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Monitoring environmental effects of marine fish aquaculture

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SUMMARY – As mariculture production increases in both northern and southern Europe its conflict with other users of the marine environment, for space and other environmental services, becomes ever greater. Implications of these increases and conflicts require that careful environmental management of aquaculture practices be considered, which rely heavily on the process of monitoring. Monitoring studies for estimation environmental effects follow directly on, and may be considered a progression of, the process of Environmental Impact Assessment. In this paper the reasons for monitoring environmental impacts of aquaculture will be addressed, particularly assessing its use in different physical environments where management practices may vary, and its use in implementing environmental regulation and Environmental Quality Standards. Presently used methods of monitoring impacts of marine cage aquaculture will be described and discussed, the usefulness of the results, and the future of monitoring employing new developments in survey techniques.

Key words: Mariculture, monitoring, survey techniques, aquaculture wastes.

RESUME – *"Surveillance des effets de l'aquaculture marine sur l'environnement". Au fur et à mesure que la production aquacole augmente dans les pays du sud et du nord de l'Europe, le conflit avec les autres usages du milieu marin devient plus important en rivalisant pour l'espace et les autres services environnementaux. Les implications de ces augmentations et conflits exigent de considérer une gestion rigoureuse des pratiques aquacoles du point de vue de l'environnement, ce qui est basé notamment sur le processus de surveillance. Les études pour estimer les effets sur l'environnement constituent une conséquence directe et sont le prolongement du processus d'évaluation de l'impact sur l'environnement. Cet article examine les raisons de contrôler les impacts de l'aquaculture sur l'environnement, notamment en évaluant son implantation dans différents milieux physiques avec différentes pratiques de gestion et son usage en application de la réglementation sur l'environnement et les normes de qualité de l'environnement. On décrit les méthodes utilisées actuellement pour contrôler les impacts de l'aquaculture en cages marines, l'utilité des résultats, et le futur du contrôle en utilisant les nouveaux développements des techniques d'études.*

Mots-clés : *Mariculture, surveillance, techniques d'étude, déchets de l'aquaculture.*

Introduction

Cage aquaculture is the most commonly used method of raising marine dwelling fish to maturity. It utilises readily available resource, seawater, to provide a substrate for culture and a renewable supply of good quality water with the necessary conditions for growing fish. Intensive fish farming by its nature grows many fish in a confined area which produces considerable amounts of nutrient waste in dissolved form – i.e. ammonia and urea – and in particulate form – i.e. uneaten food and faeces (Bergheim and Asgard, 1996). In addition, higher incidence of disease increases the use of chemotherapeutants – i.e. antibiotics and antiparasiticides – which again may be in soluble or particulate form (Midlen and Redding, 1998). These wastes are usually discharged to the surrounding environment which acts as an effective agent of dilution and dispersion. However, each form of waste can have an impact on the environment, in the form of nutrient enrichment effects or direct and indirect toxicity effects at a lethal and sublethal level, which may alter the nature or ecology of the local system.

It is rare for marine cage aquaculture to have no impact and there is usually a trade-off between acceptable environmental impact and socio-economic benefits to the local community. This trade-off is normally defined in the form of an acceptable limits of effect. This principle provides a management framework by which environmental impact can be maintained at a minimum and within acceptable

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limits. However, implementation of this framework requires generation of data from which decisions on the environmental management may be reached. This process of data generation is monitoring.

Monitoring may look at many topics and levels including the scale of impacts, general ecological change, and implementation of acceptable limits or acceptable zones of effect over a defined timeframe. The latter is achieved using environmental quality standards (EQSs) set out either within an environmental impact assessment (EIA) or by environmental bodies and governmental authorities as part of a regulatory plan. These EQSs are usually based on data derived from laboratory study and field investigation and often include a "safety" factor, using a precautionary principle approach (SEPA, 1999).

The techniques used in environmental monitoring of marine cage aquaculture are important as they must be effective in providing the necessary data to implement EQSs and investigate the environmental change with time in a scientifically rigorous manner but also be "straight forward" to employ and cost effective.

Monitoring, in this context, has therefore be defined as "the regular collection, generally under regulatory mandate, of biological chemical or physical data from pre-determined locations such that ecological changes attributable to aquaculture can be quantified and evaluated" (GESAMP, 1996).

Reasons to monitor effects

In the introduction a definition of monitoring suggested that monitoring was for compliance with regulatory standards for protection and safeguarding environmental quality. This is true and forms the basis for monitoring, but other reasons are also important.

The aquaculture industry has an important "stakeholder" interest in environmental quality. As pointed out earlier water quality (in particular) is of essential importance in maintaining the health of the cultured resource. This is true whether the reason be for optimization of fish growth to legal liability in case of litigation due to unacceptable environmental change which affects other resource users. Environmental monitoring is therefore an important part of fish farm management.

