co-cultured species gear design. It was determined that, in addition to the oceanographic component, FVCOM was also capable of modelling flows at the cage scale (10 m resolution) with some modification. The shellfish component will be modelled using the Scope For Growth (SFG) approach within the context of a larger ecosystem model. Plans were developed for additional data collection where appropriate times series for model inputs were lacking. The workshop was successful at identifying relevant data gaps while resolving best approaches for spatial modelling of the shellfish niche in two different types of IMTA systems.

Background

In March 2011, a meeting occurred at Dalhousie University (Halifax, Nova Scotia) to discuss modelling approaches for application to IMTA shellfish (Fig. 1). In attendance were Jon Grant (Dalhousie University), Peter Cranford (Fisheries and Oceans Canada, Bedford Institute of Oceanography), Lindsay Brager (M.Sc. student, Dalhousie University), Ramón Filgueira (Dalhousie University / Instituto de Investigaciones Marinas, Vigo, Spain) and Gregor Reid (University of New Brunswick, CIMTAN). Progress and limitations in modelling the IMTA shellfish niche were reviewed. Discussions ensued around data limitations and significant challenges acquiring field data at active commercial aquaculture sites. The primary consensus reached at this initial meeting was that a "simple model" was unlikely to be sufficient and an ecosystem type model, adapted to an IMTA setting, was probably the best approach. An existing Scope For Growth (SFG) mussel model[1] was proposed to accommodate the shellfish component within a larger ecosystem model with the ecosystem components supported by several published works[2, 3, 4]. There was an acknowledgement that this could be a significant undertaking and such an approach would benefit from further collaboration. Consequently, a workshop was proposed as a means to initiate this and September 2011 was chosen as the best date to accommodate recommended participants. The workshop occurred at the Riverside Resort and Conference Centre, Mactaquac, New Brunswick, from September 19-22, 2011, encompassing two full days on the 20th and 21st.

" The primary consensus reached at the initial meeting was that a 'simple model' was unlikely to be sufficient and an ecosystem type model, adapted to an IMTA setting, was probably the best approach "

It was intended that the workshop be relatively small, informal and primarily include experts from relevant disciplines and activities as a means to most effectively develop best modelling approaches (Fig. 2). The workshop was organized by Gregor Reid; the guest speaker was Pedro Duarte, and the model facilitator was Ramón Filgueira. An initial workshop agenda was developed as a general guide with an expectation that workshop direction and activities would be adjusted to reflect ongoing discussions as required. A handful of presentations were scheduled for the workshop; a few *impromptu* presentations also occurred to support ongoing discussions.

Two break-out groups were scheduled for the afternoon of the first full day: a biological and a hydrodynamic group. The objectives were to review their respective states of knowledge, necessary data inputs, determine what is possible *versus* what is practical, and identify specific linkages needed with other model components. Given the substantial differences between west coast and east coast IMTA systems, a half day of the workshop was also directed to modelling, specific to each system.

Figure 1: Initial Halifax meeting on modelling the IMTA shellfish niche. Left to right: Linsday Brager, Peter Cranford, Jon Grant, Gregor Reid and Ramón Filgueira.

West coast IMTA

Kyuquot SEAfoods Ltd. is the west coast IMTA site located in Kyuquot Sound, off the north-western coast of Vancouver Island. It is a custom designed IMTA site with sablefish as the fed trophic level. Blue mussels, scallops, kelps, sea urchins and sea cucumbers are presently on the site as extractive species. The farm has been placed in a location to take advantage of slow currents and a natural gyre that causes frequent unidirectional current flow. Consequently the location of co-cultured species is down-current from the fish most of the time. A nearby river delivers freshwater with nutrient run-off, resulting in a freshwater lens of depths of 1-5m depending on season and rainfall. This can be problematic for some of the co-cultured species such as kelps and their depth must be adjusted accordingly to avoid low salinity.

It was suggested that the spatial modelling of flows at this type of site is of less importance for design, as the scale, location and water flow patterns result in relatively predictable moment of nutrient plumes. However, there would be a benefit in detailing current movement to determine flushing rates, optimal ‘shellfish population’ filtration rate, and densities required for relative extraction.

There are several data limitations to be addressed in order to supply inputs to a shellfish SFG model for the west coast IMTA site. There are at present very limited data on nutrient levels at the farm itself. However, there are some published data on historical nutrient levels on the regional area of the continental shelf and this will be reviewed. A monthly sampling minimum was suggested at the marker buoy (edge of site lease area), narrow channel entrance, finfish cages and freshwater stream.

