Mariculture Committee **ICES CM 2003/F:05**

REPORT OF THE

Working Group on Marine Shellfish Culture

Trondheim, Norway
13–15 August 2003

International Council for the Exploration of the Sea

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1 OPENING OF THE MEETING

The Working Group on Marine Shellfish Culture (WGMASC) held its first meeting in Trondheim, at the Brattora Research Centre, University of Trondheim from 13th to 15th August 2003, to deal with its Terms of Reference (ToRs) for 2003 (Annex 1), with A Bodoy (France) as Chair. The establishment of this new Working Group, that reports to the Mariculture Committee was adopted by Council during its 2002 meeting. The ToRs were decided in a Council Resolution (C.Res.2002/2F05) adopted at the Statutory Meeting held in Copenhagen, Denmark, 2002.

The meeting was opened at 9:30 hrs on Wednesday, 13 August, with the Chair welcoming the new participants. Most of them had never previously attended ICES Working Group meetings, and were unfamiliar with the ways ICES functions.

1.1 Attendance

Seven people representing five countries attended the first (2003) meeting of WGMASC (Annex 1). Other members who were unable to attend, sent apologies (F. O'Beirn, S. Gollatsch, R. Langan and R. Wenne). Attendance was low for two reasons : the official membership of the Working Group includes today twelve persons representing 8 countries, among the19 ICES countries. Several national delegates were contacted to nominate members to the WGMASC, but no names were transmitted to the ICES secretariat or the Chair of WGMASC. The fact that some countries that are major shellfish producers were not represented was regretfully noted by the members. The next ICES Annual Science Conference in Tallin will be an opportunity to have direct contact with the national delegates of countries that are yet to be represented within the WG.

1.2 Venue

ICES is seeking to strengthen links with the European Aquaculture Society, through different actions. During the last meeting of the Mariculture Committee, it was proposed to have common meetings whenever possible to enhance contacts between scientists. It was then decided that the first meeting of the WGMASC should be held in Trondheim, where the European Aquaculture Society was planning its annual conference, Aquaculture' 2003. The date of the WGMASC meeting was chosen to allow members to participate in the EAS Workshop on "Mussel Farming: Technologies and Productions". More detailed information is given on the chapter addressing the contacts with the European Aquaculture Society.

Preliminary contacts were made with Prof. Ingve Olsen, from Trondheim University, early in November. The Chair received a positive answer, and two meeting rooms were made available for the WG at the Brattora Research Centre, University of Trondheim.

Special thanks are due to the Professor Odd Gulseth, manager of the Brattora Research Centre, to Dr. Anders Olsen, who invited us for a demonstration on the daily growth measurement of mussels by means of a laser beam, and to Gerd Tokstad, secretary of the Centre, who kindly helped with logistics and hot beverages.

1.3 Introduction to ICES organization

The meeting was opened on 13 August at 9 :30. The Chair welcomed the participants and each person introduced themselves. The first point of the agenda was devoted to an introductory discourse on ICES, as five members had no preliminary experience about how ICES functions. Explanations were given by the Chair about the history of ICES, its structure (Council, advisory committees and science committees, working groups and study groups, Annual Science Conference and statutory meeting), and its role of scientific advice on fisheries, ecosystems and marine environment. Several ICES documents were made available to the members (ICES Strategic Plan, Integrated Action Plan for 2003–2007). An emphasis was made that working groups are entitled to suggest recommendations to the parent committee, that will be reviewed and eventually endorsed by the relevant advisory committees. The ways by which Terms of Reference can be delivered were explained to the WG (through the Council and the different committees, or from the working groups). Some other explanations were given on the products produced from the working group meetings, and members agreed that, whenever possible, portions of reports corresponding to terms of reference would be in a publishable format as scientific reviews.

1.4 ToR explanations

Some members found it difficult to deal with the terms of reference as they were written, and a discussion arose on how the terms of reference were produced, and how we could address them. From these exchanges, preliminary remarks and specific comments on the terms of reference are reported in italic at the head of each chapter. They may include some restrictions on the subjects treated, proposals for a working plan to be implemented in the future and remarks on the available competence within the WG to address some subjects.

1.5 Organisation of the meeting[1]

It was proposed in the agenda to have both plenary sessions and discussions of the report, with the WG divided into two subgroups that would, at first, work separately on a specific ToR. When some part was ready, the entire WG would then reconvene for a plenary session. During this session, the WG would discuss the report from each subgroup and offer comments and suggestions before adopting the corresponding part of the final report.

During the initial plenary session on Wednesday morning, this proposal was formally accepted by the WG. It was decided that a sub-group would work on ToR b (synthesis on the development of hatcheries….), including B. Beal, S. Robinson, J. Mazurie, and D. Fraser. The subgroup working on ToR e (current sustainability of shellfish culture) included A. Bodoy, P. Kamermans, and P. Cranford. The ToR d (ecological factors affecting shellfish production) was addressed by P. Cranford.

2 ADOPTION OF THE AGENDA

The draft agenda prepared by the Chair was adopted after minor modifications to the time schedule.

3 APPOINTMENT OF RAPPORTEURS

- Brian Beal was appointed as rapporteur for the first plenary session on Wednesday morning.
- David Fraser was appointed as rapporteur for the plenary session on Thursday afternoon.
- Shawn Robinson was appointed as rapporteur for the plenary session on Friday afternoon.

Notes on other plenary sessions were taken by the Chair of WGMASC.

4 TOR (A) : REVIEW NATIONAL REPORTS OF SHELLFISH PRODUCTION AND RELATED ACTIVITIES

***PRELIMINARY REMARSK AND WG COMMENTS*[2]**

The ToR (a) concerned the review of national reports on shellfish productions and related activities, in order to provide a synthesis of the current status of shellfish production (...).

National reports on aquaculture production, including shellfish production, were usually part of the WGEIM annual report. After an internal discussion within the Mariculture Committee, it was suggested last year that such reports could be addressed within the WGMAFC for finfish aquaculture and the WGMASC for shellfish culture. A corresponding ToR was agreed by the ICES Council during the 2002 Statutory meeting. Later on, the Chair of the Mariculture Committe asked the ICES Environment Adviser (Janet Pawlack) about the utility of such Term of Reference, being argued that official organisation, the FAO and the EU, are producing annual statistics for aquaculture on national bases, and these are widely used for citation in scientific papers. In her answer, the Environment Adviser indicated that the WGMASC should not spend a great deal of time on this ToR, as the corresponding information is readily available through FAO and EU publications.

The Chair informed the participants of these exchanges. After a short discussion, it was then decided that the Term of Reference should be addressed with the information available from the participants. The working group has taken the resolution that the collection of statistics for shellfish production on national bases should not be pursued within ICES WG. This Term of Reference should be withdrawn for the 2004 WGMASC meeting.

[1] The meeting format that is used by the WGAGFM was not proposed during this first meeting as some preliminary work has to be prepared by ToR leaders, and this needs a preliminary experience of the functioning of an ICES WG. This way of functioning could be proposed for the next WGMASC meeting, after discussion within the mariculture committee.

[2] The head of each chapter (in italic) contains general remarks and a summary of the discussion that arose on the subject during plenary sessions. The report on the corresponding ToR is presented afterwards.

When discussing the subject within the WG, it appeared that official statistics may not always corresponds to actual production figures, this being due to the choice of statistical classes and to the merging within several species.

Available information on these statistics were presented by the members as follows.

- Some countries such as France have had national statistics that were "self-declared." When a different censusing system was put in place in 2002, the new statistics are at variance with the older ones.

- In Scotland, an annual shellfish production survey report (including economic data) is produced for and approved by the Aquaculture and Fisheries Minister. These data are used by policy makers, farm companies and banks to assess the feasibility of business plans and the granting of loans.

- Although official national statistics may not be entirely accurate, if the methodology for obtaining the data is similar from year-to-year, then they may be useful in helping determine trends in production or value of the commodity through time. These trends may be interpretable with respect to disease or other intrinsic or extrinsic factors.

- Spatial and temporal trends within a country may be important. For example, production of cultured mussels has dropped sharply (by more than 3,000 tonnes) during last two years in the Mediterranean Sea, due to predation by sea bream. The same is not true for Atlantic-grown mussels.

- Official national statistics of aquaculture production (for 2000) are available from FAO Fish Stats. They may be downloaded from the website : http://www.fao.org/fi/statist/FISOFT/FISHPLUS.asp

5 TOR (B) : SYNTHESIS ON THE DEVELOPMENT OF HATCHERIES, THEIR IMPACT ON SHELLFISH PRODUCTION, ON THE DISSEMINATION OF SELECTED OF MODIFIED STRAINS, AND THE GENETIC CONSEQUENCE OF REDUCED BROODSTOCKS ON NATURAL POPULATIONS

PRELIMINARY REMARK AND WG COMMENTS

When discussing this Term of Reference and analyzing the way it could be addressed by the WG members, it became apparent that information such as the number of hatcheries and the number and quantity of species produced within a given country were not readily available. Also, little information exists on the quality of spat from the different sources. To collect these data, the WG has proposed an elaborate questionnaire for hatchery managers and their staff., WG members would collect the information for the first year, making the recommendation that official services continue the initiative. The WG also produced a table to describe the current status of hatcheries production.

Selection techniques (triploids, tetraploids, disease-resistance) have been discussed. To go further, it was agreed that additional information on these subjects should be obtained from WGPDMO

Preamble

This document is a draft of work conducted by the WGMASC and is a work in progress. It will be expanded in future meetings to more thoroughly address the issues raised.

Rationale

Hatcheries are an essential tool for securing spat availability to the industry, and for the dissemination of genetic stability and improvement. There are several reasons why hatcheries exist. These include the need to restock wild fisheries which have been depleted, to satisfy the demand by culturists and shellfish farmers for a consistent, high quality source of seed and to produce organisms that are not normally available (introduced species or specific strains). Over the course of the last 20 years, there has been a dramatic increase in the number and the size of shellfish hatcheries (see Annex 4 for an example of a list of current hatcheries by country and annual production estimates by species).

Initially, most hatchery technology was developed through publicly-funded government laboratories which were later transferred to and developed by private industry. Hatcheries developed in response to three different needs:

(1) To complement the decline in wild fisheries that could not supply the market with the demand from local and foreign markets (i.e., *Pecten maximus*, France) ;

(2) To supply spat for cultivation of a non-indigenous species ; and,

(3) To diversify the sources of spat of a species naturally available and collectable ; to ensure a more consistent, higher-quality supply of material for culturists to use as well as to produce specific genetic strains.

The percentage of hatchery-produced animals seeded compared to those caught from wild sources is increasing. In France, for example, approximately 15%–20% of *Crassostrea gigas* spat are now produced from hatcheries, most of which are triploids.

Current status

The degree of hatchery technology varies widely among species. The reasons for these differences are driven by market demand for the end product and the consistent availability of wild-collected spat. Species such as mussels (*Mytilus edulis*) are often readily available from natural settlement and therefore, very few hatcheries have produced commercial quantities of mussel seed. However, owing to the vagaries of natural settlement of mussels, in Ireland and Norway in recent years, there is a perceived need for development of hatchery facilities for that species. Others, such as *C. gigas, Tapes philippinarum, Mercenaria mercenaria, Argopecten irradians* are routinely produced in hatcheries throughout the world. While hatchery technology is well developed for these species, others such as scallops (*Pecten maximus, Placopecten magellanicus*) and *Ostrea edulis* have proved more difficult to rear on a routine basis.

Currently, detailed information on hatchery production is not readily available within ICES countries and as a result comparisons on gross production, trends and new developments are difficult to provide. As a result, a survey questionnaire was developed to obtain this information (see Annex 4).

Some of the basic requirements of the design of hatcheries are related to the maintenance of high-quality standards and the implementation of a good biosecurity policy. Hatcheries require high-quality water supply, secure from future developments that may negatively impact it. Facilities should be designed to maintain high standards of hygiene and efficiency in all phases of production (larval rearing, algal production, etc.) with physical separation of those phases and duplication to avoid failures of any one component. A quarantine unit (strict confinement, effluent treatment) is essential in hatcheries using broodstock from non-native origins, from genetically unique forms (tetraploids), and from areas of unknown disease status. Hatcheries require a highly competent staff that is trained in mariculture principles through hands-on learning and formal coursework. Because technology is continually advancing, there should be a requirement for on-going training and development.

Shellfish nurseries are a natural extension of the hatchery system to enable successful and cost-effective rearing of juveniles to a suitable growout size. They are usually located in relatively close proximity to the hatchery, but the feasibility of transporting competent larvae, e.g., in moist containers lacking water, has lead to the technology of remote setting. This enables skilled farmers to nurse spat themselves. Nurseries require a high quality, secure water supply in areas of high primary productivity. The nursery should also be sited in areas with a low probability of introduction of pollutants, bio-fouling, pests or diseases. They may ideally be sited in an approved, disease-free area, thus allowing unrestricted movement of stocks However, nurseries sited in restricted areas may still send their products in identical areas. In addition to a nursery site, some hatcheries will be more vertically integrated with growout (on-growing) facilities that require environmental and biological characteristics similar to the nursery.

Regulations

Establishment of a shellfish hatchery depends on national or local legislation to ensure that regional development balances with environmental sustainability, and this may vary in different countries. Specific legislation that may affect hatcheries includes classification of waters and approved zonation for disease agents. Both of these can influence the movement of shellfish for production and utilization of areas. In some cases, shellfish hatcheries, because of poor water quality or the presence of disease agents such as *Bonamia ostrea*, can be severely restricted in their development. For example, in Scotland an oyster hatchery relocated to a more remote location because of lowering water quality standards which affected conditioning of broodstock and hatching of larvae.

Other legislation includes land-use issues where shellfish hatcheries may not be sited in regions zoned for other activities (Readers will find in the revised Code of Practice in the Introductions and Transfer of Marine Organisms detailed information about the risks of transferring species and methods to reduce those risks). These regulations, in conjunction with local land prices (real estate costs), will often make siting of a hatchery difficult. In other areas, hatcheries are more easily established because they occur in remote locations with low population densities. There is often a lack of education and knowledge of these regulations and, as a result, hatchery owners may circumvent these rules. The implementation of Codes of Practice will be important to increase awareness of responsibilities and bring the existing industry into compliance.

Impacts

Hatchery production, as previously stated, responds to both quantitative and qualitative needs of the shellfish industry, and, therefore, has positive impacts on this sector as well as consumption. These positive impacts will continue to grow as efficient production practices for the cultured species continue to evolve.

Hatcheries which follow operating codes of practice and biosecurity policies will typically have a low impact on the local environment with respect to water quality, and discharges from these hatcheries will generally be of a high standard. In the absence of accepted facility operating standards, there are potential risks that include the uncontrolled growth of pathogens (e.g., *Vibrio* spp.), discharges of antibiotics, chemicals, disease-agents, fouling organisms and genetically modified materials.

The main function of a shellfish hatchery is to produce seed for planting into the natural environment. The two main biological impacts from these activities are flooding the natural populations with potentially less genetically diverse stock and interaction (competition, predation) with other organisms, including conspecifics in the environment. The significance of this impact (genetic diluting) will be related to the proportion of cultured seed and origin of parent broodstock, in relation to wild stocks in a particular area.

Although the goal of producing cultured seed is to create a high quality, vigorous progeny, in reality, because of low numbers of broodstock used in the hatchery and inadequate rearing (culling) techniques, large numbers of poor quality (low fitness or lowered genetic variability compared with wild stocks) juveniles may be released. The long-term impact of this practice could compromise the success of wild populations by diluting the genome and introducing more undesirable traits into the overall population. A monitoring programme to assess genetic variability would ensure the development of diversified broodstock.

One solution to this may be the production of sterile triploids as in the case with *C. gigas* in France and *Mytilus galloprovincalis* on the West Coast of the U.S. Currently, there are two methods to produce triploid animals. One is via chemical induction and the other is crossing of tetraploids with diploid broodstock. The dangers in the former technique are that less than 100% of the animals produced are triploid while the dangers of the latter technique would be the unintentional release of tetraploids into the marine environment which could potentially interact with natural diploids producing sterile triploids. Obviously, bio security protocols must be strictly enforced in these cases. For example, a negotiated protocol between French hatcheries (in charge of implementing quarantine facilities), the administration and scientists (ploidy surveys on natural stocks) is under discussion at the moment. Another issue with genetic selection is the development of disease-resistant strains. Although these animals may not be susceptible to local pathogens, they could act as a reservoir and pass the disease on to wild populations[3]. The wild populations should be considered as a valuable source of genetic material (gene bank) and as such, adequately protected.