Effective marketing of fish to the consumer is of paramount importance to any commercial fish farming company. The consumer therefore has a need to be certain that what they are consuming is safe and been cultured in conditions of the highest quality. Monitoring shows the changing state of the environment and allows effective data to allow disease control in fish. Good environmental conditions often lead to the healthiest fish.

Effective environmental management of aquaculture requires constant research into a better understanding of associated environmental process and change. Effective monitoring provides essential research data for many processes including, identification of impacts, development of methods for future monitoring and the validation of decision making tools used by environmental managers, i.e. dilution and dispersion models (Gowen *et al.*, 1994; Telfer, 1995; Cromey *et al.*, 2000) (Fig. 1). Modelling is important for prediction of impacts and estimation of environmental capacity for implementation of a sustainable approach to aquaculture. It is also useful in implementing EQSs be granting pre-operational consents. Monitoring is also used in validating newly developed model programs for general use and in a post-operational capacity to confirm models generated for a particular site. The latter is important as any prediction should be tested and management decisions based on the original prediction modified in light of the results.

Monitoring is also an essential *post hoc* part of the EIA procedure. EIA is a process where the environmental risk of a development is assessed in terms of acceptable environmental impact and balanced against the projected benefits of the development (Walthern, 1988). It is required as a prerequisite for many developments and allows effective environmental management and decision making. An EIA consists of three stages: (i) screening, to define in what context the EIA is needed; (ii) scoping, to define what risks should be assessed and in what terms; and (iii) a written report and consultation phase to produce an environmental impact statement which should include an environmental monitoring strategy to ensure the assessment of risk has been effective.

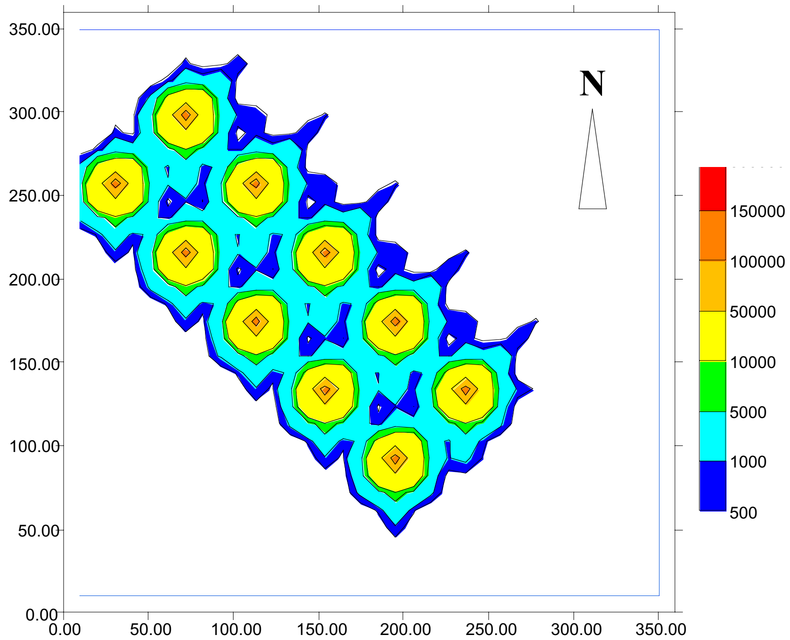

Fig. 1. Graphical output of model of particulate waste material settled to the seabed from a multiple cage pontoon. Axis units in metres, contour units are g Carbon/m^2/yr (after Telfer, 1995; Institute of Aquaculture, unpublished data).

The process of monitoring

There is no set way of monitoring the environment for impact or discovery of change, and many articles and books have been published suggesting methods for particular circumstances. However, monitoring technique, in terms of what should be used or how monitoring should be achieved, must be decided in light of the ecological endpoints under investigation. It should also take cost into consideration.

In monitoring environmental effects of aquaculture, as in all studies on environmental change, data is collected at various time points and compared with original pre-development data and with contemporary reference data. This will show changes with time due to impacts but also allow natural environmental change to be taken into consideration. Survey techniques vary but generally require a design that collects data before development – a baseline survey – and collection of post-development data – a monitoring survey:

(i) Baseline survey. This provides essential background ecosystem data for subsequent comparison. The survey may be both spatial and temporal giving pre-development data on the natural environment and its changes throughout the proposed development area. This data can aid in the design of an appropriate monitoring study, i.e. focusing on the areas which are most relevant for investigating change in any particular environment. The survey will also answer important management questions for the developer. In this case, will the site support aquaculture? There are several types of experimental design incorporating the baseline survey. One of the most commonly used is the BACI or BACUP systems (Underwood, 1991).