There is no detailed shellfish growth data at the moment, which will ultimately be needed to validate the modelling approach. However, instantaneous growth rate data (*e.g.* RNA/DNA ratios) collected this summer from co-cultured and local feral species are presently being analyzed. Absorption and faecal production data for scallops, oysters, sea urchins and sea cucumbers are also required for any system-wide assessment, irrespective of an SFG approach. Much of these data are presently being acquired through some ongoing CIMTAN laboratory research projects.

Faecal load from the fed trophic level (*i.e.* sablefish) is one of the key parameters for IMTA system modelling. To estimate this load, digestibility data for sablefish fed a commercial feed are needed before this can be determined. Ongoing experimentation on Apparent Digestibly Coefficients (ADC) is presently occurring through a CIMTAN project and it is expected that these coefficients will be available soon. Plans are also underway to deploy a sediment trap at the site to assist in faecal quantification under field conditions.

East coast IMTA

A wide range of data has been collected at the east coast IMTA sites over the last few years and additional data collection is ongoing. There are several years of mussel growth data available (*e.g.* shell length, whole weight, shell thickness), stable isotope data at some sites to determine proportion of diet sources, some fatty acid tracer data, extensive temperature data throughout Passamaquoddy Bay, as well as some particulate organic matter (POM) data. Some dissolved nutrient data such as ammonium concentrations have been collected at a number of IMTA sites this past summer. Ammonium, nitrite, nitrate and phosphorus data are also available for some locations since 1991. There have also been historical measures and routine sampling data of chlorophyll and primary productivity in the Passamaquoddy Bay area by Fisheries and Oceans Canada. However, much of these data need to be reviewed to determine if the spatial scale and time series are readily applicable to the proposed model approach.

Workshop participants

- Thierry Chopin, CIMTAN / University of New Brunswick Saint John
- Meryl Coes, CIMTAN / University of New Brunswick Saint John
- Peter Cranford, Fisheries and Oceans Canada, Bedford Institute of Oceanography
- Stephen Cross, University of Victoria / Kyuquot SEAFoods Ltd.
- Pedro Duarte, University Fernando Pessoa, Portugal
- Ramón Filgueira, Dalhousie University / Instituto de Investigaciones Marinas, Vigo, Spain
- Mike Foreman, Fisheries and Oceans Canada, Institute of Ocean Sciences
- Jon Grant, Dalhousie University
- Thomas Guyondet, Fisheries and Oceans Canada, Gulf Fisheries Centre
- Susan Haigh, Fisheries and Oceans Canada, St. Andrews Biological Station / Fredericton
- Tiger Jeans, University of New Brunswick Fredericton
- Nicole Leavitt, University of New Brunswick Fredericton
- Randy Losier, Fisheries and Oceans Canada, St. Andrews Biological Station
- Fred Page, Fisheries and Oceans Canada, St. Andrews Biological Station
- Chris Pearce, Fisheries and Oceans Canada, Pacific Biological Station
- Gregor Reid, CIMTAN / University of New Brunswick Saint John / St. Andrews Biological Station
- Shawn Robinson, Fisheries and Oceans Canada, St. Andrews Biological Station

Despite availability of some relevant data, IMTA sites on the east coast are part of a particularly complex environment and a different modelling strategy than that suggested for the west coast site may be warranted. At east coast IMTA sites, co-cultured species are added to full scale commercial salmon farms located in aquaculture dense areas in the Bay of Fundy with high tidal flushing and complex hydrodynamics. This presented several challenges to modelling IMTA systems in this environment. One concern was accounting for the volume change resulting from changes in the tidal amplitude of several meters. Another concern was how to account for neighbouring farms, and if these were also modelled it could turn into a considerable exercise. In addition to incorporating an IMTA site into a larger ecosystem type model, other farms would require inclusion as anthropogenic inputs.

It was decided that this was impractical and that instead, appropriate time series of water quality and nutrient data is required to determine the relevant boundary conditions. Specifically these would include POM, nutrients and chlorophyll a as monthly time series. Water movement at most aquaculture and IMTA sites in the Passamaquoddy Bay area have been modelled at the lease area scale and beyond[5, 6], so there are some good initial data available for simulations. Due to a mandatory, one year fallowing period and general aquaculture management, IMTA sites may move to different locations depending on the year. Plans are underway to select an appropriate candidate IMTA site for modelling over the next two years.