When introducing non-indigenous species, adverse ecological impacts would involve direct competition for space and food with wild stocks and increasing the number of species interactions. By adding a potentially large biomass of filter-feeding organisms to the environment some resources may become depleted and limiting to other species. The degree of this impact will be related directly to the volume of the system and its relative productivity. The addition of increased numbers of cultured organisms will likely result in a numeric response by predators. Depending on stocking densities and on the scale of this response, predation rates on natural populations may either increase or decrease. For example, the increase of cultured seed may deflect some predation from the wild stocks due to their relative proportion or simply encourage an increase in the population of predators by providing an increase in the supply of food.. Another potential impact is the intentional introduction of an exotic species to an area through hatchery cultivation (e.g., *T. philippinarum* in France). Unintentional introductions are more numerous and have often arrived at a location with broodstock or juveniles (i.e., *Carcinus maenas*, *Urosalpinx cinerea*, MSX, *Crepidula fornicata*, etc.). The danger of these introductions is that the spread of new species is often unrestricted due to the lack of local biotic and abiotic controls. This highlights the need for a quarantine facility.

[3] This issue should be discussed together with ICES working groups : WGAGFM and WGPDMO, respectively.

Although the risks of culturing unwanted organisms are relatively low in the hatchery environment due to a higher level of control, movement of cultured seed from nursery to growout areas may result in the spread of pests and diseases within and between countries (e.g., *Polydora* infestation of *C. gigas* and *P. maximus* in Scotland). Current legislation encourages trade between EU member states and, unless good legislation and high standards of biosecurity are employed, such pests and diseases are likely to spread.

Future directions

Hatcheries are playing a larger role in the production of juveniles for both intensive and extensive (stock enhancement) aquaculture operations, as they allow a better control on juvenile availability. It is predicted that production requirements will increase dramatically for many currently cultured species, either related to declining commercial stocks, or to improvement in cultural traits.

The trends in marine shellfish hatcheries appear to be toward larger, more efficient and automated systems. As scale of production increases, this will result in the creation of more small hatcheries and/or larger facilities. Hatcheries will likely diversify production toward newer, novel, higher-valued species (e.g., *Haliotis* and *Panope*) or bulk species easy to rear at moderate cost and amenable to genetic improvement, (e.g., Pacific oysters and mussels).

There is an overall recognition of the importance of high quality water, well-selected broodstock and appropriate technology to improve production. Broodstock selection presently based on empirical methods should take benefit from the increasing scientific knowledge and expertise available in genetics (genetic markers, heritability of useful traits, selection protocols). There is also a need for scientific support in the field of broodstock conditioning, nutrition, larval and post-larval pathology, so as to ensure reliability of hatchery productions, and effective gains from genetic improvement.

In the future, the WG will address several of these subjects, to provide a review of the knowledge concerning the development of shellfish hatcheries and the related questions.

References

Anonymous. 2003. Report of the ICES Working Group on Introductions and Transfers of Marine Organisms. Vancouver, Canada, 26–28 March 2003. Advisory Committee for Marine Environment, CM 2003/ ACME :04, 168 pp.

6 TOR (C) : REVIEW THE ECOPHYSIOLOGY CAUSATIVE FACTORS OF ABNORMAL MORTALITIES ON CULTURED POPULATIONS OF MOLLUSCS AND WAYS TO AVOID THEM WITH IMPROVED HUSBANDRY

PRELIMINARY REMARK AND WG COMMENTS

This Term of Reference prompted a long discussion among members on how it should be addressed. The group had difficulties determining what "abnormal" mortality means; rather, it decided that it should discuss the different types of mortalities, classify them, and then determine causative agents. The term « Ecophysiology » has such a broad meaning, which makes the topic difficult to review without further input and interaction with the parent committee.

The common feeling among the group was that this Term of Reference should be refined, and a more precise definition should be determined before preparing the review.

Because of these difficulties and the lack of time (only seven members attended this meeting), this term of reference was not given a high priority during the time available.

There was an internal discussion about merging ToR c and ToR d, into one ToR based on "Internal vs. External" factors causing shellfish mortalities. It was finally decided (i) to propose a new Term of Reference for the year 2004, on a review of stress indices used to detect declining conditions leading to death, and (ii) to prepare a working plan for the ToR d, detailing the subject which will addressed in the future.

The WGMASC will not report on the ToR d for the year 2003.

7 TOR (D): ECOLOGICAL FACTORS AFFECTING SHELLFISH PRODUCTION (CARRYING CAPACITY, FOULING, PREDATION, HAB) AND ALTERNATIVE SOLUTIONS TO MITIGATE EFFECTS

PRELIMINARY REMARKS AND WG COMMENTS

A general comment was that the ToR d covered a very broad topic, thus making it difficult to produce a review on the subject in the alloted time schedule. It was then decided that the ToR should be clarified, and the report restricted to a review of the biotic and abiotic factors affecting shellfish production. A proposal is made to rewrite the corresponding ToR..

After a wide discussion, the WG agreed to propose the establishment of a working plan for the coming meetings. The subjects were ranked according to their priority. Some of them will need to include the adequate competences within the WG.

1) Carrying capacity (Hydrographic factors, Primary productivity, food supply) ;
2) Predation ;
3) Fouling ;
4) HAB Blooms ;
5) Disease ;
6) Pollution (water quality) .

During this meeting, it was agreed that the report should focus specifically on the effects of the physical environment and the carrying capacity on shellfish production.

7.1 Introduction

A mechanistic knowledge of how coastal ecosystems functions is fundamental for developing strategies for improving aquaculture sustainability. An understanding of aquaculture-based ecosystems requires consideration of biological, physical, and chemical factors. Physical processes governing water circulation and mixing determine the transport and supply of dissolved and particulate matter, including bivalve food particles and waste products (faeces, pseudofaeces and ammonia). Important biological processes to be considered include feeding and egestion by both cultured and wild organisms, the dynamics of the supporting planktonic ecosystem, interactions between pelagic and benthic communities, and exposure to infectious diseases and pathogens. Important chemical considerations include nutrient and contaminant dynamics and chemical transformations mediated by the cultured organisms and various ecosystem components, including bacteria.

The following review and recommendations are aimed at supporting decision-making needed to improve the sustainability of the shellfish industry. The initial focus of the WGMASC was on identifying some of the major physical and biological processes that may limit bivalve production and which may affect sustainability over space- and time-scales relevant to the aquaculture industry. In addition, international modelling efforts to assess the carrying capacity of coastal systems are examined as they quantitatively address the interactions between bivalves and the environment. Subsequent meetings will expand on this report by identifying additional abiotic (chemical and physical) and biological considerations affecting shellfish production.

7.2 Major environmental controls on shellfish production

A basic understanding of bivalve production requires tracking of the total particulate load (bivalve food abundance) and composition (nutritional value), and the water flux (mixing and exchange) (Grant and Bacher, 2001). Coastal waters exhibit a variety of physical oceanographic processes, for example tidal and estuarine circulation. Dissolved and suspended matter in the water column is transported and mixed by water motion and are eventually exchanged with the adjacent open ocean, or deposited (utilized) locally. It is hypothesized that the carrying capacity of an embayment is regulated to a large extent by water motion and mixing. Inclusion of oceanographic parameters in studies of culture systems is essential to a quantitative assessment of the validity of this hypothesis (Cranford *et al.,* 2003).

Some relatively simple scaling exercises have been conducted that provide intuitive indicators of the limiting effect of water motion on aquaculture productive capacity (Cloern, 1982; Officer *et al.,* 1982; Nichols, 1985; Hily, 1991; Smaal and Prins, 1993; Dame, 1996; Dame and Prins, 1998; Prins *et al.* 1998; Cranford *et al*., 2003). This approach compares factors supplying food to bivalves, including the residence time (RT) of water in an embayment (determined by degree of tidal exchange of water) and phytoplankton turnover or primary production time (PPT), with the time required for the bivalves to clear the whole water body (clearance time; CT). Tidal exchange may limit system productive capacity if CT/RT is less than 1, which means that tidal exchange is unable to compensate for particle depletion by bivalves. Studies of this type suggest that intensive shellfish culture may have the capacity to deplete food supplies on a coastal ecosystem scale in some regions, with potentially negative consequences to aquaculture yields (Dame and Prins, 1998; Prins *et al.* 1998; Cranford *et al*., 2003). Dame and Prins (1998) examined 11 coastal ecosystems and suggested that many systems produce sufficient phytoplankton internally to prevent overgrazing by resident bivalve populations. However, these authors concluded that some systems under intense bivalve culture require the physical import of food resources from outside the system to prevent particle depletion.

Carrying capacity is theoretically at maximum if CT/RT < 1 and CT/PPT = 1 (Smaal and Prins, 1993; Dame, 1996; Dame and Prins, 1998). To date, the only system studied that appears to meet these criteria for overexploitation by shellfish aquaculture is the Bay of Marennes-Oléron, the most intensive growing region of the Atlantic coast of France (Dame and Prins, 1998). Research on the whole-basin environmental effects of intense mussel and oyster aquaculture in Marennes-Oléron has focused on the impact of bivalve overstocking on growth and survival (Héral, 1993; Héral *et al.*, 1986). Excessive culture on two occasions led to large-scale growth reduction and high mortalities in the Bay.

Environmental controls on aquaculture capacity are believed to be greatest in estuaries and inlets where water residence time is long and bivalve biomass is high. In such areas, bivalve feeding could dramatically reduce the concentration and alter the nature of suspended particulate matter with the resultant potential to change pre-culture productivity within a defined area. In areas with greater flushing, water depleted of particles by bivalves can be renewed by tidal exchange.

The above scaling and mass-balance approaches are useful and intuitive indices for addressing the issue of system productive capacity. However, they are limited in that they neglect potentially important physical processes, such as water column stratification, mixing, and flow velocity, that could influence the effects of bivalve culture operations on suspended particles. These approaches also use single flushing estimates for estuaries, when flushing is spatially dependent, and do not include additional particle utilization by fouling organisms associated with shellfish culture as well as by other resident suspension-feeding organisms that include zooplankton and benthic invertebrates. The cumulative grazing pressure on the phytoplankton needs to be considered when assessing system productive capacity for aquaculture.

7.3 Ecosystem and carrying capacity models

A variety of models have been applied to assessing the environmental interactions of bivalve aquaculture operations (Dowd, 1997; Grant *et al*., 1993; Grant and Bacher, 1998; Smaal *et al*., 1998; Meeuwig, 1999). While all of the approaches include a comparison of physical water exchange to some sort of biological process like filtration, there are no standard methods for assessing ecosystem effects. Bearing in mind the complexity of interacting factors, this is not surprising. Empirical studies such as the calculation of budgets (e.g., carbon, nitrogen, and energy) and simulation modeling have been some of the more focused approaches used to evaluate potential bivalve aquaculture effects at an ecosystem level. As an example of the former, Carver and Mallet (1990) calculated the mussel carrying capacity of an inlet in eastern Canada by comparing estimated food demand to food supply based on organic seston concentrations delivered by a simple tidal prism model. The latter approach was used by Raillard and Menesguen (1994) who constructed a simulation model for a macrotidal estuary in France to describe relationships between oyster feeding, primary production and seston transport. Both approaches yielded different, but complimentary, information. Meewig *et al*. (1998) used a mass-balance approach to model phytoplankton biomass in 15 Prince Edward Island embayments and estimated that the mussel farms in six of these systems reduced phytoplankton biomass by 45% to 88%. Dowd (2000) examined a simple biophysical model that quantified the relative roles of flushing, internal production and bivalve grazing on seston levels. These order of magnitude calculations strongly suggest that intensive bivalve culture has the capacity to alter particulate food supplies for long periods in some coastal systems as a result of limitations in the tidal exchange of food from outside the system.

More complex numerical models are powerful tools that may help to guide aquaculture management because they integrate important biological and physical processes that represent the complexity of this system (Cloern, 2001). Fully coupled biological-physical models may be envisioned (e.g., Prandle *et al*., 1996; Dowd, 1997) that predict shellfish production and carrying capacity as a function of culture density and location. To do this, shellfish ecosystem models, including carrying capacity models, must be integrated with information on water circulation, mixing, and exchange to account for transport and spatial re-distribution of particulate and dissolved matter. Box models (Chapelle *et al*., 2000; Dowd, 1997; Raillard and Menesguen, 1994) offer a practical means to couple coastal ecosystem models with physical oceanographic processes. The bulk parameterizations of mixing required for these box models can be derived directly from complex hydrodynamic models (Dowd *et al*., 2002).

Simulation models that focus on estimating bivalve carrying capacity and related ecosystem impacts provide effective tools for quantitative descriptions of how food is captured and utilized by bivalves as well as site-specific information on ecosystem variables and processes (Carver and Mallet, 1990; Brylinsky and Sephton, 1991; Grant, 1996). The ability to predict physiological responses of bivalves under culture conditions permits calculation of clearance, biodeposition, and growth rates and this ability presents tremendous opportunities to manage the sustainability of the industry (Carver and Mallet, 1990; Labarta *et al*. 1998). From a mathematical perspective, the nonlinear functional relationships used to describe bivalve bio-energetics have often led to poor model predictions due to their high sensitivity to inadequately known physiological parameters (Dowd, 1997). Robust mathematical relations are being developed with the needs of simulation models in mind, such that bioenergetic models have been successful in predicting growth (Grant and Bacher, 1998; Dowd, 1997; Scholten and Smaal, 1998).

Decision support systems have been developed that integrate available knowledge about natural- and human-driven parts of coastal ecosystems into computer-based models (Crooks and Turner, 1999; deJonge, 2000). Simulation models can be directed towards assessment of bivalve growth and carrying capacity from the standpoint of farm management. For instance, bivalve studies based on physical transport of food particles to bivalves and their bioenergetic use by the animals are part of a growth equation. Coupled with estimates of stocking density, these models produce farm yields, which may then be exported to economic models of profitability (e.g., Samonte-Tan and Davis, 1998). An essential feature of the growth models is that they may be fully ground truthed using bivalve harvest/growth data from the farm sites. Ultimately, these models may be used to actively manage the location and extent of culture in coastal estuaries for multiple users. Such models will need to take into account culture dynamics such as seed-stocking and fouling biomass, depth of activity, and cumulative effects of neighbouring human activities (e.g., agriculture run-off, construction sedimentation, boating, and ballast activities, etc.).

Another new development, which must be taken into consideration for ecological modelling, is increasing interest in bivalve polyculture. Bivalve culture is rarely conducted in isolation from other bivalve culture. Some leases accommodate several bivalve species. All have different habitat, physiologies and production dynamics. Accurate modelling of single species culture interactions with surrounding habitat ecology needs to take this into account in the future.

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8 TOR E : SUSTAINABILITY OF SHELLFISH CULTURE AND OPTIONS TO IMPROVE SUSTAINABILITY

PRELIMINARY REMARK AND WG COMMENTS

When discussing this Term of Reference, strong remarks were made about the danger of delivering wide and practically useless considerations. Several questions arose: What does the word « sustainable » mean in an aquaculture setting? Should we be discussing sustainability on the basis of ecosystem-based management? What is the benchmark ? What time-scale should be considered when addressing the recovery of environmental impacts of shellfish mariculture? It was agreed that the report should include pragmatic factors to improve sustainability in shellfish culture.

The establishment of guidelines or "Codes of Conduct" for molluscs that may be for both farm managers and hatchery operators was considered as an option which could be addressed in future meetings of the working group.

Because of the available competence within the working group, it was decided that the present 2003 report should focus on the interactions between the environment and the shellfish culture, from the point of view of sustainability. The working group used published documents on the environmental impacts of shellfish mariculture, one of them being given as an annex.

8.1 Introduction

There is a need to review all aspects of shellfish production related to the environment and asses how they comply with sustainability requirements (Goals 3 and 4 of ICES Strategic Plan). Based on this evaluation, options to improve sustainability can be identified. In our review, sustainable relates to ecological sustainability only and not economic sustainability. Since the subject is interactions with the environment, only those phases of the culture that are being carried out in the marine environment (spat collection, grow-out and harvesting) are being reviewed here.

