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MODELLING ENVIRONMENTAL INTERACTIONS OF MARICULTURE

by

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ABSTRACT

Modelling of mariculture interactions has progressed to the point where some degree of standardisation is possible. This permits easy comparison between alternative approaches and facilitates co-operative modelling programs. We have broken the modelling process into four main categories, as follows:

Effluents: The production of particulate and dissolved effluents by cultured marine organisms. This generally is based on physiological models and is the area of greatest difference between models of finfish and shellfish mariculture.

Dispersal: The physical transport of effluents from a farm into the water column and sediments, including processes such as flushing, sedimentation and resuspension.

Effects: The actual environmental effects that these wastes generate in the environment, such as changes in primary production due to nutrification and turbidity, or changes in benthic conditions.

Implementation: The use and presentation of models in a management framework. This can include the use of graphical user interfaces (GUIs) and expert systems, as well as protocols for the use of models in environmental impact assessment for mariculture operations.

These four categories are further broken down on the basis of the space and time scales of these processes. The use of this approach in developing models of the environmental interactions of mariculture will be described in both a regional and international context.

INTRODUCTION

Modelling mariculture interactions involves a number of different processes acting on different space and time scales. As in all complex models there is a tendency to focus on the better-understood processes at the expense of those that may be equally important but less easy to deal with; this paper tries to develop an overall perspective to serve as the basis for an evenly-balanced approach to modelling.

This type of modelling is highly multidisciplinary. It involves the physiology of the cultured organisms, the physical transport of effluents and sediments, and the ecological and geochemical changes in the benthos and water column (see for example the multi-authored volumes by Håkanson et al. 1988, Mäkinen 1991, and Ervik et al. 1994).

This complexity raises problems in the utilisation of such models, since providing advice to management requires work by a team of scientists, and yet regulatory decisions often have to be made in remote locations on a timely basis. The development of models cannot be dissociated from the implementation of advisory tools, and therefore an important component of the development of mariculture interaction models must be the design of expert systems and decision support tools for practical management purposes.

The context of this paper is the use of models in the regulatory process, and the incorporation of models of the environmental interactions of mariculture in coastal zone management. This does not imply that such models cannot also be of great value in the management of individual farms as a tool for proper husbandry, but this is not the focus of the present study.

An important step in the development of integrated modelling approaches is a Workshop on Modelling the Environmental Interactions of Mariculture, organised by the ICES Working Group on Environmental Interactions of Mariculture and held at the Bedford Institute of Oceanography (Dartmouth, Canada) on 6-8 September 1995. Although this manuscript will have to be printed before then, this paper is based on the draft program for the Workshop, and the oral presentation will reflect developments at the Workshop.

I have not attempted a comprehensive review of literature in this field, which would hopefully be at least partially obsoleted by the Workshop. Emphasis has been placed on review articles and conference proceedings rather than on original sources, which necessitates an apology to the many pioneers in this field whose contributions are only obliquely acknowledged.

EFFLUENTS

The calculation of effluents is the area of greatest difference between finfish mariculture and shellfish culture. Whereas the growth of shellfish depends on the availability of planktonic food and therefore the cultured organisms can be seen as replacing natural grazers in the food web, finfish are fed manufactured feed which greatly increases the inputs available to the site and can produce far greater biomasses.

This is reflected in the terminology that is often used to characterise the upper limit on fish production in an inlet; shellfish farms are limited by the carrying capacity, while finfish farms are constrained by the holding capacity. The former is a food limitation which restricts the quantity of shellfish which can be fed profitably on the available plankton resources, while the latter is the maximum production that can be sustained (by controlled feeding) without unacceptable environmental consequences.

Finfish

Although the loadings from finfish farms are usually higher than those from shellfish culture, it is easier to do the necessary budget calculations to estimate these loadings. This paradox arises because feed is controlled by the farmer, and since it is a major expense it is usually well documented and carefully regulated.