Hydrodynamics

Following presentations on near-field hydrodynamics, CFD and ongoing developments with FVCOM, a discussion on the merits of applying CFD ensued. Detailed rendering of aquaculture structures is computationally expensive. This appears to be the case even if individual net threads are not rendered and a porous structure is used (described elsewhere in this issue). Given the geometric complexity of a single cage, application of CFD to an entire site becomes even more daunting. It was decided that given the resources available it was impractical to use a CFD approach as a means of detailing water-flow and nutrient plume morphology in and around an IMTA site. It was, however, thought that CFD may have a greater role in the design of gear at IMTA sites. For example, designing suspended tray systems holding deposit feeders would benefit from a CFD approach to identify drag and re-suspension potential of organic solids in trays. Some tentative plans were made to pursue this for future development at the west coast IMTA site.

Given that the CFD approach was deemed impractical, this broached the subject of whether FVCOM would be able to accommodate the small resolutions anticipated for open-water IMTA systems. In areas where small spatial resolution is required, FVCOM has been applied to scales of 10m or less. After discussions on the matter, it was agreed that application of FVCOM to a 10m scale would be appropriate, as this should accommodate the cage and rearing-unit scale. It was also noted that it is possible to incorporate porous structures into FVCOM and this would be a viable solution to account for cage influences on water flow. It was further discussed that applying FVCOM to this scale would require a greater consideration for the effects of turbulent diffusion and this can be accommodated in FVCOM. Micro-turbulence around cage structures may need to be accounted for as well. One of the FVCOM developers has done some work on this and it was felt that there would be some merit in contacting him to discuss this particular aspect. FVCOM and CFD are described in detail elsewhere in this issue.

Workshop presentations

Scheduled presentations

- Workshop orientation and background developments (Gregor Reid)
- FVCOM developments in aquaculture (Mike Foreman, Susan Haige)
- Scope For Growth model (Ramón Filgueira)
- Near-field hydrodynamics (Gregor Reid, Tiger Jeans)
- Modelling IMTA: Issues of scale and carrying capacity (Pedro Duarte)

Impromptu presentations

- Near-field dispersal dynamics from cages: Dye release trials (Fred Page)
- Update of mussel data from east coast IMTA sites (Shawn Robinson)
- Review of the west coast IMTA site: Kyuquot SEAfoods Ltd. (Stephen Cross)

Other points of discussion

While SFG was favoured as the more appropriate modelling tool for shellfish growth at the initial Halifax meeting, some discussion ensued regarding the merit of using the SFG *vs.* Dynamic Energy Budget (DEB) model. As it has been reported that both model outputs are comparable[1], the issue became a matter of modelling objectives and ease of implementation. It was decided that for the purposes of determining growth and organic uptake a SFG model would be simplest, mainly due to the ability to acquire data inputs empirically for multiple species. Although it was further discussed that should an improved mechanistic understanding be required, the DEB model may be better suited.

One of the data gaps for determining removal efficiency of farm particulates by IMTA shellfish is a lack of knowledge regarding the *relative proportion* of organic particulates from fish farm activities (feed 'fines' or faeces) that are within the filtering size range of mussels. While it is possible to determine particulate concentration and size range in a water sample, this does not provide information on the overall portion of the load that is within that size range. While there is some information on this for land based systems, it is generally unknown for open-water systems(7). Modelling shellfish growth may at the least be able to determine the amount filtered. Once the amount of augmented growth attributed to the upper trophic level (*i.e.* the fish) is determined, the amount of organic particles filtered can be back-calculated with knowledge of absorption efficiency and retention.

Discussion of scale also figured prominently in the workshop. What are the relevant scales for aquaculture modelling and carrying capacity? What is the right resolution? Model time steps should be smaller than the water residence time. These aspects are detailed by Duarte elsewhere in this issue.

The incorporation of an SFG model into a larger ecosystem model was discussed. The "ecosystem" and its components will need to be accounted for. In an IMTA system, seaweeds for example, will require inclusion as well, due to their influence on net oxygen production, and net uptake of carbon dioxide and nutrients. This is advantageous as this will further foster model development of the inorganic extractive species in IMTA systems, also an objective of CIMTAN.

Figure 2: Second day of workshop discussions at the Riverside Resort and Conference Centre, Mactaquac, New Brunswick.

There was also a brief discussion on what constitutes IMTA and if there is a role for modelling to help define this? At the moment an operator could reap marketing benefits by claiming IMTA production simply by deploying a token but irrelevant amount of co-cultured species (*e.g.* a dozen mussels). An agreed upon definition of IMTA might be required to alleviate such an issue. It was mentioned that while this was a relevant issue, until we could provide better estimates of nutrient uptake effectiveness, it would be difficult to advise on this matter and this might be best left for a future discussion.