There is a large difference between the culture of fish and shellfish. Most farmed fish are carnivorous and food is added to the environment, while shellfish are herbivorous and eat algae and bacteria that are available in the water. Unlike finfish aquaculture, bivalve culture requires minimal additions to the environment, except for the animals themselves and the infrastructures used to grow them. Their food is supplied by the environment and their wastes return nutrients and minerals to the ecosystem. Many cultivated species are indigenous to environment and release reproductive products to the surrounding area. Mollusk culture is therefore much more intricately and inextricably linked to its environment than most finfish culture, including mariculture cages. At present, many shellfish operations worldwide do not show a detectable impact at the current level of production (e.g., Crawford *et al.,* 2003). Nevertheless, there are concerns about potential environmental impacts as culture areas and biomass are expanded. The impacts can be both negative (e.g., removal of food for other organisms and organic enrichment of seabed) and positive (e.g., potential reduction in coastal eutrophication). The degree of environmental impact is expected to differ greatly between culture sites depending on the type and extent of culture activities and local environmental conditions (Chamberlain, *et al.,* 2001). The workplan of the WGMASC includes an initial review of the *potential* interactions between shellfish culture and the marine environment. Following the review, these potential impacts will be prioritized according to the degree of environmental concern in order to identify ways to improve sustainability. Further discussion on priorities and options to maintain sustainability is planned for the next meeting.

Different species of shellfish are cultured in various ways. For example, mussels are cultured on rafts, longlines, Bouchot poles and bottom plots, or oysters are cultured on trestle tables, longlines and bottom plots (Table 8.1.1). For these different techniques, different structures are introduced in the marine environment. Harvesting from bottom plots involves diving and dredging, while harvesting from lines does not. Not all species and not all culture types will have the same effect on the environment. The effect of these different culture techniques are outlined below.

8.2 Synthesis of scientific knowledge on the potential interactions of shellfish aquaculture production on the environment

Dense populations of bivalve filter-feeders, including both wild and cultured populations, can potentially modify, maintain and create entire habitats through their effects on suspended particles and the formation of structurally complex shell habitat. Suspended and bottom culture of bivalves increase the surface area available for attachment and grazing by other species, and spaces between shells provide refugia from physical stress (currents and waves) predation, pests and disease. Potential mechanisms for ecosystem level effects include the utilization of particulate food resources (primarily phytoplankton and detritus, but including some auto- and heterotrophic picoplankton and microzooplankton) by the bivalves and associated epifauna, the subsequent release of unutilized materials in dissolved (ammonia) and particulate (faeces and pseudofaeces) form, and the removal of minerals from the system in the bivalve harvest.

The following is a synthesis of the scientific knowledge of potential environmental controls on aquaculture production. A comprehensive literature review of the current state-of-knowledge on the ecosystem-level impacts of marine bivalve culture was recently published as part of a Fisheries and Oceans Canada technical report (Cranford *et al.,* 2003). This report is attached as Appendix 1 and served as a basis for discussion by the WGMASC. The report focused on the consequences of aquaculture practices in Canada, and particularly on suspended mussel culture. Several additional potential environmental concerns were discussed by the WGMASC to include aquaculture activities conducted in other ICES nations (e.g., bottom, table, and raft culture).

The culture of bivalve mollusks may involve a number of effects on the current state of coastal marine ecosystems. Important biological processes to be considered include feeding and egestion by both cultured and wild organisms, the dynamics of the supporting planktonic ecosystem, interactions between pelagic and benthic communities, and exposure to infectious diseases and pathogens. Important chemical considerations include nutrient and contaminant dynamics and chemical transformations mediated by the cultured organisms and various ecosystem components, including bacteria.

The rapid and extensive transformations of water bodies into mussel production could potentially change the ecological function of some bays. Potential impacts (positive and negative) related to intensive bivalve aquaculture may occur at different stages of cultivation. The following list of environmental concerns were identified by the WGMASC and should not be considered comprehensive at the present stage. Considerations of the environmental consequences of diseases associated with shellfish aquaculture were not considered as this is the topic of another working group. These will be expanded at future meetings.

8.2.1 Spat collection stage

- Juvenile collection methodologies may result in environmental effects. Bottom dredging for spat removal can cause positive and negative benthic community impacts. The removal of spat also reduces their availability to predators.[4]
- Heavy spatfall in regions of bivalves culture causes competition with wild populations while also reducing predation pressure on wild species through the addition of new prey. A positive impact can be a recruitment onoverfished wild fisheries.
- Introduced Japanese oysters in SW Netherlands reproduced successfully resulting in the creation of extensive reefs that possibly compete for food and space with wild populations (Kater and Baars, 2003).
- The introduction of shell substrate for settlement and protection of cultured bivalves can have beneficial or negative impacts on benthic communities. The substrate can negatively affect existing species, but it can also increase diversity or recruitment of already present wild species.
- There is a potential that suspended spat collectors in coastal regions may alter local sedimentation patterns.
- Pest species can be introduced to systems during transport of spat between culture sites.
- Generally, the area that is needed for spat collection is much smaller than the grow-out areas. Consequently, the interaction with the environment is smaller as well.

[4] This subject is also covered by the Benthic Ecology Working Group.

8.2.2 Grow-out stage

8.2.2.1 Potential effects of bivalve filter feeding

- Bivalve filter feeders have a high filtration capacity and high density cultivation may deplete the resident phytoplankton and seston so that they depend on the tidal input of offshore phytoplankton to sustain high density culture.
- The spatial scale of particle depletion is an important issue. Depletion has been documented within culture sites (mussel rafts and long-lines) and there is the potential for interaction between leases in extensively cultured bays. Large scale particle depletion would impact food webs within the system.
- Bivalve aquaculture may help to reduce excess coastal phytoplankton caused by eutrophication through their feeding activities.
- Competition for food between cultured bivalves and zooplankton, and direct ingestion of zooplankton by the bivalves may alter pelagic food webs.
- Bivalve selective feeding behaviour may cause a shift in phytoplankton size spectra.
- Feeding activity could potentially alter marine particle dynamics (i.e., aggregation and sedimentation) by reducing particle concentration or by disrupting flocs.
- Extra grazing on phytoplankton can reduce competition with macroalgae, which may result in the formation of macroalgal blooms (Sfriso and Pavoni, 1994).
- Bivalve filter feeders may be forced, through depletion of important nutritional requirements, to browse on algal species toxic to human health, delaying harvest and increasing pressure within a system

8.2.2.2 Potential effects of biodeposition

- Bivalve faeces and pseudofaeces contains organic matter (15% to 50% organic content) that can cause benthic enrichment effects. The recycling of these organic biodeposits increases the oxygen demand in sediments, potentially generating an anaerobic environment that promotes ammonification and sulfate reduction, leading to alterations in benthic species abundance and community composition.
- By diverting suspended organic matter to the seabed, suspended culture may impact food webs and nutrient dymanics. The rate of nitrogen cycling in coastal regions is increased through the rapid biodeposition of suspended organic matter and the subsequent nutrient regeneration in sediments. A shortened cycle of nutrients between the benthos and phytoplankton can increase local nutrient availability as less material is exported. The increased sedimentation of organic matter through biodeposition therefore can act to retain nutrients in the coastal region. The greater availability of nutrients may lead to enhanced primary production, potentially contributing to more frequent algal blooms, including toxic species.
- The degree of organic enrichment is closely related to hydrodynamics such that the potential for impact is highly site specific. Estuaries identified as having the greatest risk of biodeposition effects are generally shallow, have a relatively small tidal exchange and have a high percentage of the total estuarine volume under culture.
- Oxygen depletion in the water column resulting from the high BOD of biodeposits is generally limited and localized near the seabed.
- Mussel fall-off from suspended culture creates additional organic loading and alterations to benthic communities.

8.2.2.3 Potential effects of excretion

- Shellfish excrete ammonia. The dominant form in which nitrogen is occurring in the marine environment is nitrate. Thus, excretion of ammonia may alter coastal nutrient dynamics. For example, the change in abundance of ammonia may alter phytoplankton species (Philippart *et al.,* 2000). This in turn can have an effect on grazer species composition and abundance. In addition, a change in the ratio of nitrogen to phosphorus may have similar effects. e.g., the formation of Phaeocystis blooms may depend on this ratio (Riegman *et al.,* 1992). Also, there is much speculation on the contribution of bivalve culture to phytoplankton blooms, including HABs (Parsons *et al*., 2002; Cloern, 2001).
- Harvesting of nutrients via removal of bivalves may remove nutrients from the coastal system. This method can be used to alleviate effects of addition of nutrients by fish farms. A number of salmon farms in Scotland and Canada are combining the culture of mussels and salmon on an experimental basis (Robinson *et al.,* 2003; Cook *et al.,* 2003).

8.2.2.4 Other potential effects

- Shellfish culture uses various materials such as ropes, buoys, rafts, poles or shells. In addition, the shellfish themselves are introduced into the marine environment. This material can act as a substrate or refuge for epibionts. Increased shell substrate/refuge for epibionts (fouling organisms and parasites) caused by the introduction of cultured species and associated holding structures will compound any impacts from the bivalves due to the additional food utilization, biodeposition, and excretion. Epibionts or fouling organisms can make up a large part of the biomass of suspended cultures of bivalves. They comprise of a variety of organisms such as macro algae, sponges and ascidians. When filter feeding the epibionts may have effects that are comparable to those of bivalves such as removal of algae, biodeposition, or excretion. In the Thau lagoon (France) ascidians are 5% of the total stock of cultured bivalves (Gangnery, 2003). These ascidians can maximally filter 205 liter per day per individual, while oysters can filter 211 $l^{-1}.d^{-1}.ind^{-1}$ and mussels 162 $l^{-1}.d^{-1}.ind^{-1}$. Tunicates can retain particles smaller than 2 µm, which is smaller than what most bivalves can take up, but they also ingest larger particles. Thus, competition for food with the cultured bivalves is possible. The introduction of parasites, such as Polydora species, can impact on both food availability, and inadvertent mortality of the cultured stock.
- Diseases are introduced with the movement of aquaculture species, introducing and transmitting pathogens, often resulting in significant mortalities which add to the organic load within a system.
- The reef effect caused by the aquaculture structures and animals increases habitat and food availability to some species (positive effect). E.g. it is known that Eider ducks feed on ropes of mussel longline culture (Ross, 2000). A higher abundance of crabs and flatfish was observed under rope cultures of mussels. Seabream feeds on mussels that are cultured in the Mediterranean (Lagardère *et al.,* 2001).
- The potential interactions of shellfish installations with the hydrodynamic conditions may lead to reduced waters currents within the area occupied by shellfish culture, and an increase in the sedimentation beneath the installations. It has been observed that the tables used for the intertidal culture of oyster in France are provoking an increased localised sedimentation underneath the tables (Sornin *et al.,* 1983).
- Predation of cultured bivalves by birds, seabream, and other predators may also cause increased predation on wild species while having a positive effect on the predators.
- The dedication of certain areas to aquaculture can exclude other activities that may negatively influence the environment (e.g., protection from trawling impacts).
- Hydrocarbons and wastes introduced to the environment from increased boating activity in culture areas can have deleterious effects.
- The structures utilized for bivalve culture are frequently visited by the farmers and this may create some disturbance for birds and marine fauna. These disturbances can even become intentional, to frighten those birds which predate on cultured shellfish.
- Any attempt to assess environmental effects on bivalve aquaculture must consider the complexity of natural and human actions in estuarine and coastal systems. Shellfish responses to multiple stressors (nutritive, contaminant, fishing activities, invasive species, habitat loss, climate change, coastal construction, etc.) are intimately connected. For example, infectious diseases associated with shellfish overstocking, combined with enhanced food limitation and exposure of cultured organisms to “exotic” pathogens introduced with seed or broodstock, can have a significant and frequently permanent impact on shellfish physiological and nutritional status.

8.3 Prioritizing potential environmental interactions

Table 8.3.1 summarizes the potential interactions between shellfish culture and the environment identified in Section 2 (above). The WGMASC, at the 2003 meeting, began to assigned different priority ratings (low, medium, high and unknown) to each interaction to reflect the degree of environmental concern associated with each interaction. At present, the discussion was limited to identifying interactions that presently appear to be of greatest environmental concern. This exercise will be completed at the next meeting of the WGMASC. Reasons for a “high” rating include considerations of the relative stocking density per unit area (related to the type of culture), the potential for the environment to assimilate the impact, and considerations of the recovery rate. *It should be noted that any actual impact will be site specific and will only occur under specific environmental and culture conditions.*

8.4 Relative impact of different husbandry practices

It is believed that certain culture methodologies and practices potentially have a greater degree of environmental impact than others. Suspended culture of mussels on longlines, rables and rafts permits the holding of large numbers of bivalves per unit area, and this culture method is therefore believed to have the greatest potential for impacts. Even with these types of culture, impacts may not be significant if local hydrographic conditions permit the dispersion of wastes. Table 8.3.1 also includes an initial comparison of the degree of environmental interaction associated with different culture activities. This activity is incomplete and the WGMASC work plan for 2004 includes assessing the degree of environmental interactions associated with different types of shellfish culture activities in greater depth. The relative environmental impacts of the culture of traditional and exotic species will be assessed, as will the impact of different culture structures.

8.5 Options to improve sustainability

The WG cannot state what impacts are acceptable. There are socioeconomic aspects to the sustainability question that cannot be addressed by scientists alone. Ecosystem-based management approaches and objectives developed elsewhere by several countries may be helpful for addressing the aquaculture sustainability issue.

The WGMASC work plan for 2004 will include examination of options to improve sustainability including: identification and evaluation of impact mitigation measures; incentives that improve culture and environmental performance; the identification of environmental performance indicators and reference points; the development of responsive management frameworks for farm expansion based on environmental effects monitoring programs; and the development of decision-support systems.

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Table 8.1.1. Overview of different methods used for the cultivation of different shellfish species groups in different culture phases.

Phase	**Method**	**Shellfish species group**			
		Mussels	**Oysters**	**Clams**	**Scallops**
Spat collection	Bottom dredging	X			
	Use of shell substrate		X		X
	Use of artificial collectors	X	X	X	X
	Hatchery produced	X	X	X	X
Nursery	Subtidal floating cages		X	X	X
	Bottom cages		X	X	X
	Bottom plots			X	
Grow out	Subtidal rafts/tables	X	X		
	Subtidal longlines	X	X		X
	Subtidal nets/cages		X	X	X
	Subtidal plots	X	X	X	X
	Intertidal plots	X	X	X	X
	Intertidal tables		X		
	Intertidal poles	X			
Harvesting	Stripping ropes, poles	X	X		
	Subtidal and intertidal dredging	X	X	X	
	Intertidal digging			X	
	Removing bags, nets/cages, diving		X	X	X

Table 8.3.1. Classification of the interactions between shellfish culture and the marine environment. Effects will be classified as low, medium, high, unknown, or not applicable (n.a.) and as positive (+), negative (-), or both (+/-). Numbers that refer to sections in the text will be added.

Type of culture →	Suspended			Bottom			
Interaction ↓	Subtidal rafts/tables	Subtidal longlines	Subtidal nets/cages	Subtidal plots	Intertidal plots	Intertidal tables with bags, cages	Intertidal poles
Dredging for spat					medium		
Seeding of shells for spat collection				medium			
Placement of spat collectors		low					
Removal of collectors	low	low	n.a.	n.a.	n.a.	n.a.	low
Filter feeding: algal consumption and zooplankton predation							
Filter feeding: nutrient removal							
Excretion of nutrients							
Deposition of (pseudo)faecal pellets	high	high					
Changed current, sedimentation							
Increased substrate for epibionts							
Increased shelter							
Increased food availability							
Increased predation	low	medium	low	Medium	Medium	Low	medium
Competition for space					low	low	
Pollution							
Stripping ropes and poles	low	low	n.a.	n.a.	n.a.	n.a.	low
Dredging	n.a.	n.a.	n.a.	high	high	n.a.	n.a.
Intertidal digging	n.a.	n.a.	n.a.	n.a.	medium	n.a.	n.a.
Diving	n.a.	n.a.	n.a.	low	n.a.	n.a.	n.a.
Removing bags, nets, cages	n.a.	n.a.	low	n.a.	n.a.	low	n.a.