The simplest way to calculate the loading is to use a fixed budget as described by Silvert et al. (1990) and Silvert (1994a, 1994f), although Nijhof (1994) cautions that effluent calculations can be very sensitive to small errors in the feed conversion ratio. The inputs are easily determined (they can usually be obtained from the feed label) and can be compared to carbon utilisation either in terms of growth or expressed as a feed conversion ratio. More sophisticated physiological models can be used (cf. Ackefors and Enell 1994), but the calculation of effluents is perhaps the easiest component of the modelling process (an important symposium on the topic is covered in Cowey and Cho 1991).

Lest this point of view appear overly optimistic, it should be noted that the physiological models underlying this approach are almost entirely based on laboratory studies which have not been clearly shown to apply to fish raised under culture conditions. It is also dangerous to assume that even the physical properties of the effluents are the same; anecdotal descriptions of fæcal matter found in the vicinity of salmon pens as long aggregated mucoid strings bear little resemblance to the perfect pellets sometimes found in models.

Shellfish

Effluent calculations from shellfish farms are less easy to predict because of the dependence on naturally occurring plankton in the water column. Budget calculations based on fixed ratios between production and effluents are probably the best easily available means for doing these calculations (Rodhouse and Roden 1987, Carver and Mallet 1990). However, increasingly sophisticated models of the feeding, growth, and excretion of cultured shellfish are being developed, as illustrated by the work of Raillard and Ménesguen (1994). These models incorporate the full range of biological and physical interactions between the shellfish and other components of the ecosystem such as plankton and seston, as reflected in the proceedings of a recent NATO Advanced Research Workshop on the subject (Dame 1993).

Husbandry

The issue of husbandry is an important concern in estimating effluent production, but it does not always receive adequate attention. Models are usually based on data collected either at special experimental sites or from farms whose owners are willing to cooperate with scientific researchers. These farms are usually quite well run, and effluent levels are low. Then these results are translated into predictions that are assumed valid for all farms, including those which may not conform to such high standards.

It can be politically difficult to suggest that some farmers may not be doing as good a job as those who cooperate in research programs, but it is a factor that merits consideration, and if it is ignored there is a substantial risk that effluent models will seriously underestimate the quantity of wastes being released into the environment.

DISPERSAL

The dispersal of fish farm effluents involves a number of different processes (Silvert 1992a) which operate on different space and time scales (Silvert 1994e). It is most common to distinguish between models which describe the dispersion of particulate matter that eventually arrives on the sea floor, and of material which remains in the water column and is transported passively by water movement.

Particulates

Particulate matter, consisting mainly of fæces and (in the case of finfish) unconsumed feed, falls to the bottom and can accumulate there with serious environmental effects. The current situation for depositional modelling has been discussed in detail by Gowen et al. (1994), but there are many additional complications which do not appear to have been dealt with in the study of mariculture interactions. The flocculation of settling material is probably not very important, since much of it is quite large to begin with, but some fæcal matter is quite soft and sticky, and the process of falling through pens which may have complex mooring systems and predator nets under them may lead to unexpected results.

Resuspension plays a major role in determining the distribution of waste material on the seabed. Although the modelling of deposition is straightforward, material is constantly being moved both continuously through the prevailing currents and episodically because of storms and other events.

An important aspect of resuspension is that ageing of wastes affects their susceptibility to suspension. Dissolution, microbial degradation, and bioturbation all contribute to the redistribution of farm waste products.

Dissolved and Suspended Material

Soluble effluents and fine particulates are passively transported by water motion, and their concentrations are determined by the balance between loading and flushing.

Flushing calculations are scale-dependent and are difficult to carry out with the degree of geographical accuracy required for managing and regulating fish farms. The siting of farms depends on a trade-off between factors which can affect their impacts. For example, deep water and strong currents are theoretically desirable because effluents are diluted by the large water volume and quickly removed by the currents, but the costs of mooring in such areas may be prohibitive, and excessive currents can be bad for fish. Flushing calculations that cover an entire inlet are easiest and require relatively low-resolution data, but although they are useful for general holding- or carrying-capacity calculations, they may not give reliable results for smaller regions within the inlet.