Final remarks

The workshop was successful at identifying relevant data gaps while resolving an approach combining SFG to model shellfish production with FVCOM for spatial quantification of hydrodynamics. A number of new CIMTAN students will be starting projects at the west coast IMTA site and several of the aforementioned data gaps will be addressed through their research activities. A candidate east coast IMTA site needs to be identified for future modelling prior to pursuing necessary sampling activities. In the interim, however, a general model is being developed with the ability to run a variety of scenarios. This model will be populated with actual data sets as they become available. Publishing workshop presentations and discussions in this issue of the Bulletin of the Aquaculture Association of Canada was deemed a good approach for making the material available to the public while ensuring directions and approaches were documented.

References

1. Filgueira R, Rosland R, Grant J. 2011. A comparison of scope for growth (SFG) and dynamic energy budget (DEB) models applied to the blue mussel (Mytilus edulis). *J Sea Res*. 66(4):403-410
2. Grant J, Curran KJ, Guyondet TL, Tita G, Bacher C, Koutitonsky V, Dowd M. 2007. A box model of carrying capacity for suspended mussel aquaculture in Lagune de la Grande-Entree, Iles-de-la-Madeleine, Quebec. *Ecol Modell.* 200(1-2):193-206.
3. Filgueira R, Grant J. 2009. A box model for ecosystem-level management of mussel culture carrying capacity in a coastal bay. *Ecosystems.* 12(7):1222-1233.
4. Grant J, Dowd M, Thompson K, Emerson C, Hatcher A. 1993. Perspectives on field studies and related biological models of bivalve growth and carrying capacity. In, *Bivalve filter feeders in estuarine and coastal ecosystem processes* (RF Dame, eds.), p. 371-420, Springer-Verlag, New York.
5. Chang BD, Page FH, Losier RJ, Lawton P, Singh R, Greenberg DA. 2007. Evaluation of Bay Management Area Scenarios for the Southwestern New Brunswick Salmon Aquaculture Industry: Aquaculture Collaborative Research and Development Program Final Project Report. St. Andrews Biological Station, Fisheries and Oceans Canada. *Can Tech Rep Fish. Aquat. Sci.* 2722.
6. Chang BD, Page F, Losier RJ, Greenberg DA, Chaffey JDMEP. 2005. Water Circulation and Management of Infectious Salmon Anemia in the Salmon Aquaculture Industry of Letete Passage, Back Bay, Bliss Harbour, and Lime Kiln Bay in Southwestern New Brunswick. Fisheries and Oceans Canada. *Can Tech Rep Fish. Aquat. Sci.* 2599.
7. Reid GK, Liutkus M, Robinson SMC, Chopin T, Blair T, Lander T, Mullen J, Page F, Moccia RD. 2009. A review of the biophysical properties of salmonid faeces: implications for aquaculture waste dispersal models and integrated multi-trophic aquaculture. *Aquac Res.* 40(3):257-273.

Acknowledgements

Special thanks to Dr. Chris Pearce from Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, BC, and Ms. Meryl Coes from the Canadian Integrated Multi-Trophic Aquaculture Network, Saint John, NB, for assistance with note taking and documentation.

Authors

Gregor Reid is with the Canadian Integrated Multi-Trophic Aquaculture Network (CIMTAN) (greid@unb.ca) working out of the St. Andrews Biological Station, St. Andrews, NB. Thierry Chopin is the Scientific Director of CIMTAN and a Professor in the Department of Biology, University of New Brunswick Saint John, Saint John, NB.

Bridging Technology and Economic Growth

NEW FRONTIERS

Aquaculture Canada OM 2012

Aquaculture Canada OM 2012

New Frontiers: Bridging Technology and Economic Growth
Nouvelles frontières : lier technologie et croissance économique

Come join us in the beautiful province of Prince Edward Island for special symposia, sessions and workshops that will not only let us work together to advance the Canadian aquaculture industry, but will also highlight achievements and successes within the various sectors. A full social program will provide ample opportunity for networking and information exchange.

Rodd Charlottetown
May 27 – 30, 2012
Charlottetown, Prince Edward Island

Venez vous joindre à nous dans la belle province de l'Île-du-Prince-Éduard pour des colloques spéciaux, des séances techniques et des ateliers qui permettront de travailler ensemble pour faire avancer l'industrie aquacole canadienne. Les colloques nous permettront aussi de souligner les réalisations et les réussites dans les différents secteurs de l'industrie. Un programme social complet offrira d'amples occasions pour le réseautage et les échanges d'informations.

Charlottetown, Île-du-Prince-Édouard
27 - 30 mai 2012
Rodd Charlottetown

General Information/Renseignements généraux
Conference coordinator : Joanne Burry
tel : 709-437-7203 email : jmburry@nl.rogers.com www.aquacultureassociation.ca