9 REPORT ON THE CONTACTS WITH THE EUROPEAN AQUACULTURE SOCIETY

The WG participants were reminded that ICES seeks to strengthen links with the European Aquaculture Society. During the last ICES Annual Science Conference and statutory meeting in Copenhagen, it has been expressed at higher levels that ICES was preparing a Memorandum of Understanding with the EAS.

It was decided that the first meeting of the WGMASC should occur in Trondheim, Norway where the European Aquaculture Society was planning its annual conference, Aquaculture' 2003. The date of the WGMASC meeting was chosen to allow members to participate at the EAS Workshop on «Mussel Farming: Technologies and Productions».

Preliminary contacts were established with Dr. Alistair Lane (General Secretary of EAS). It was agreed that a short presentation of ICES and the WGMASC, including its objectives, could be given during the workshop on Mussel Farming. After discussing with the co-conveners of this workshop (Dr. D MacLeod and and Dr. S. Hansen), some time was scheduled for this presentation, at the end of the morning session on « biological and technical aspects of mussels farming ».

During the ten-minute presentation, ICES was presented by the Chair of WGMASC, with its aims, its advisory role towards national and international bodies. A short statement of ICES structure was given, insisting on the different committees. The Working groups under the responsibility of the Mariculture Committee were presented, and a more detailed explanation on the objectives of the WGMASC was given. Comments were made on some possible means to strengthen cooperation between the two organisations, at the scientist level:

- WG members from the Mariculture Committee should be encouraged to register with the European Aquaculture Society.
- WG members are encouraged to participate in the main events organised by the EAS (annual conference Aquaculture Europe, special workshops and symposiums).
- The names and e-mail addresses of the WGMASC members should be made available to membership of the European Aquaculture Society (EAS), so as to improve contacts. EAS members could exchange with WG members, on the subjects that could be addressed by the WGMASC.

Four participants in the WG, out of seven, attended the workshop, and participated in the discussions following the communications.

A letter will be sent by theChair to the General Secretary of EAS, to make a report of these contacts.

10 RECOMMENDATIONS

10.1 Recommendations on hatcheries for shellfish production

There is no coordinated effort at present to compile the activities and outputs of hatcheries within ICES countries. Considering the relative role of hatcheries in future, it will be important to document their production and methodologies. In the application of statutory controls, it is essential to identify hatchery location, species cultivated, and scale of production.

Hatcheries should be registered with the competent authorities, and develop a code of practice (i.e., biosecurity). Collection of data detailing facilities infrastructure and production, annual production by species, and movement of all life stages (including broodstock) should be conducted by the competent authorities on a continuing basis.

A substantial risk exists that hatcheries may release undesirable products into the marine environment (pathogens, pests, exotic species, and genetically unique individuals). It will be essential for hatcheries to have facilities available for the adequate containment of these organisms and for codes of practice to be developed by industry and the competent authorities.

- The ICES Code of Practice for Introduction and Transfers of Marine Organisms should be used when and where exotic species are reproduced or where biological risks are associated with release of hatchery products.

One of the most important questions facing the hatchery production industry and wild fisheries is the unquantifiable risk of compromising the genetic variability of wild stocks. With the increase in affordable access to new genetic tools (e.g., PCR), the ability to monitor the resulting output of particular families is now available. We should ensure that the competence of broodstock is maintained and the adverse ecological impacts between wild and cultured stocks are minimized. This should be linked to the ICES WGAGFM.

- Control and monitor genetic diversity among broodstock and cultured juveniles and compare to “wild” stocks. Study the ecological (reproductive output; behaviour; susceptibility to predators, etc.) impacts of hatchery-produced animals on natural populations (indigenous and non-indigenous).

As more intensive hatchery production increases, there will be a gradual shift from the collection of wild progeny to hatchery-reared individuals. This will affect local organizations and traditional spat-collection operations.

- Evaluate the social impact of hatchery production vs. wild production (sector organization; diversification of activities).

10.2 Recommendations on the ecological factors affecting shellfish production

- Numerical models should be employed for different environmental settings to determine the relative degree by which shellfish production capacity is limited by internal primary production and by the tidal import of external food supplies to the cultured bivalves.

- Evaluate the relative value of increasing levels of model complexity (simple indices to ecosystem models) in estimating shellfish production capacity.

10.3 Recommendations on the sustainability of shellfish culture

- Given that bivalve physiological processes (feeding, biodeposition and excretion) are the primary mechanisms for potential interactions between bivalve aquaculture and the ecosystem, and therefore the sustainability of coastal operations, a more complete understanding of the physiological ecology of cultured species is needed to facilitate accurate prediction of ecosystem responses.

- Studies are required to improve our understanding of the density-dependant role of cultured bivalves in controlling phytoplankton and seston concentrations in coastal embayments under traditional and novel culture scenarios.

- Studies are needed on the capacity of different environmental settings to assimilate organic enrichment impacts from aquaculture. Additional studies are also needed on nutrient dynamics in coastal systems supporting bivalve aquaculture to quantify potential interactions with nutrient availability and cycling and phytoplankton blooms.

- Knowledge obtained on the consequences of bivalve culture to ecosystem structure and function needs to be integrated objectively through the use and predictive power of ecosystem modelling. The ability of numerical models to provide decision support for the development of effective area-wide management strategies for promoting the environmental sustainability of the aquaculture industry needs to be evaluated. Numerical models should also be employed to test the hypothesis that shellfish aquaculture can mitigate environmental effects of eutrophication.

11 PROPOSAL FOR NEW TERMS OF REFERENCE

The WG suggests that the **ToR a** (review national reports of shellfish production and related activities) should be deleted.

The WG suggests that the **ToR b, c, d and e** will be rewritten as follow**:**

- Provide a synthesis on the development of hatcheries, the proportion of cultured animals to wild conspecifics and the relative proportion of triploids and other selected strains produced by hatcheries.

- Review literature on stress indices to identify potential diagnostic tools to detect declining condition leading to death in cultured populations of molluscs.

- Review the ecological factors affecting shellfish production (carrying capacity, fouling, predation, HAB, disease, pollution and water quality) and alternative solutions to mitigate effects.

- Evaluate the current sustainability of shellfish culture and develop a workplan to improve sustainability

The scientific justifications will be modified according to these proposals.

The **Working Group on Marine Shellfish Culture** [WGMASC] (Chair: A. Bodoy, France) will meet in Portland, Maine (USA) from 13–15 May 2004 to:

a) Provide a synthesis on the development of hatcheries, the proportion of cultured animals to wild conspecifics and the relative proportion of triploids and other selected strains produced by hatcheries;

b) Review literature on stress indices to identify potential diagnostic tools to detect declining condition leading to death in cultured populations of molluscs ;

c) Review the ecological factors affecting shellfish production (carrying capacity, fouling, predation, HAB, disease, pollution and water quality) and alternative solutions to mitigate effects;

d) Evaluate the current sustainability of shellfish culture and develop a workplan to improve sustainability.

WGMASC will report by 1 June 2004 for the attention of the Mariculture and Living Resources Committees.

Supporting Information

Priority :	WGMASC is of fundamental importance to ICES Member Countries
Scientific justification :	Despite the extensive progress made in salmon culture in ICES Member Countries shellfish production still accounts for half of the mariculture production. As such, issues related to shellfish production, in relation to the environment and technological development of the industry, have not previously been addressed within ICES. Shellfish production is based, with very few exceptions, on the use of the natural productivity of coastal waters as a source of food. Even seed availability relies primarily on spat collection in the field. The industry requires a clean environment: Shellfish production is strongly affected by the level of contamination, since shellfish act as filters and bioconcentrators of harmful substances (heavy metals and biotoxins). Molluscs concentrate and excrete faeces which affect the sediment and benthic fauna beneath and may cause localised degradation. Questions relative to the environmental impact of shellfish culture are currently being addressed by the WGEIM, and progress in genetics and pathology of molluscs is currently being reviewed by WGAGFM and WGPDMO, respectively. However, problems related to ecosystem productivity and the specific scientific and technological developments directed at the further expansion of the shellfish industry have not been addressed in ICES. TORS explanation: a) Hatcheries are an essential tool for the dissemination of genetic improvement, and for securing the spat availability to the industry. Information about their production for different species is not available anywhere, and should be collected on a national basis. Current research in broodstock conditioning, in reproductive processes, in larval rearing and spat settlement for hatchery-reared species needs to be reviewed, in order to support the development of a hatchery industry with updated knowledge (through collaboration with WGAGFM) b). Unexplained mortalities that can affect significant numbers of animals are often found in shellfish culture. Stress in animals can be caused by either chronic or acute extrinsic factors that may act to decrease the fitness of the animal or to cause its premature death. Chronic factors will often be manifested by changes in the overall health of the animal (i.e., in a stepwise cellular-tissue-organ-physiological levels). Acute factors produce immediate responses that may only show up at the molecular\cellular levels. Therefore, detecting acute effects is usually done with

	biochemical techniques. Some bio-indices that have been tried are: adenylate energy charge (AEC) (Maguire *et al.* 2002)[5], heat shock proteins (Oguma *et al.* 1998, Snyder *et al.* 2001), total oxyradical scavenging capacity (TOSC) (Regoli *et al.* 2000), glycogen content (Monroe and Newton 2001), metallothioneins (MT), cytochrome P4501A1 activity (Snyder *et al.* 2001), DNA damage, total lipids, relative levels of vitellins, and phagocytic activit y(Gagne *et al.* 2002) and histology (Agirregoikoa *et al.* 1991). c). The environmental impacts on shellfish production may be deleterious. There is a need to identify all the potential impacts and their effects on the production of shellfish, in order to establish the requirements for the industry in terms of water quality, ecological perturbations and biological competitors. This should be prepared with the view of establishing Ecological Quality Standards (EcoQS) regarding the shellfish activity. Also, settling the ecological requirements for shellfish production will be useful in the process of coastal zone management, when an arbitrage may be found within the requirements of the different users. The Working Group has given priorities to the different impacts : 1- Carrying capacity (Hydrographic factors, Primary productivity, food supply), 2- Predation, 3- fouling, 4- HAB Blooms, 5- Disease, 6- Pollution (water quality). d) According to the goals expressed in the strategic plan of ICES, there is a need to review all aspects of shellfish production related to the environment and to assess how they comply with sustainability requirements. Such a review will open the way for improving the sustainability of the shellfish industry.
Relation to strategic plan :	Responds to Goal 3: Evaluate option for sustainable marine-related industries, particularly fishing and mariculture. Activity 2: *Develop environmentally sound mariculture methods*. Responds to Goal 4: Advise on the sustainable use of living marine resources and protection of the marine environment. Activity 7: *Develop procedures for integrated coastal zone management, including protocols for environmentally sound mariculture practices.*
Ressources requirements :	None required other than those provided by the host institute.
Participants :	WG potential members are shellfish culture technologists e.g., Aad Smaal (Netherlands), Pauline Komermans (Netherlands) etc.
Secretariat facilities :	None required
Financial :	N/A
Linkage to advisory Committee :	ACME
Linkage to other Committees or groups :	MARC, MHC, WGHAB, WGITMO, WGPDMO, WGAGFM
Linkage to other organisations :	EAS
Cost share	ICES 100%

[1] **References**

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Maguire, J.A., Coleman, A., Jenkins, S., and Burnell, G.M. 2002. Effects of dredging on undersized scallops. Fisheries Research, 56: 155–165.

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Snyder, M.J., Girvetz, E., and Mulder, E.P. 2001. Induction of Marine Mollusc Stress Proteins by Chemical or Physical Stress. Archives of Environmental Contamination and Toxicology, 41: 22–29.

12 DATE AND VENUE OF THE NEXT MEETING

This meeting was scheduled to occur just after the EAS 2003' conference, entitled « Beyond Monoculture », and the workshop on « Mussels farming technology and development ». As said previously, four members of the Working group registered at the workshop.

The next meeting of the European Aquaculture will be devoted to the following theme:

« Aquaculture Europe 2004, Biotechnologies for quality » . It will occur from 20–23 October 2004 in Barcelona, Spain, and the title of Aquaculture Europe'2004 will be «Biotechnologies for quality ».

Both the theme of the conference and the date, which would hardly match the ICES calendar for reviewing the working group annual report, led the participants to suggest that having the next meeting of WGMASC occuring around the dates of the EAS annual conference will be unsuitable.

Following the proposal made by Brian Beal, it is therefore suggested that this meeting could occur from 12–14 May 2004, at the University of Southern Maine, Portland, USA. Saturday 15 May could be devoted to a field trip on oyster culture.

The 2005 meeting is planned to occur in La Rochelle, France. The date will be proposed during the next meeting of the WG.

13 ANY OTHER BUSINESS

Theme session during ICES ASC 2004 in Vigo

Participants were informed by the Chair that a theme session on shellfish culture was accepted by the ICES Council for the Annual Science Conference to be held in Vigo (2004). Aad Small and Alain Bodoy were selected as co-conveners of this session, but this could not be definitive, due to political discussions at higher levels. A discussion was opened to suggest more precise indications on the content of this session. It was proposed by the WG that this session may concentrate either : (i) on the role of hatcheries in the shellfish production or (ii) on shellfish culture in integrated aquaculture systems and polyculture.

Proposal for a new theme session on shellfish culture, in the next ICES ASC (2005 to 2007)

From the same discussion, came a proposal for a new theme session during the ICES Annual Science Conference, to be held between 2005 to 2007. The subject could be entitled :

Impact of selection on marine shellfish species and populations.

Invitation of external experts to participate to WGMASC meetings and work

In order to improve contacts and scientific exchanges with the shellfish producers, the possibility of inviting an external expert was mentioned. This would allow the view from the industry to be presented and their needs in terms of scientific research and expertise to be prioritised. A name was even suggested. Therefore the WGMASC would like to have comments from MARC and ICES about such a request. The financial aspects of an invitation were not addressed at this stage.

14 CLOSURE OF THE MEETING

The 2003 meeting of WGMASC in Trondheim was formally closed at 6 pm on 15 August 2003.

ANNEX I : LIST OF PARTICIPANTS

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ANNEX 2: AGENDA OF THE MEETING

WEDNESDAY, August 13

09:30 Welcome of the participants by the Chair

Self introduction of participants

09:30 Plenary session :

- ICES Strategic plan and Integrated Action Plan

- Introduction to ICES Committees and Working Groups,

- The reviewing processes within ICES

- General Comments on theTerms of Reference

- Comments on the ToR a (on production statistics) and ToR b (provide a synthesis on the development of hatcheries)

11:00 ***Health break***

11 :30 plenary session :

- Discussion on the two ToR c: review the ecophysiological causative factors of abnormal mortalities and d : ecological factors affecting shellfish production, with a view to the possibility of merging them.

- Comments on the ToR e (develop a work plan to evaluate the current sustainability of shellfish culture and identify options to improve sustainability)

- Subgroups implementation

- Adoption of agenda.

- Designation of rapporteurs

13:00 ***LUNCH***

14:00 Subgroups ToR b and ToR e

16:00 ***Health Break***

16:15 Subgroups ToR b and ToR e

17:40 Plenary session :

- Report on status for ToR b and e

19:30 End of session

THURSDAY, August 14

09:00 Subgroups ToR b and ToR e

11:00 ***Health break***

11:15	Subgroups ToR b and ToR e
13:00	***LUNCH***
14:00	Subgroups ToR b and ToR e
16:00	***Health Break***
16:15	sub groups ToR b and ToR e
17:40	Plenary session :
	- Report on status for ToR b and ToR e
19:00	End of session

FRIDAY, August 15

09:00	Sub-group ToR d (review and report on ecological factors affecting shellfish production)
	Sub groups ToR b and ToR e
11:00	***Health break***
11:15	Sub-group ToR d
	Sub groups ToR c and ToR e
13:00	***LUNCH***
14:00	Plenary session :
	- Adoption of reports on ToR b, ToR d and ToR e
15:30	***Health Break***
16:00	Plenary session :
	- Approval of the Recommendations
	- Proposal of ToRs for 2004
	- Meeting location in 2004
17:30	Any other business, completion and adoption of the report
18:00	Meeting adjournment

ANNEX 3: TERMS OF REFERENCE FOR THE WGMASC YEAR 2003

2F05 A **Working Group on Marine Shellfish Culture** [WGMASC] (Chair: A. Bodoy, France) will be established and will meet in Trondheim, Norway from 13–15 August 2003 to:

a) review national reports of shellfish production and related activities (prepared by members) and provide a synthesis of the current status of shellfish production, trends in production, techniques, and biological and economic events regarding shellfish cultivation, in the ICES area;

b) provide a synthesis on the development of hatcheries, their impact on shellfish production for the different species, on the dissemination of selected or modified strains, and the genetic consequences of reduced broodstocks on natural populations;

c) review the ecophysiological causative factors of abnormal mortalities on cultured populations of molluscs, and ways to avoid them with improved husbandry;

d) review and report on ecological factors affecting shellfish production (carrying capacity, fouling, predation, HAB) and alternative solutions to mitigate effects;

e) develop a work plan to evaluate the current sustainability of shellfish culture and identify options to improve sustainability.