One of the difficulties with flushing calculations is that it seems that every model is too simple. Although this is a general problem with modelling, it tends to be especially severe in this area because of the degree of sophistication that has been achieved in physical oceanography. For example, the simplest approach to estimating tidal flushing is to assume that the tidal prism is replaced on every cycle, but this ignores the possibility that an appreciable amount of the water that gets flushed on the ebb returns on the flow. If this is included in the calculation, additional problems arise from stratification, and so on.

Fortunately the different types of flushing are approximately additive, so that when several factors affect flushing, the exchange volumes can be added to calculate a total flushing rate; for example, one can add the tidal prism to river runoff (Silvert 1994a). This requires that flushing calculations be expressed in terms of exchange volumes, which makes it difficult to incorporate the results of strictly empirical models, although it should be possible to add the effects of wind and wave forced dispersion in a generic model of flushing (cf. Wallin and Håkanson 1991, Håkanson 1994).

Biological Effects

Dispersal is usually treated as an issue of physical transport, but biological factors play an important role. Wild fish both inside and around fish pens can significantly affect particle and nutrient fluxes, and bioturbation is an important factor in the breakdown of particulates on the seabed and thus their susceptibility to resuspension.

These processes are often highly variable and episodic in nature, which makes them extremely difficult to model. For example, bioturbation by resident macrofauna can be modelled in terms of a Pearson and Rosenberg (1978) type of succession, but bioturbation by fish and migratory macrofauna is important (Angel, pers. comm.) although far more difficult to predict.

EFFECTS

The aspect of mariculture interactions that has probably seen the least modelling is the understanding and prediction of the effects of farm loadings. Although the potential effects are important and widely recognised, including eutrophication, changes in community structure, and gas ebulliation, most studies of these processes are empirical rather than predictive. But certainly if we area to manage mariculture effectively, we need to understand these effects and develop an ability to predict them.

A key issue in environmental regulation is setting limits on the degree of impact that is acceptable. Frequently the effects of anthropogenic loadings are not immediately evident and may take years to reach steady-state levels (Sowles et al. 1994). Predictive modelling is an essential tool in evaluating not only the short-term but also the long term impacts of fish farming.

Eutrophication

The effects of eutrophication in the marine environment are seldom as dramatic as those observed in freshwater, where massive mats of algae are often the sign of serious pollution (Persson 1991). In the well-mixed and well-flushed turbid estuaries of the Bay of Fundy and other macrotidal systems it is unlikely that the release of effluents into the water column can have major ecological consequences, but in non-tidal systems like the Baltic and in stratified fjords and sheltered lochs the situation can be quite different (Gowen 1994).

Stratified systems pose a particular problem, since nutrients in the water column that diffuse through the pycnocline and combine with those released by settling particulates can build up to high levels. This is particularly true in fjords with sills and has been extensively modelled by Aure and Stigebrandt (1994, and other papers cited therein).

Benthic Enrichment

Benthic changes under fish farms are easily observed, although it is easier to characterise them qualitatively than quantitatively. Changes in community structure have been documented by Pearson and Rosenberg (1978), and under extreme conditions the seabed can degenerate into bacterial mats and exhibit ebulliation of toxic gasses. A valuable review by Gowen et al. (1991) summarises the immediate effects of deposition under a fish farm, but although the review describes many of the changes that can occur with time, there is a marked lack of predictive models.

One of the few quantitative studies of benthic deterioration was carried out by Sowles et al. (1994), who showed that a benthic score based on a mix of quantitative and qualitative observations could be calculated from the benthic carbon loading using a model based on a system of differential equations. These results are similar to empirical observations by Kupka-Hansen et al. (1991) that show a nonlinear dependence of benthic fluxes on carbon accumulation. Efforts are under way to quantify the various relevant benthic observations in a form that can be more rigorously related to benthic processes (Angel et al., in prep.).

Feedback on the Cultured Stock

The effects of greatest concern to mariculturists are those which affect the growth and viability of the stock itself. Often these effects become noticeable only after there has been substantial environmental impact; by the time that the seabed begins to release toxic gasses for example, serious damage has already been done. In areas of heavy carbon loading it is probably more useful to point out that valuable feed is being wasted than it is to focus on changes to the seabed.