WGMASC will report by 1 September 2003 for the attention of the Mariculture and Living Resources Committees.

Supporting Information

Priority :	WGMASC is of fundamental importance to ICES Member Countries
Scientific justification :	Despite the extensive progress made in salmon culture in ICES Member Countries shellfish production still accounts for half of the mariculture production. As such, issues related to shellfish production, in relation to the environment and technological development of the industry, have not previously been addressed within ICES. Shellfish production is based, with very few exceptions, on the use of the natural productivity of coastal waters as a source of food. Even seed availability relies primarily on spat collection in the field. The industry requires a clean environment: Shellfish production is strongly affected by the level of contamination, since shellfish act as filters and bioconcentrators of harmful substances (heavy metals and biotoxins). Molluscs concentrate and excrete faeces which affect the sediment and benthic fauna beneath and may cause localised degradation. Questions relative to the environmental impact of shellfish culture are currently being addressed by the WGEIM, and progress in genetics and pathology of molluscs is currently being reviewed by WGAGFM and WGPDMO, respectively. However, problems related to ecosystem productivity and the specific scientific and technological developments directed at the further expansion of the shellfish industry have not been addressed in ICES. TORS explanation: a) Shellfish statistics are often produced at state levels on the basis of self declaration from stakeholders. Linkage with tax recovery on such bases might introduce biases. There is a need for statistical estimates relying on other sources. Also, the technological improvements and the major events of the biological cycle need to be addressed in national reports, so as to propose adequate research programmes which may be conducted to resolve emerging problems affecting shellfish production. b) Hatcheries are an essential tool for the dissemination of genetic improvement, and for securing the spat availability to the industry. Information about their production for different species is not available anywhere, and should be collected on a national basis. Current research in broodstock conditioning, in reproductive processes, in larval rearing and spat settlement for hatchery-reared

	species needs to be reviewed, in order to support the development of a hatchery industry with updated knowledge (through collaboration with WGAGFM). c) Aside from natural mortalities, the shellfish industry is often affected by abnormal mortalities linked with environmental conditions. The climatic changes forecasted for the near future will increase the risk of abnormal temperatures and rainfalls, which may provoke critical environmental conditions for molluscs. Some are already identified, such as the summer mortality syndrome. Because of their drastic and extended effects on production, there is a need to review the current knowledge of the causative agents of environmentally-related mortalities, and on the physiological adaptative capacities of molluscs. d) The environmental impacts on shellfish production may be deleterious. There is a need to identify all the potential impacts and their effects on the production of shellfish, in order to establish the requirements for the industry in terms of water quality, ecological perturbations and biological competitors. This should be prepared with the view of establishing Ecological Quality Standards (EcoQS) regarding the shellfish activity. Also, settling the ecological requirements for shellfish production will be useful in the process of coastal zone management, when an arbitrage may be found within the requirements of the different users. e) According to the goals expressed in the strategic plan of ICES, there is a need to review all aspects of shellfish production related to the environment and to assess how they comply with sustainability requirements. Such a review will open the way for improving the sustainability of the shellfish industry.
Relation to strategic plan :	Responds to Goal 3: Evaluate option for sustainable marine-related industries, particularly fishing and mariculture. Activity 2: *Develop environmentally sound mariculture method*s. Responds to Goal 4: Advise on the sustainable use of living marine resources and protection of the marine environment. Activity 7: *Develop procedures for integrated coastal zone management, including protocols for environmentally sound mariculture practices.*
Resources requirements :	None required other than those provided by the host institute.
Participants :	WG potential members are shellfish culture technologists e.g., Aad Smaal (Netherlands), Pauline Komermans (Netherlands) etc.
Secretariat facilities :	None required
Financial :	N/A
Linkage to Advisory Committee :	ACME
Linkage to other Committees or groups :	MARC, MHC, WGHAB, WGITMO, WGPDMO, WGAGFM
Linkage to other organisations :	EAS
Cost share	ICES 100%

ANNEX 4: INTERSESSIONAL WORKPLAN 2003–2004

Two documents have been prepared during the 2003 meeting of WGMASC, to be completed by inter-sessional work during 2003-2004.

The first document is a list of the shellfish hatcheries within ICES area, indicating the species which are currently reproduced and the number of spat produced.

The second document is a questionnaire survey which be fill in by having direct or telephone contacts with the managers of the hatcheries

1 – List of current hatcheries by country and their production estimates for each species (to be completed)

Country	Hatchery Name	Lat & Long	Species	Production (millions)
France	Ecloserie de KERNE	Dpt 56	*C. gigas*	20 million
France	GRAINOCEAN sa	Dpt 17	*C. gigas*	300 million
France	Sarl SODABO	Dpt 85	*C.gigas, T. philippinarum*	80 million
France	Vendée-naissain	Dpt 85	*C. gigas, T. philippinarum, O. edulis*	300 million
France	SATMAR	Dpt 50 & 11	*C. gigas, T. philippinarum, O. edulis, M. edulis*	A few 100 million
France	Ecloserie du Tinduff	Dpt 29	*Pecten maximus*	10 million
France	Écloserie d'ormeaux	Dpt 50	*Haliotis tuberculata*	To be precised
France	Ifremer (public)	Dpt 17 and 29	Diverse, mainly oysters	experimental

2 - Questionnaire on the production and developement of shellfish hatcheries

1) Identity (location) of hatchery/nursery

2) Hatchery infrastructure

    a. number of employees (year-round vs. seasonal)
    b. quarantine capacity
    c. water supply
    d. effluent treatment

3) Species produced

4) Number of animals produced per species

    a. size (larvae, spat)
    b. hatchery vs. nursery

5) Broodstock

    a. origin
        i. wild stock
        ii. hatchery – crosses between wild and hatchery stock?

b. selection
   i. types – disease; growth; survival; morphology;

6) Broodstock conditioning methods

   a. triploids (methodology)?

7) Larval rearing

   a. techniques
   b. problems encountered

8) Spat settlement

   a. techniques
   b. problems encountered

9) Microalgae systems

   a. species

10) Hatchery/Nursery moralities

   a. cause – environmental; biotic
   b. treatment methods

11) Destination of spat (local, national, international)

12) R & D concerns/issues/requirements

Confidentiality statement: Data from the survey will be summarized to ensure that sensitive information cannot be traced to individual companies.

Each respondent will receive a copy of the final report upon completion.

ANNEX 5: ECOSYSTEM LEVEL EFFECTS OF MARINE BIVALVE AQUACULTURE

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1. Introduction

The bivalve aquaculture industry has expanded rapidly in Canada over the last two decades. Although highly diverse in structure, capital and material infrastructure, the most rapid development has occurred with mussel culture - an industry which, until recently, developed at an exceptional pace throughout Atlantic Canada. Ease of mussel spat collection and deployment throughout the water column with comparatively inexpensive capital investment has fueled the development of mussel aquaculture. In contrast, oyster, clam and scallop culture systems generally involve relatively small area operations, intertidal, or bottom-culture. Significant suspended longline culture of oysters and scallops does occurs in British Columbia, but the areas leased for these activities generally, with a few exceptions, occupy a small fraction of coastal embayments. Estuarine and coastal systems in Prince Edward Island support 80% of bivalve culture in Canada and 98% of the total value of mussel landings in the Maritimes and Gulf Regions (www.gfc.dfo.ca), and a high proportion of suitable embayments are leased for mussel culture. The implications of such rapid and extensive water body transformation into mussel production have been recognised as having the potential for significant impact on ecological and oceanographic processes in Prince Edward Island (Shaw, 1998).

Unlike finfish aquaculture, bivalve culture requires minimal additions to the environment, except for the animals themselves and the infrastructures used to grow them. Their food is supplied by the environment and their wastes return nutrients and minerals to the ecosystem. However, dense populations of bivalve filter-feeders are characterized as "ecosystem engineers" (Jones *et al.*, 1994; Lawton, 1994) owing to their ability to modify, maintain and create entire habitats through their effects on suspended particles, and the formation of structurally complex shell habitat. Suspended and bottom culture of bivalves increases the surface area available for attachment and grazing by other species, and spaces between shells provide refugia from physical stress (currents and waves) and predation (Ragnarsson and Raffaelli, 1999). Potential mechanisms for ecosystem level effects include the utilization of particulate food resources (primarily phytoplankton and detritus, but including some auto- and heterotorphic picoplankton and microzooplankton) by the bivalves and associated epifauna, the subsequent release of unutilized materials in dissolved (urine) and particulate (faeces and pseudofaeces) form, and the removal of minerals from the system in the bivalve harvest.

This paper reviews the present state of knowledge on environmental issues related to bivalve aquaculture, with particular attention given to the potential effects (both positive and negative) of suspended mussel culture. Our focus is on identifying potential changes in ecological processes (material and energy fluxes as well as nutrient cycling) at the coastal ecosystem scale (e.g., estuary or embayment), and on identifying gaps in knowledge that need to be addressed through continued research. The temporal scale addressed is primarily long term to include ecosystem changes over seasonal, life-cycle, and aquaculture site development time-scales. However, shorter time-scale are considered when important physical, chemical and biological processes have longer-term implications.

2. Potential Ecological Effects of Filter-Feeding

Bivalve filter feeders have a large capacity to filter water, directly altering concentrations of the seston in the surrounding water (Bayne *et al.*, 1989; Jørgensen, 1996; Dame, 1993; and 1996; Smaal *et al.*, 1997). It has often been suggested that dense bivalve populations exert a strong long-term influence on energy flow at the scale of whole estuaries, bays and coastal systems by controlling phytoplankton and seston concentrations through their filter-feeding activity (Cloern, 1982; Officer *et al.,* 1982; Nichols, 1985; Hily, 1991; Smaal and Prins, 1993; Dame, 1996; Dame and Prins, 1998; Prins *et al.* 1998). This speculation stems primarily from measurements of water clearance (filtration) rate made on individual animals that are scaled-up to predict population or community grazing capacity. Several authors have compared estimates of the time required for resident bivalve populations or communities to clear all of the water volume in their coastal system (clearance time) with the time required for the water mass to be replaced by tidal exchange (residence time) and concluded that the bivalves can exert a significant and controlling influence on particulate matter in many shallow coastal systems (reviewed by Dame, 1996; and Dame and Prins, 1998). A similar comparison, based on estimates by Grant (2000) of mussel culture area, feeding rate and tidal flushing in PEI embayments, is presented in Figure A5.1. This analysis suggests that for 12 of the 15 embayments studied, the mussel biomass presently under culture is potentially capable of removing food particles much faster than tidal exchange is capable of replacing them, and therefore appears to control phytoplankton and seston at the coastal ecosystem scale through overgrazing. Meewig *et al*. (1998) used a different mass-balance approach to model phytoplankton biomass in 15 PEI embayments and estimated that the mussel farms in six of these systems reduced phytoplankton biomass by 45 to 88%. These order of magnitude calculations are strongly suggestive that intensive mussel culture has the capacity to alter matter and energy cycling for long periods in some coastal systems.

While simple scaling exercises such as the one illustrated in Figure A5.1 are intuitive ecosystem indicators of carrying capacity and the potential impacts of existing and proposed aquaculture operations (includes biotic and abiotic factors controlling bivalve food supplies), this approach neglects potentially important physical processes, such as water column stratification, mixing, and flow velocity, that could influence the effects of mussel culture operations on suspended particles. These approaches also use single flushing estimates for estuaries, when flushing is spatially dependent. Several biotic factors also need to be considered before placing too much emphasis on these results. First, comparison of water clearance and residence times does not consider replenishment of food particles within the estuary through internal primary production. Estimates of the time required for primary production within the system to replace the standing crop of phytoplankton (phytoplankton doubling time) are required before more definitive conclusions of the impact of bivalve filtration in these and other embayments can be reached (Dame, 1996). Dame and Prins (1998) examined 11 coastal ecosystems and suggested that most of the systems produce sufficient phytoplankton internally to prevent overgrazing by resident bivalve populations. However, several of the systems studied, and particularly those under intense bivalve culture, require the import of food resources from outside the system to prevent particle depletion. Dowd (2000) examined a simple biophysical model that quantifies the relative roles of flushing, internal production and bivalve grazing on seston levels.

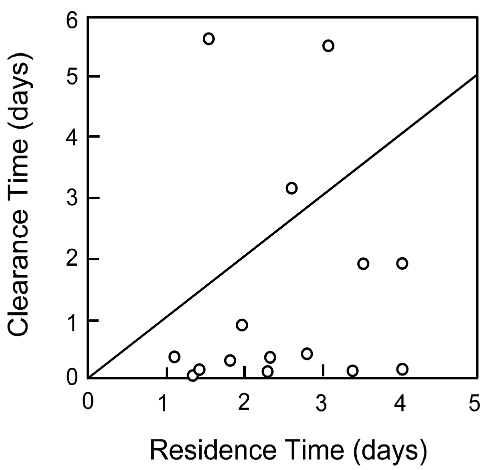

Figure A5.1. Comparison of predicted water mass residence time (tidal) and clearance time by mussel culture operations for 15 embayments in PEI. Mussel aquaculture potentially controls suspended particle concentrations (phytoplankton and detritus) where clearance time is less than residence time (point falls below unity line).

Another important consideration when assessing the potential impact of bivalves on their and other filter feeders (e.g., zooplankton) trophic resources is that bivalve grazing may directly stimulate system primary production such that algal cell removal may be compensated by an increase in algae growth rate. Factors that may contribute to this bivalve-mediated optimization of primary production are (1) increased light through reduced turbidity (assumes algae are light limited); (2) greater growth of algae through continuous grazing of older cells; (3) a shift to faster growing algae species; (4) increased rate of nutrient cycling; and (5) increased nutrient availability (Prins *et al*., 1995). Mesocosm studies examining the role of the clam *Mercenaria mercenaria* in controlling seston concentration indicated that a relatively low abundance of clams doubled primary production and altered the community structure of the plankton (Doering and Oviatt, 1986; Doering *et al*., 1989). Grazing by mussels was also shown to result in increased picoplankton abundance (Olsson *et al*., 1992) and a shift to faster growing diatoms (Prins *et al*., 1995). While bivalve filter feeders apparently contribute to optimizing primary production at relatively small temporal and spatial scales, the larger scale significance of this interaction in natural ecosystems remains speculative.

An understanding of bivalve feeding rate is fundamental to accurate predictions of the role of bivalves in controlling seston availability and primary production. Mussels have been one of the most extensively studies marine organisms, but uncertainties and controversies regarding their physiology still exist that affect our capacity to accurately predict growth and the consequences of environmental variables on mussel bioenergetics (reviewed by Bayne, 1998; J¢rgensen, 1996). Theories and models of bivalve functional responses to ambient food supplies vary widely in concept resulting in considerable uncertainty on the actual ecological influence of dense bivalve populations (Cranford and Hill, 1999; Riisgard, 2001). Controversy has been generated by the continued use of feeding rates measurements obtained in the laboratory using pure algal diets that are extrapolated to field conditions where cell types and concentrations and the presence of detritus may alter bivalve filtration and ingestion rates (Cranford, 2001). Continued research is particularly needed on how the large seasonally variable energy/nutrient demands of mussels influence the uptake and utilization of naturally available food supplies (Cranford and Hill 1999). Further, genotype- and phenotype-dependent differences in marine bivalves also contribute to the large variance in feeding rate (reviewed by Hawkins and Bayne, 1992) and this has yet to be considered in estimates of population clearance time.

The accuracy of some scaled-up estimates of bivalve population clearance time has been questioned based on the results of mesocosm studies (Doering and Oviatt, 1986) and the use of new methodologies that permit bivalve feeding rates to be measured continuously under more natural environmental conditions than has previously been employed in the laboratory (Cranford and Hargrave, 1994; Iglesias *et al.,* 1998). Cranford and Hill (1999) used an *in situ* method to monitor seasonal functional responses of sea scallops (*Placopecten magellanicus*) and mussels (*Mytilus edulis*) and suggested that the coupling of coastal seston dynamics with bivalve filter-feeding activity may be less substantial than previously envisaged. That study confirmed previous results indicating that bivalves in nature do not always fully exploit their filtration capacity, but generally feed at much lower rates (Doering and Oviatt, 1986). Prins *et al.* (1996) and Cranford and Hill (1999) showed that *in situ* and field measured clearance rates that use natural diets are similar and provide accurate predictions of bivalve growth. While it is therefore possible to scale up from individual measurements to bivalve populations, feeding behaviour has also been shown to vary greatly over short to long time scales owing to external (variable food supply) and internal (variable energy demands of reproduction) forcing (Bayne, 1998; Cranford and Hargrave, 1994; Cranford and Hill, 1999). The common practice of using average clearance rates for calculating population influences on phytoplankton may give equivocal results for much of the year.

Perhaps the best indication of the potential for bivalve filter feeders to control suspended particulate matter at the ecosystem scale come from observations of ecosystem changes that occurred after large biomass variations in natural bivalve populations, as well as the observed density-dependent effects of intensive cultivation practices. Population explosions of introduced bivalve species in San Francisco Bay and dramatic reductions in oyster populations in Chesapeake Bay have been implicated as the cause of the large changes in phytoplankton biomass and production experienced in these systems (Nichols, 1985; Newell, 1988; Nichols *et al*., 1990; Alpine and Cloern, 1992; Ulanowicz and Tuttle, 1992). Numerous similar examples can be drawn from the limnology literature with respect to the introduction, rapid growth, and effect of zebra and quagga mussels (*Dreissena spp.*) on the water column in the Laurentian Great Lakes. Research on the whole-basin environmental effects of intense mussel and oyster aquaculture in the Bay of Marennes-Oléron, the most intensive growing region of the Atlantic coast of France, has focused on the impact of bivalve overstocking on growth and survival (Héral, 1993; Héral *et al*., 1986). Overstocking on two occasions led to large-scale growth reduction and high mortalities in the Bay. Overstocking of scallops in Mutsu Bay, Japan also resulted in growth reduction and high mortality (Aoyama, 1989). These impacts of intensive aquaculture appear to result in a feedback on bivalve growth from bivalve-induced changes in particulate food abundance and quality.

3. Potential Ecological Effects of Biodeposition

An important issue related to particle consumption by bivalve filter feeders is the resulting re-packaging of fine suspended material into larger faeces and pseudofaeces. Bivalves effectively remove natural suspended matter with particle sizes greater than 1 to 7 μm diameter, depending on species, and void them as large faecal pellets (500–3000 μm) that rapidly settle to the seabed, especially under conditions with slow or poor water flushing and exchange. This particle re-packaging diverts primary production and energy flow from planktonic to benthic food webs (Cloern, 1982; Noren *et al*., 1999). While the dynamics of bivalve faeces deposition (settling velocity, disaggregation rate, and resuspension) are poorly understood, enhanced sedimentation under shellfish culture is well documented (Dahlback and Gunnarsson, 1981; Tenore *et al.*, 1982; Jaramillo *et al.*, 1992; Hatcher *et al.*, 1994). Furthermore, mortality and fall-off of cultured bivalves, induced by seasonal colonization by fouling organisms that use suspended bivalves and their lines as substrate, can result in additional acute benthic organic loading.

Sediment organic enrichment effects are generally believed to be less dramatic with bivalve culture than with finfish culture where uneaten and partially digested food is deposited on the seabed (Kasper *et al.,* 1985; Baudinet *et al.*, 1990; Hatcher *et al.*, 1994, Grant *et al.,* 1995). However, the zone of influence may be larger with bivalve aquaculture if a large fraction of the total volume of coastal embayments is under culture, and if hydrographic conditions permit the deposition and accumulation of biodeposits. Bivalve culture occupies a very significant portion of many embayments in PEI (mussel lease volume averaged 36% of total estuary volume for eight major PEI embayments; Grant *et al.,* 1995), but this is rare in other parts of Canada.

Organic enrichment of the seabed under suspended bivalve culture is due to the increased vertical flux of naturally occurring particles (Hatcher *et al.*, 1994; Barranguet *et al.*, 1994; Stewart *et al.*, 1998). The seasonal biodeposition rate and organic content of faecal pellets was measured for scallops (*P. magellanicus*) and mussels (*M. edulis*) in two coastal regions in Nova Scotia (Cranford and Hill, 1999) and organic matter biodeposition was observed to reach maxima in the spring and fall. That study showed that the daily biodeposition rate of a cohort of 25 mussels (80 mm shell length) increased natural sedimentation rates (g dry weight m^{-2} day^{-1}) by an average factor of 26 (mean of 160 daily biodeposition and sedimentation measurements). Faecal pellet organic content ranging from 20–70% with the highest values observed during the spring phytoplankton bloom. Faeces generally had a similar organic content as other settled particles (Cranford and Hill, 1999) despite containing partially digested organic matter.

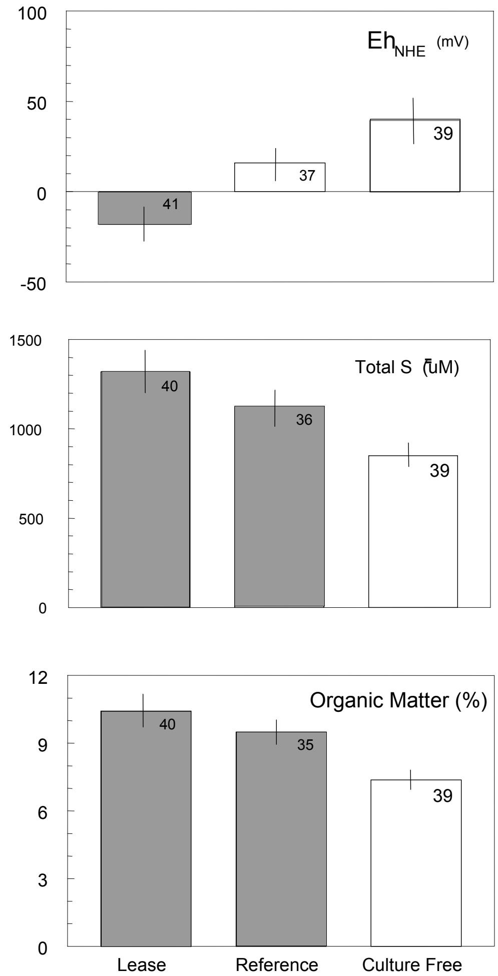

Figure A5.2. Data from Shaw (1998) summarizing mean (±SE) values for Eh (redox) potentials, total $S^{=}$ and percent organic matter in surface sediment (2–4 cm depth layer) from 20 inlets in Prince Edward Island. Samples were collected during late summer 1997 at stations under mussel lines on lease sites (Lease), at reference sites in the same inlet but >50 m away from mussel lines (Reference) and in inlets where mussel culture had not previously occurred (Culture Free). Numbers indicate pooled sample sizes. Differences in shading indicate significant differences (Mann Whitney U test, $p<0.05$) between variables grouped by location.

If organic biodeposition by bivalves is sufficiently high, decomposition of organic biodeposits can increase the oxygen demand in sediments and generate an anaerobic environment that promotes ammonification and sulfate reduction. This is the classic response of sediments to eutrophication (Cloern, 2001). An increase in benthic sulfate reduction has been observed under some intensive mussel culture sites (Dahlback and Gunnarsson, 1981; Tenore *et al.*, 1982), but not under others (Baudinet *et al.*, 1990; Jaramillo *et al.*, 1992; Grant *et al.* 1995; Chamberlain *et al.*, 2001). Benthic responses to increased organic enrichment under suspended bivalve culture include increases in phytopigments, bacterial abundance and meiofauna community structure and biomass (Dahlback and Gunnarsson, 1981; Mirto *et al.*, 2000), and localized reductions in macrobenthic infaunal abundance and/or diversity (Tenore *et al.*, 1982; Mattsson and Linden, 1983; Kasper *et al.*, 1985; Stenton-Dozey *et al.,* 1999; Chamberlain *et al.*, 2001). These community impacts appear to be long-term as little recovery of disturbed communities was observed 18 months after mussels were harvested (Mattsson and Linden, 1983), and four years after an intensive mussel raft culture operation was removed

(Stenton-Dozey *et al.,* 1999). Although common in Europe and the northeastern US, the raft culture technique is not utilized in Canada.

The pattern of enrichment effects can be observed in data from a survey of PEI inlets during 1997 (Shaw 1998). Eh, total $S^{=}$ and organic matter (OM) were measured in sediment collected at active lease sites, in adjacent reference areas away from mussel lines and in culture free inlets where no mussel aquaculture occurred (Figure A5.2). The three geochemical variables have been shown to be indicators of benthic enrichment due to increased organic matter loading in areas of intensive finfish aquaculture (Hargrave *et al.* 1997). Significant ($p<0.05$) differences in Eh, total $S^{=}$ and OM occurred between the three types of sampling sites. The most negative redox potentials (indicative of more anoxic conditions due to enhanced OM deposition) occurred in sediments under mussel lines. Concentrations of total $S^{=}$ and OM were not significantly different at lease and reference sites but both of these variables were significantly higher than at culture free sampling locations. The similarity in total $S^{=}$ and OM at lease and reference sites and differences in Eh potentials between sampling locations implies that intensive mussel culture in PEI has had inlet-wide benthic impacts that are observable using sediment geochemical measurements.

The degree of benthic impact is expected to differ greatly between culture sites depending on the type and extent of culture activities and local environmental conditions. Observations of organic enrichment impacts from bivalve culture in PEI are not generally applicable to bivalve culture site in other regions of Canada. The sedimentation patterns and dispersion of bivalve biodeposits are controlled by water depth and local water movement. Slight differences in these physical properties appear to explain the marked differences in the degree of impact observed on seabed geochemistry and communities under different suspended mussel culture sites (Chamberlain *et al*., 2001). Many embayments in PEI are also already stressed by similar eutrophication effects from land-use (see Section 5 below) while culture activities in other regions tend to occur in areas with much lower agricultural nutrient inputs.

Grant (2000) developed an approach for addressing the capacity of tidal action to redistribute materials deposited by mussel aquaculture operations in PEI estuaries. This modelling effort consists of estimating the balance between mussel egestion rate and the rate of tidal flushing. The aim was not to predict biodeposition effects, but to estimate the potential for whole coastal systems to resist organic loading through physical exchange processes. Estuaries identified as having the greatest risk of biodeposition effects had a relatively small tidal exchange and high percentage of the total estuarine volume under culture. There is little information available on the capacity of coastal ecosystems to assimilate organic loading and subsequently to resist biodegradation, and further research is needed.

The coupling of planktonic and benthic food webs caused by the bivalves modifying, repackaging, and increasing the sedimentation rate of fine suspended particles changes the flow of energy in the ecosystem by altering the availability of food resources to other species. Crabs and demersal fish appear to benefit from culture activities as a result of the increased food availability from the fall-off of mussels and epibionts from lines (Lopez-Jamar *et al*., 1984; Freire *et al*., 1990). However, grazing competition with mussel culture can affect zooplankton and larval fish dependent on suspended seston as food. Bivalve filter feeders have a huge competitive advantage over zooplankton as they may significantly reduce the abundance of micro-zooplankton (< 200 µm; Horsted *et al.*, 1988) and meso-zooplankton up to 6 mm (Davenport *et al*., 2000) through ingestion, and are capable of immediately responding to increased food availability (e.g., phytoplankton bloom). The zooplankton must go through a complete life cycle before they can begin to fully exploit new resources. Mesocosm studies indicate that *Mercenaria* (infauna) and *Mytilus* (suspended culture) populations can alter pelagic food webs by suppressing the zooplankton (Doering *et al.,* 1989; Horsted *et al*., 1988). Competitive pressure on zooplankton also comes from the periodic presence of large populations of larvae of the cultured species. The decline of oyster populations in Chesapeake Bay has been implicated in the observed increase in abundance of zooplankton and their major predators (Newell, 1988). However, these potential effects on zooplankton communities are largely speculative as they have never been documented in field studies.

4. Changes in Nutrient Dynamics and Potential Consequences

The consumption and deposition of suspended particulate matter by farmed bivalves can play a significant role in controlling the amounts and forms of nitrogen in coastal systems and the rate of nitrogen cycling (reviewed by Dame, 1996). This translocation of matter can provide a means of retaining nutrients, trace elements and contaminants in coastal areas where they are recycled within detrital food chains, rather than being more rapidly exported (Jordan and Valiela, 1982). Benthic nutrient mineralization can increase at culture sites as a result of the increased organic matter sedimentation, greatly increasing rates of nitrogen cycling (Dahlback and Gunnarsson, 1981; Kaspar *et al.,* 1985; Feuillet-Girard *et al*., 1988; Barranguet *et al.,* 1994; Grant *et al.* 1995). Chlorophyll and nutrient mass-balance calculations for PEI estuaries show a tight correlation between phytoplankton biomass and nutrients, suggesting that nutrient availability in these intensively cultured systems primarily limits ecosystem productive capacity (Meeuwig *et al*., 1998). Nutrient cycling rates and availability may be increased at mussel farms through the mineralization of the large amounts of faeces and pseudofeces trapped within the mussel socks. This permits nutrients to be released at shallower, more nutrient depleted depths than occurs if the nutrients are regeneration in the sediments. Decomposition of organic matter in aerobic surface sediments aids in recycling nutrients back to the water column for uptake by phytoplankton while anaerobic decomposition in sediments under conditions of excessive organic enrichment (i.e., overstocking) results in the production of nitrogen gas that may increase nitrogen limitation within the system. Conversely, phosphorous release from sediments is promoted under anaerobic conditions (Nixon *et al.,* 1980).

An additional ecosystem consequence of bivalve aquaculture potentially stems from the transformation of much of the ingested particulate minerals into dissolved nutrients that are excreted as a necessary part of bivalve metabolic processes. The high flux of ammonia from dense bivalve populations appears to exert a controlling influence on nitrogen concentrations in some coastal regions (Dame *et al.,* 1991; Strain, 2002) and this aspect of bivalve culture may have a major positive effect on the phytoplankton (Maestrini *et al.,* 1986; Dame, 1996). There is little information available on the relative importance on ecosystem nutrient availability of the direct transformation of suspended particulate matter (excretion) into nutrients compared with nutrients supplied as a result of particulate matter translocation (biodeposition and remineralization) by bivalves. However, mineralization of biodeposits appears to be a more important nutrient source for phytoplankton production than direct excretion (Asmus and Asmus, 1991; Prins and Smaal, 1994).

While the greater availability and faster cycling of nutrients in aquaculture systems can lead to enhanced production of phytoplankton and seagrass (Peterson and Heck, 2001), these changes may also contribute to more frequent algal blooms, including those of the domoic-acid-producing diatom *Pseudo-nitzschia multiseries* (Bates, 1998; Bates *et al.,* 1998). Domoic acid production is enhanced by two- to fourfold when *P. multiseries* is grown in the presence of high concentrations of ammonium (220 to 440 µm) relative to the same concentration of N in the form of nitrate (Bates *et al.,* 1993). Observed aquaculture-induced changes in the relative concentrations of Si, P and N (e.g., Hatcher *et al*., 1994) may also favour the growth of harmful phytoplankton classes (Smayda, 1990). Impacts of changing nutrient ratios on phytoplankton community composition, including the promotion of harmful algal blooms such as *Pseudo-nitzschia*, have been documented in relation to coastal eutrophication (e.g. Parsons *et al*., 2002), but a causative connection has yet to be proven rigorously (Cloern, 2001). Similarly, no definitive conclusions can be drawn from the sparse literature on the scale of aquaculture impacts on microalgae community composition.