The complex interactions between shellfish and their environment has been described by Raillard and Ménesguen (1994) and others, and this includes nutrient balances between effluents from the cultured organisms and that required to grow the plankton they feed upon. For finfish the situation is complicated by the inclusion of antibiotics and other chemicals in the feed, and by the generally greater sensitivity of finfish to low levels of pollutants (Tarazona and Muñoz 1995).

IMPLEMENTATION

Establishing the link between modelling and management is a difficult process, and mariculture is no exception (Silvert 1989, 1992b). A proper implementation strategy requires both the development of models suitable for integration into the management framework, and the creation of user interfaces that help bridge the gap between scientific expertise and the constraints of regulating a growing commercial field.

Modelling Implications

As stated previously, modelling mariculture interactions involves many different disciplines and is very much a team effort. This makes it difficult for one individual to provide adequate advice in a timely fashion. Furthermore, the type of advice required may not be available under the constraints of practical management advice. A monolithic modelling program may be suitable for centralised decision making with lots of time and money available, but in many countries the regulation of mariculture involves reasonable prompt evaluation in a decentralised structure.

This situation means that the interface between modelling and the regulatory process has to be developed with as much care as the models themselves. Models have to be developed with a clear conception of the context in which they will be used, and this context can be a serious constraint on the kinds of modelling that is reasonable.

One of the most serious constraints is the type of data that are likely to be available. Site-specific data are expensive to collect, and model developers must be aware of the limitations that are likely to be imposed by economic factors.

Decision Support Systems

The ultimate output of any modelling project with practical goals has to be a procedure for applying the results to the decision-making process. In countries with a large and diverse mariculture industry it is difficult to envision a centralised regulatory process with the necessary high level of day-to-day involvement by scientific experts. This has led to a search for alternate approaches that might simplify the scientific consultative process.

One possibility is the use of expert systems to emulate the role of a scientific team in the evaluation of potential mariculture interactions. The basic ideas underlying decision support systems for mariculture regulation have been described previously (Silvert 1992a, 1992b, 1994b, 1994c, 1994d) and will not be elaborated on here.

The use of a decision support system has clear pros and cons. The pros are that it is fast, available for use at any time and any place, and many copies can be produced and distributed. The negative aspects are that it can never hope to be more than a simplified representation of the process of scientific evaluation, and the more it gets simplified, the worse it is likely to be. These trade-offs will have to be evaluated as decision support systems are developed, and it is premature to judge whether they will be effective management tools.

Innovative Approaches to Regulatory Criteria

No matter how refined the models and how sophisticated the user interfaces may be, there are fundamental problems in environmental management that limit the effectiveness of any set of regulatory rules. These are rooted in basic uncertainties about how to evaluate environmental change and how to set limits on the allowable levels of different kinds of environmental impact.

For example, what degree of nutrient enrichment is acceptable? Clearly when eutrophication reaches the point where a water body is choked with algae it is excessive, but lesser degrees of nutrification may even be seen as beneficial in stimulating local productivity. Even if all the consequences of fish farming were completely and accurately known, translating these into a sharp division between acceptable and unacceptable impacts would be extremely difficult.

Work has recently been initiated on using *fuzzy logic* to quantify the environmental impacts of finfish farming (Angel at al., in preparation) and more generally as a tool for pollution regulation (Silvert, in preparation). The central idea in this approach is derive a formalism for describing degrees of acceptability in a way that can better be evaluated by managers and possibly can be used more effectively in the arena of regulatory decision-making.

SUMMARY

Modelling the environmental interactions of mariculture is a complex matter which draws on many different disciplines. This is intimidating, but since most problems in environmental management are comparably complex and multifaceted, it should not be cause for alarm.

We are fortunate in having at our disposal a large body of tools which, while far from perfect, provide an adequate starting point and provide a basis for good management. We need to improve our science in this area, but we also need to make sure that existing scientific knowledge is recognised and applied.

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