The retention and remineralization of limiting nutrients in coastal systems is necessary to sustain system productivity. Benthic filter feeders promote the retention and recycling of nutrients within coastal ecosystems by storing assimilated minerals as tissue biomass that is released upon death and decomposition (Dame, 1996). Kasper *et al.* (1985) suggests that the harvesting of cultured mussels may lead to nitrogen depletion and increased nutrient limitation of primary production. However, ecosystem-level effects resulting from the removal of nutrients stored in the cultured biomass are largely speculative and further studies are needed to examine the consequences to the marine food web of nutrient removal.

5. Aquaculture Interactions with Land-use

Any attempt to assess ecosystem-level effects of bivalve aquaculture must consider the complexity of natural and human actions in estuarine and coastal systems. Ecosystem responses to multiple stressors (contaminants, fishing activities, invasive species, habitat loss, climate change, coastal construction, etc.) are intimately connected (Cloern, 2001). The determination of the cumulative effect of all anthropogenic activities on coastal ecosystems is difficult, but is essential as this is a legal requirement in Canada for environmental assessments, including aquaculture site approvals. The capacity of cultured mussels to alter and control food supplies, energy flow, and nutrient cycling depends on how other stressors positively or negatively influence important bivalve physiological processes (clearance rate, digestive efficiency, biodeposition rate, and ammonia excretion) and growth. For example, infectious diseases associated with overstocking, as well as exposure of cultured organisms to "exotic" pathogens introduced with seed or broodstock, can have a significant and frequently acute and permanent impact on the organisms physiological and nutritional status (Banning, 1982; Bower *et al.,* 1994; ICES, 1995; Hine, 1996; Renault, 1996; Bower and McGladdery, 1996; Minchin, 1999; Miyazaki *et al*., 1999). As a mostly sessile component of an ecosystem, bivalves play a sentinel role, acting as a sponge for many of the components actively or passively added to its aquatic surroundings (Dewey, 2000). Important biochemical, cellular, physiological and behavioral changes in bivalves occur with contaminant exposure and these can affect populations and disrupt energy flow and the cycling of materials within coastal ecosystems (Capuzzo, 1981).

Land-use practices which result in nutrients being transported into estuaries can be a major determinant of coastal water quality and eutrophication (Chapelle *et al*., 2000). Concentrations of nitrogen and phosphorous in PEI estuaries have increased substantially between the 1960s and 1990s and ten of the 20 embayments sampled in 1998 and 1999 exhibited nitrogen levels exceeding the threshold for eutrophic conditions (DFO, 2000). The large influence of agricultural activities on PEI embayments was indicated by the close correlation between chlorophyll biomass and the area of the watershead over which agriculture extends (Meeuwig, 1999). Speculations that intense mussel culture can affect coastal ecosystems in positive ways by reducing eutrophication have been supported by observed changes in estuarine ecosystems in which natural bivalve populations have either dramatically increased (e.g., San Francisco Bay: Cloern, 1982; Officer *et al.* 1982) or decreased (e.g., Chesapeake Bay: Newell, 1988). Both of these systems are highly eutrophic owing to intense farming and industrial/residential development within their watersheds.

Bivalve filter-feeders in these and other estuaries are believed to mitigate eutrophic trends by ingesting large quantities of algae and suspended particulate matter. However, this suggestion has not been proven rigorously and is based primarily on scaled-up bivalve filtration rates that may have been overestimated (Cranford and Hill, 1999), and on mass balance calculations (Meeuwig *et al.,* 1998). Asmus and Asmus (1991) suggested that the ability of mussel beds and culture sites to reduce the standing stock of phytoplankton is unlikely to combat anthropogenic eutrophication because they also promote primary production and accelerate the turnover of phytoplankton through their effects on nutrient cycling. As noted above, intense shellfish farming also increases the retention of nutrients within coastal systems (see also review by Cloern, 2001), further focusing the negative effects of nutrient loading on this region. While elevated phytoplankton levels have a clear benefit to aquaculture farm productivity, the accompanying increase in organic biodeposition rates (i.e., bivalves augment pelagic/benthic coupling) could stimulate benthic microbial metabolism, alter sediment chemistry, and increase the probability that benthic communities, which are highly sensitive to eutrophication, will change. Eutrophic conditions can also depress bivalve physiological functions and growth through exposure to toxic algal blooms (Chauvaud *et al*., 2000), limiting their perceived grazing control on algae biomass. Conversely, the removal of nutrients from the system in the bivalve harvest may help to alleviate some of the eutrophication problem. Interactions in the coastal zone between farmed bivalves and the environmental consequences of nutrient loading are highly complex and all aspects need to be addressed objectively, and integrated quantitatively before any conclusions can be reached on whether or not bivalve farming has a net positive or negative result on ecosystem quality.

Sediment released into coastal waters during land-use has the potential to alter physical habitats and directly impact marine organisms, including cultured species. There is limited quantitative data available on the effect of agriculture run-off on substrate composition and suspended sediment concentrations in PEI waterways, but anecdotal observations indicate high suspended concentrations during rainfalls and an increasing proportion of bottom covered by fine sediments (DFO, 2000). Cultured bivalves and their support structures could alter sedimentation patterns within embayments by altering flow dynamics with the net result being a tendency towards accelerated deposition of fine-grained sediment. With the exception of raft culture, little is presently known about how suspended culture alters water flow (Grant and Bacher, 2001), but the impact on sedimentation patterns will likely be dependent on culture spacing, and local hydrographic conditions. Sediment deposition, re-suspension and transport are governed in the marine environment by particle aggregation processes, which effectively control the settling velocity of fine-grained sediment by orders of magnitude. If bivalve cultures influence the natural equilibrium among the major factors controlling aggregation rate (particle concentration, particle stickiness, and turbulence; Hill, 1996), sedimentary conditions within a bay may be altered.

Pesticides have been detected in 75% of stream water samples collected in PEI between 1996 and 1999 (DFO, 2000). While concentrations were well below acute lethal concentrations (rainbow trout LC_{50} values), there were 12 fish kills downstream from potato fields in 1994-1999 that were suspected, or shown, to be caused by pesticides (DFO, 2000). There is also increasing concern over the endocrine disrupting potential of released pesticides, as well as possible links between exposure of bivalves to contaminants and the incidence and severity of bivalve diseases (Kim *et al.* 1999; Pipe and Coles, 1995; Pipe *et al.* 1995, 1999; DaRos *et al.* 1998; Anderson *et al.,* 1998, 1996; Coles *et al*. 1994). The principal mechanism by which dissolved contaminants are transported in the marine environment is by scavenging (uptake) onto particulate matter and particle settling. This particle-reactive nature of organic contaminants increases their availability for filter-feeders, including wild and cultured bivalves. Bivalves bioaccumulate many abiotic contaminants and, as a result, have been widely used since the 1970s as sentinel organisms for monitoring such contaminant levels. In fact, many "Mussel Watch" experiments have used suspended mussels in cages or other infrastructures to monitor contaminant drift in plumes, a holding mechanism akin to suspension culture (e.g., Salazar and Salazar, 1997). Mussels are also used to monitor changes in environmental quality by combining and linking measurements of chemical inputs and concentrations in tissues with a pollution stress response called 'scope for growth' (SFG). SFG integrates physiological responses that effect changes in growth rate and has successfully been used to detect, quantify and identify the causes and effects of pollution (e.g., Widdows *et al*. 1997). Bivalve clearance rate is a component of the SFG equation and is highly sensitive to contaminant stress (Donkin *et al.* 1989; Widdows and Donkin 1992; Cranford *et al.* 1999). Although largely speculative, reduced feeding rates associated with exposure to contaminants (e.g., simultaneous nutrient and contaminant loading from agriculture) could influence their perceived capacity to mitigate coastal eutrophication by reducing their influence on ecosystem energy flow and nutrient cycling.

Although the rapid breakdown of agricultural pesticides and herbicides in water may seem to negate their significance in impacting bivalves and other aquatic organisms, there is growing concern and evidence that even the transient passage of the chemicals themselves (acute exposure) or the chronic exposure to their breakdown products, may play a role in long-term or sub-acute effects. This complicates correlation to point-source or wider influent effects, and makes ‘mystery mortalities’ difficulty to resolve. This conundrum has recently gained a higher profile as a knowledge gap, especially with respect to molluscs, due to growing evidence that bivalve neoplasias appear to show strong correlations to heavily contaminated environments. Elston *et al* (1992), summarise a long list numerous neoplasia triggers that have been, and are, associated with bivalve neoplasias. These include pesticides, herbicides, organo-chlorides (Farley *et al* 1991; Craig *et al*. 1993; Gardner, 1994; Harper *et al*.1994, van Beneden, 1994; Dopp *et al*. 1996; Strandberg *et al*. 1998), retroviruses (Appeldoorn and Oprandy, 1980; Oprandy *et al*. 1981; Cooper and Chang, 1982; Cooper *et al*. 1982; Farley *et al*. 1986; Sunila and Farley, 1989; Sunila and Dungan, 1991; House *et al*. 1998), senescence (Bower, 1989; Bower and Figueras, 1989) and natural environmental extremes, such as changes in water temperature (Brousseau, 1987; Brousseau and Baglivo, 1991a,b; McLaughlin *et al*. 1996). The species that are most susceptible to neoplastic diseases are mussels (*M. edulis* and *M. galloprovincialis*), and clams (*Mya arenaria* and *Mercenaria* spp.). Blue mussels have had acute outbreaks of haemic neoplasia (blood cell dysfunction and proliferation) along the northwest coast of the USA and southern BC, Canada (Bower, 1989). A correlation to water quality was not apparent. However, severe outbreaks of haemic neoplasia have been found in soft-shell clams from Chesapeake Bay, VA, New Bedford Basin, MA and, more recently, along the north shore of PEI (McGladdery *et al*. 2001). All these areas are subject to high agricultural run-off or organo-chloride industrial waste (Craig *et al*. 1993; Dopp *et al*. 1996; Strandberg *et al.* 1998). In addition, samples of the same species, collected from the Sydney tar ponds, NS, also showed levels of the condition in significant excess of ‘normal’ levels (McGladdery *et al.*, 2001).

Another neoplasia condition that affects both hard-shell clams and soft-shell clams is gonadal neoplasia. The germinal cells proliferate without undergoing meiosis or differentiating into sperm or ova (Barber, 1996; Beneden *et al*. 1998). This condition shows a distinct geographic focus of infection, with rare outlying distribution spots. The hot spot in northern Maine shows a close correlation to forestry pest control programs, coinciding with spring warm up and gametogenesis, but there is no such correlation evident with the other hot spot in southern New Brunswick (Gardner *et al*. 1991; Barber and Bacon, 1999). Bivalve neoplasias, whether in cultured or wild populations, can be triggered by many different factors, including natural and anthropogenic causes.

Habitat degradation is well-documented as having the potential to adversely effect bivalve health (Croonenberghs, 2000; Dewey, 2000; Moore, 2000). For example, the ciliostatic properties of many *Vibrio* species (ubiquitous marine and estuarine Gram-positive bacteria) is well-documented (DePaola, 1981; Brown and Roland, 1984; Nottage and Birbeck, 1986; Nottage *et al*. 1989; DePaola *et al*. 1990). Although not demonstrated as being a factor in open-water (Tubiash, 1974), the effects of these exotoxins on the ciliated larval stages of bivalves has been proven for numerous species under hatchery-rearing conditions (Tubiash *et al*. 1965, 1970; Elston *et al*. 1981, 1982, 2000; Elston, 1989; Nicolas *et al*. 1992). Severity of infection is most commonly related to sub-optimal growing conditions (accumulation of dead or dying larvae, contaminated algal food, residual gametes, etc.) that enhance bacterial proliferation and compromise the immune responses of infected larvae (Elston 1989). Sensitivity to *Vibrio* spp. can vary considerably. Sindermann (1988) cites 10^2 *vibrio* cells ml^{-1} as being potentially pathogenic to oyster larvae, while other bivalves can tolerate 10^5 cells ml^{-1} (Perkins 1993). There is, therefore, a strong likelihood that chronic or acute blooms of these bacteria under open-water conditions could have a deleterious affect on bivalve larval recruitment, especially under conditions of warm water, rainfall and bivalve spawning (DeLuca-Abbott *et al*. 2000; Herwig *et al*. 2000). In addition, the effects of ciliostatic toxins on the ciliated digestive tracts of adult bivalves cannot be overlooked. At least two shell-deforming conditions in juvenile oysters and juvenile to adult clams have been linked to bacteria. “Brown ring disease” of *Tapes* spp. in Europe is caused by a new *Vibrio* species, *V. tapetis* (Allam *et al*. 2000; Novoa *et al*. 1998; Castro *et al*. 1997; Borrego *et al.* 1996) *and* juvenile oyster disease of American oysters (*Crassostrea virginica*) is caused by a novel alpha-proteobacterium (Boettcher *et al*. 1999, 2000). Both these bacteria appear to proliferate in estuarine conditions and elicit energetically-costly defense mechanisms in the bivalves that are manifest in conchiolin deposition around the mantle margins. Histological profiles of the epithelial tissues of the mantle and digestive system have also shown extensive haemocyte infiltration, indicative of physiological stress (Allam *et al.* 1996; Plana and LePennec, 1991). The linkage of these bacteria to overall habitat quality has yet to be determined.

Another set of recent studies has focussed on immunosuppression induced in bivalves exposed to heavy metals and hydrocarbon-based chemical waste. The effect of these chemicals is complex and initial results shows a potential for hormesis (lower concentrations suppress haemocyte-mediated defence activities and greater concentrations show a neutral or increase in phagocytic activity), both ends of which have energetic costs to the bivalve (St-Jean, 2002a,b). If these results are extrapolated for chronic, sub-lethal effects, some studies using scope for growth as a measure for carrying capacity may need to be revisited. This applies equally to the neoplasia conditions discussed above. Mortality and weakening due to infectious disease is relatively easy to quantify and correlate to environmental factors (epidemiology of the disease). However, immunosuppression and carcinogenic effects are more insidious and could readily be masked by, or distort other more obvious environmental correlations. This is also important for assessment and interpretation of bivalve aquaculture impacts on environmental conditions. Weakening, impeded feeding and filtration activity, along with spawning failure or poor quality spawn can all contribute to morbidity, mortality and fall-off, with the environmental consequences discussed above.

There have been attempts to bring the effect of infection status on overall physiological performance of bivalves into bilateral correlations between physiological scope for growth and environmental carrying capacity as well as contamination, but such studies are rare and inconclusive (DaRos *et al.* 1998). Conceptual models of interactions between bivalve culture activities, eutrophication, and ecosystem functioning are more rapidly evolving (Cloern, 2001), but gaps in knowledge need to be addressed on how these, and other stress components work together if we are to broaden our understanding of cumulative environmental effects in the context of aquaculture.

6. Integration of Aquaculture/Environment Interactions

A mechanistic understanding of coastal ecosystem functions is fundamental for formulating management strategies. The study of aquaculture ecosystems requires consideration of biological, physical, chemical and geological factors. Important biological processes include mussel feeding and egestion, as well as the dynamics of the supporting planktonic ecosystem and interactions with the benthic community. Physical processes governing water motion and mixing determine the transport and supply of dissolved and particulate matter. Nutrient dynamics and cycling depends on the transformations mediated by the various ecosystem components including bacteria. The sedimentation of particles is governed by the competing processes of flocculation and turbulence. These areas require research involving field measurements as well as comprehensive modeling studies that integrate available knowledge about natural- and human-driven parts of coastal ecosystems.

Coastal waters where aquaculture is practiced exhibit a variety of physical oceanographic processes, for example tidal and estuarine circulation. Dissolved and suspended matter in the water column is transported and mixed by water motion and eventually exchanged with the adjacent open ocean, or deposited (utilized) locally. A basic understanding of particle dynamics requires tracking of the total particulate load (turbidity), food particles for shellfish (chlorophyll), and the water flux (mixing and exchange) (Grant and Bacher, 2001). The effects of mussels on water column and sediment properties are influenced by circulation and mixing processes. It is hypothesized that the severity of these ecosystem effects in different coastal areas is regulated by water motion and mixing. Inclusion of oceanographic parameters is essential to a quantitative assessment of the validity of this hypothesis. Aquaculture effects are believed to be greatest in estuaries and inlets where water residence time is long and mussel biomass is high. In such areas, mussel feeding could dramatically reduce the concentration and alter the nature of suspended particulate matter with the resultant potential to change pre-culture productivity within a defined area. In areas with greater flushing, water depleted of particles by mussels can be renewed by tidal exchange and culture-generated biodeposits may be flushed from the system.

A variety of models have been applied to assessing the environmental interactions of bivalve aquaculture operations (Dowd, 1997; Grant *et al*., 1993; Grant and Bacher, 1998; Smaal *et al*., 1998; Meeuwig, 1999). While all of the approaches include a comparison of physical water exchange to some sort of biological process like filtration, there are no standard methods for assessment of ecosystem effects. Bearing in mind the complexity of inter-acting factors, this is not surprising. Empirical studies such as the calculation of budgets (e.g. carbon, nitrogen, and energy) and simulation modeling have been some of the more focused approaches to evaluating potential mussel aquaculture effects at an ecosystem level. As an example of the former, Carver and Mallet (1990) calculated the mussel carrying capacity of an inlet in eastern Canada by comparing estimated food demand to food supply based on organic seston concentrations delivered by a simple tidal prism model. The latter approach was used by Raillard and Menesguen (1994) who constructed a simulation model for a macrotidal estuary in France to describe relationships between oyster feeding, primary production and seston transport. Both approaches yield different, but complimentary, information.

Numerical models are powerful tools to help guide coastal ecosystem management because they integrate the important processes that represent this system complexity (Cloern, 2001).

The use of models also provides an excellent means to identify gaps in knowledge. Simulation models may be the most practical way to assess the potential net negative effect of the impact of mussel grazing on phytoplankton and zooplankton abundance and the potentially positive effect of increased remineralisation on primary production (Fréchette and Bacher, 1998). Similarly, ecosystem modelling can be used to quantitatively assess the contribution of cultured bivalves in combating eutrophication, and of the ecological importance of nutrient losses in the mussel harvest. Fully coupled biological-physical models may be envisioned (e.g., Prandle *et al*., 1996; Dowd, 1997) that predict ecosystem changes in chlorophyll, nutrients and other variables of interest as a function of culture density and location. To do this, shellfish ecosystem models, including carrying capacity models, must be integrated with information on water circulation, mixing and exchange to account for transport and spatial re-distribution of particulate and dissolved matter. Box models (Chapelle *et al*., 2000; Dowd, 1997; Raillard and Menesguen, 1994) offer a practical means to couple coastal ecosystem models with physical oceanographic processes. The bulk parameterizations of mixing required for these box models can be derived directly from complex hydrodynamic models (Dowd *et al*., 2002). One interesting feature of the ecosystem model of Chapelle *et al*. (2000) is that the ecosystem effects of shellfish are incorporated by prescribing their biomass levels and thereby their effect of grazing and nutrient generation on the ecosystem while avoiding the inclusion of mussel bio-energetic relations in detail. A promising avenue for improving ecosystem models is the use of inverse, or data assimilation, methods (Vallino, 2000). These systematically integrate available observations and models, thereby combining empirical and simulation approaches, and improve predictive skill.

Simulation models that focus on estimating mussel carrying capacity and related ecosystem impacts provide effective tools for quantitative descriptions of how food is captured and utilized by mussels as well as site-specific information on ecosystem variables and processes (Carver and Mallet, 1990; Brylinsky and Sephton, 1991; Grant, 1996). An increased understanding of mussel feeding rates and efficiencies (ecophysiology) is fundamental to most model-based predictions of ecosystem effects as the bivalve functional response is the basis for potential interactions between bivalves and the ecosystem. The ability to predict physiological responses of bivalves under culture conditions permits calculation of clearance, biodeposition, and growth rates and this ability presents tremendous opportunities to manage the sustainability of the industry (Carver and Mallet, 1990; Labarta *et al*. 1998). From a mathematical perspective, the nonlinear functional relationships used to describe mussel bio-energetics have often lead to poor model predictions due to their high sensitivity to inadequately known physiological parameters (Dowd, 1997). Robust mathematical relations are being developed with the needs of simulation models in mind, such that bioenergetic models have been successful in predicting growth (Grant and Bacher, 1998; Dowd 1997; Scholten and Smaal, 1998).

Validation of models with field observations ("ground truthing") is essential. *In situ* observations indicate where models are deficient and suggests how model structure should be altered. Model simulations can, in turn, provide a focus for field efforts. A variety of oceanographic instruments exist for monitoring biological and physical processes and include: tide gauges, current meters, fluorometers and transmissometers. Their deployment in mooring mode or as towed vehicles, in the case of particle sensors, is essential for monitoring the changing environmental conditions that occur at culture sites and the influence of mussels on these conditions. They also provide important ground-truthing information for other monitoring technologies such as remote sensing (Herut *et al*., 1999). Additionally, collection of data with this instrumentation is vital in the construction of models to predict the transport of water and particles at culture sites (Ouboter *et al*., 1998).

Decision support systems have been developed that integrate available knowledge about natural- and human-driven parts of coastal ecosystems into computer-based models (Crooks and Turner, 1999; deJonge, 2000). While the prediction of future ecosystem changes is largely unfeasible as ecosystems do not exist in a stable state, computer models can be used to explore the main direction of effects on ecosystem functioning that result from various culture practices (deJonge, 2000), and are useful for developing general ecological principles. It should also be emphasized that the study of culture impact using simulation models and field measurements can also be directed towards assessment of mussel growth and carrying capacity from the standpoint of farm management. For instance, bivalve studies based on physical transport of food particles to mussels and their bioenergetic use by the animals are part of a growth equation, including biodeposition. The intake of food used to predict biodeposition is also part of a growth equation. Coupled with estimates of stocking density, these models produce farm yields, which may then be exported to economic models of profitability (e.g., Samonte-Tan and Davis, 1998). An essential feature of the growth models is that they may be fully ground truthed using mussel harvest/growth data from the farm sites. Ultimately, these models may be used to actively manage the location and extent of culture in coastal estuaries for multiple users. Such models will need to take into account culture dynamics such as seed-stocking and fouling biomass, depth of activity, and cumulative effects of neighbouring human activities (e.g., agriculture run-off, construction sedimentation, boating, and ballast activities, etc.).

Another new development which must be taken into consideration for ecological modelling is increasing interest in bivalve polyculture. Mussel culture, although predominant in Atlantic Canada, is rarely conducted in isolation from other bivalve culture. Some leases accommodate mussels, oysters, clams and, more recently, scallops. All have differing physiologies and production dynamics. Accurate modelling of single species culture interactions with surrounding habitat ecology needs to take this into account in the future. Likewise, spat collection is frequently a 'hit and miss' operation, trying to maximise collection of the species of interest in amongst all the other bivalve species forming a continuum of production through the spring and summer spawning seasons. This further highlights the need to take the multi-species and interactive nature of bivalves into account, both within culture and pre-collection from the wild. As indicated at the start of this review, mollusc culture is much more intricately and inextricably linked to its environment than most finfish culture (even mariculture cages). Monospecific models of aquaculture interactions with habitat ecology cannot, therefore, be readily extrapolated to other bivalve species.

7. Synopsis and Recommendations

The culture of bivalve molluscs may involve a number of effects on the current state of coastal marine ecosystems. Extensive bivalve culture (suspended and benthic) has the potential for causing cascading effects through estuarine and coastal foodwebs, altering habitat structure, species composition at various trophic levels, energy flow and nutrient cycling. There have been few direct studies on the influence of mussel at the ecosystem level, but several studies have speculated on the potential for mussel cultivation to approach and even exceed the capacity of the ecosystem to maintain environmental quality (Rodhouse and Roden 1987, Deslous-Paoli *et al.,* 1987, Dame 1993 and 1996, Prins and Smaal 1990, Asmus *et al.,* 1990). The rapid and extensive transformations of water bodies into mussel production could change the ecological function of some bays. Potential ecosystem level effects (positive and negative) related to intensive bivalve aquaculture include:

- bivalve filter feeder populations crop the resident phytoplankton so that they depend on the tidal input of offshore phytoplankton to sustain high density culture;
- large bivalve farming operations may help to reduce excess phytoplankton caused by eutrophication through grazing;
- the substitution of bivalves for zooplankton in estuaries and bays alters food webs;
- the increased sedimentation of organic matter through biodeposition acts to retain nutrients in the system;
- recycling of organic biodeposits increases the oxygen demand in sediments, generating an anaerobic environment that promotes ammonification and sulfate reduction;
- the rate of nitrogen cycling is increased through rapid deposition of organic matter, nutrient regeneration in sediments and the excretion of ammonia by mussels;
- a shortened cycle of nutrients between the benthos and phytoplankton may increase local nutrient availability as less material is exported; and,
- the greater availability of nutrients leads to enhanced primary production, potentially contributing to more frequent algal blooms, including toxic species.

Few studies have been completed which adequately assess these potential environmental interactions of this newly developed industry and few quantitative measures exist to measure ecosystem level effects. A commonly employed means of addressing uncertainty resulting from gaps in knowledge is to establish rigorous environmental effects monitoring (EEM) programs that can provide early warning of adverse environmental effects and aid in identifying unforseen effects (additional areas of concern). However, research is also needed to develop ecosystem-based EEM approaches and indicators that specifically address the close linkage that exists between cultured bivalves and numerous biotic (ecosystem structure and function) and abiotic ecosystem components. Development of effective EEM approaches would help to minimize the potential for exceeding system carrying capacity while benefiting industry by optimizing farm yield.

The following research topics and associated R&D studies were identified by the authors for further study. While short-term laboratory and field studies at culture operations will be useful to address the identified gaps in knowledge, longer-term studies at new lease development sites (baseline to full development sampling) would be particularly insightful. While a priority for such research exists for heavily leased PEI embayments, the extensive development of the mussel industry in PEI largely precludes such studies owing to the lack of many baseline data, and difficulties in selecting the control sites needed for effective experimental designs. Such studies may be best conducted in regions where the industry is less well developed. Intentional ecosystem manipulation experiments could also provide insights but would be both challenging and costly. Readers should note that the following separation of research topics is strictly an exercise to identify specific gaps in knowledge. The development of a mechanistic understanding of the temporal and spatial scales of ecosystem level impacts from bivalve aquaculture requires a closely integrated multidisciplinary approach that includes major elements from each of the following research topics. Such an approach will permit even short time/small space observations to be fully utilized to address the long term/large space issue that is the topic of this review.

1. *Ecological role of bivalve filter feeders.* Studies are required to improve our understanding of the density-dependant role of bivalves in controlling phytoplankton and seston (including microbes) concentrations, and to determine if bivalves have a net negative (reduce standing stock) or positive (stimulate production) effect on suspended matter concentrations.

    - Conduct seasonal studies of suspended particulate matter, phytoplankton biomass and primary production in estuarine and coastal systems under culture and use the results to assess the potential for overgrazing of food resources by cultured bivalves.
    - Determine the effect on suspended particulate matter, phytoplankton abundance, community structure, and production of different levels of bivalve grazing pressure.

- Assess the capacity of available *in situ* and remote sensing technologies to visualize near- and far-field effects of mussel aquaculture on suspended particle fields (e.g. chlorophyll).

2. *Bivalve Bioenergetics.* Given that bivalve physiological processess (feeding, respiration, biodeposition and excretion) are the primary mechanisms for potential interactions between bivalve aquaculture and the ecosystem, and therefore the sustainability of coastal operations, a more complete understanding of the physiological ecology of each species is needed to facilitate accurate prediction of ecosystem responses.

   - Identify interspecific differences in feeding and absorptive selectivity, particularly under field conditions, to quantify contributions from different food resources (e.g., retention of bacteria, differential ingestive and absorptive selection for algal species, absorption efficience of detritus sources) for use in carrying capacity predictions.
   - Develop robust predictive relations for the functional responses of culture species to environmentally relevant conditions.
   - Establish a clear genetic base to bivalve physiological performance.
   - Quantify the effect of the variable energy demands of gonad growth on bivalve feeding behaviour.
   - Use mathematical relations for bivalve responses to internal and external forcing for continued improvement of bioenergetic models. Test growth predictions using site-specific harvest/growth data from aquaculture farms.

3. *Organic Loading.* Studies are needed to determine the capacity of different coastal ecosystems to assimilate organic matter for use in predicting environmental impacts and ecosystem management .

   - Quantify organic biodeposition rates, benthic organic enrichment effects (e.g., anoxic conditions, sulfate reduction, and reduced biodiversity), and recovery times at aquaculture and reference sites.
   - Study the settling and transformation of faecal wastes as a function of different physical environmental conditions.
   - Quantify the capacity of different environmental conditions to mediate organic enrichment impacts from aquaculture.
   - Develop and test surrogate measures of the total assimilative capacity of coastal systems.

4. *Nutrient Dynamics.* Conduct detailed studies of nutrient dynamics in coastal systems including those supporting and associated with bivalve aquaculture to address the potential effects on nutrient availability and cycling.

   - Confirm nutrient limitation of phytoplankton production in coastal embayments and identify biotic and abiotic processes contributing to nutrient limitation.
   - Document the import and export of nutrients in coastal aquaculture ecosystems and determine the role of cultured bivalves in retaining and promoting the rapid recycling of nutrients within the system.
   - Assess the relative importance of bivalve excretion and particle biodeposition in the recycling of nutrients and the production of phytoplankton.
   - Conduct field studies to provide insights into potential interactions between nutrient dynamics and the onset of harmful algal blooms, especially those of the domoic-acid-producing diatom *Pseudo-nitzschia multiseries.*
   - Assess the potential consequences to ecosystem productivity of large nutrient losses to the bivalve harvest.

5. *Ecosystem Structure*. Investigate the ecosystem-level effects of bivalve culture on ecosystem structure (abundance and biodiversity of pelagic and benthic communities) through direct competition for food resources by bivalves, zooplankton, and epibionts, and the transfer of energy and nutrients to the benthic foodweb.

   - Assess the implications of reduced zooplankton abundance and composition on higher trophic levels including fish.
   - Determine the ecological role of fouling organisms (epibionts) associated with bivalve culture.
   - Investigate the ecological threat imposed by aquaculture resulting from the introduction and transfer of exotic fouling and infectious agents with live shellfish transfers, and the potential increased incidence of infectious diseases associated with overstocking.

6. *Cumulative Effects.* Assess cumulative effects of anthropogenic land- and marine-use on coastal ecosystems.

- Conduct research on the inputs and impacts of sediment, toxic chemicals, animal waste including bacteria, and nutrients reaching embayments supporting bivalve aquaculture.
- Assess the capacity of bivalve aquaculture to mitigate coastal eutrophication trends through their grazing on phytoplankton.
- Investigate the effect of aquaculture on marine particle aggregation processes (particle dynamics) and the consequences to coastal sedimentation trends.
- Conduct studies on the potential for culture activities to alter the transport and fate of particle-reactive contaminants originating from land-use.

7. *Ecosystem Modelling.* Integrate knowledge obtained on the consequences of bivalve culture to ecosystem structure and function through the use and predictive power of ecosystem modelling.

    - Test ability of models to provide decision support for the development of effective area-wide management strategies for promoting the environmental sustainability of the aquaculture industry.
    - Conduct sensitivity analysis of modelled variables to assess the suitability of different ecosystem indicators for use in characterizing and monitoring ecosystem health and productive capacity.
    - Develop and utilize new instrumentation and data collection strategies to obtain ecosystem data, including measurements of contaminants, for testing (ground-truthing) model predictions.
    - Use models to test the hypothesis that the severity of aquaculture impacts in different estuaries is regulated primarily by water motion and mixing.

8. *Ecosystem Status.* Develop indicators (methodologies and technologies) for use in aquaculture monitoring programs that provide information on ecosystem function. Test the effectiveness of selected indicators for detecting potential ecosystem-level effects of bivalve aquaculture. Identify indicator reference points that characterize ecosystem status.

    - Identify sensitive and cost effective ecosystem health indices.
    - Establish baseline environmental condition and the degree of natural variation in ecosystem health indices.
    - Develop a scheme for classifying the state of ecosystem functioning, including the identification of relative threshold levels.
        - Establish cause-effect relationships between culture practices (e.g. stocking density, husbandry practices) and identify candidate indicators.
        - Developing standard protocols for rapidly assessing mussel performance (growth rate, meat yield, and yield per sock) at lease sites as an indicator of ecosystem impacts (i.e., impact on growth depends on impact of mussels on environment) and establish cause-effect relationships between environmental conditions and mussel performance.
        - Develop tools that incorporate information provided from ecosystem indicators that provide an integrated assessment of ecosystem status.

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