(ii) Monitoring study. This provides data on the actual impacts, in relation to the contemporary reference and baseline data. Once interpreted the results may be used directly for management decisions by both fish farmer and environmental regulator by ensuring adherence to EQSs and acceptable zones of effect (AZEs). Care should be taken in designing the monitoring study so that data is generated to answer the questions posed by all users of the data. For the environmental regulator – are AZEs and EQSs or the original conditions of the EIA being adhered to? For the fish farmer – is our environmental resource being damaged?

What to monitor

As mentioned earlier fish farms discharge soluble wastes into the water column and particulate wastes which tend to settle to the seabed. Monitoring of these wastes may be undertaken by selecting determinants which measure wastes directly in a relevant environmental partition or measure their direct or indirect effects.

Soluble wastes often lead to poor water quality and occasionally eutrophication due to excess nutrient input (Beveridge, 1996). Useful determinants for inputs from fish farming would include direct measures, i.e. ionised and un-ionised ammonia, nitrate, nitrite and dissolved reactive phosphorus, and indirect measures of productivity, i.e. dissolved oxygen, chlorophyll "a" content, turbidity and biochemical oxygen demand. In order to interpret these data effectively standard measures, including temperature and pH, should also be taken. Long term measurement and monitoring of effects of soluble wastes are difficult due to the high mixing and dilution afforded by the marine environment. This ensures that impacts in all but the most sheltered and enclosed conditions are transient.

Particulate wastes tend to settle to the sediments creating a "footprint" of effect usually distributed in the direction of the main current flow (Beveridge, 1996), as illustrated in Fig. 2. The wastes usually form a gradient of effect away from the discharge point which cause a variety of changes on the seabed. These changes can be monitored using a range of determinants including changes in sediment composition (Edwards and Griffiths, 1996), decrease in dissolved oxygen or sulphur reduction due to increase in microbial production (Davies *et al.*, 1996) and changes in benthic biota (Gowen and Bradbury, 1987; Karakassis *et al.*, 1998).

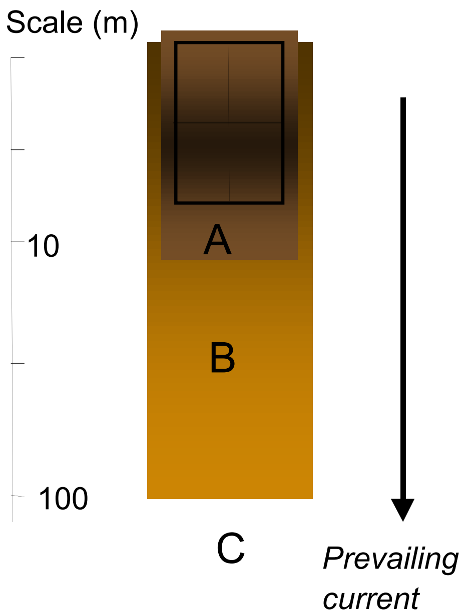

Fig. 2. Distribution "footprint" of particulate waste material discharged from a sea cage pontoon, forming a gradient away from the cages in the direction of the prevailing current. The gradient can be investigated by studying change in benthic community with distance and time; from A high numbers of few opportunist species, through B an intermediate community exploiting moderate waste levels to C the background community.

A variety of measures are used as indicators of these effects. Physical and chemical changes in sediments can be investigated using: particle size analysis, determination of concentration of organic carbon and nitrogen, redox potential (Pearson and Stanley, 1979), and measurement of sulphide content. Biological changes can be seen by looking at many factors, the presence of the sulphur reducing bacteria *Beggiatoa*, abundance of species which are indicative of nutrient enrichment and investigation of community structure (infauna and *Posidonia* and associated fauna).

Monitoring methodology

There are several considerations to be taken into account when deciding on monitoring methodology. These include: (i) frequency of sampling; (ii) position of sampling stations; (iii) method of sampling water or sediments; and (iv) method of analysis of the samples taken to measure the determinants.

These factors will be different with type of aquaculture and method of waste discharge. Again, there is no fixed method of deciding on these factors as this is dependant on the purpose of the monitoring study. However, examples of possible sampling station layout for a fish cage pontoon and shore based culture system with a discharge are given in Fig. 3. Sample strategies usually attempt to maximise data collection per expended effort, which normally entails the use of transects aligned with the direction of principle current flow rather than a less efficient but more statistically rigorous random sample or grid approach. Transects are particularly good at allowing detailed investigation of gradients from a discharge point, such as that illustrated in Fig. 2.

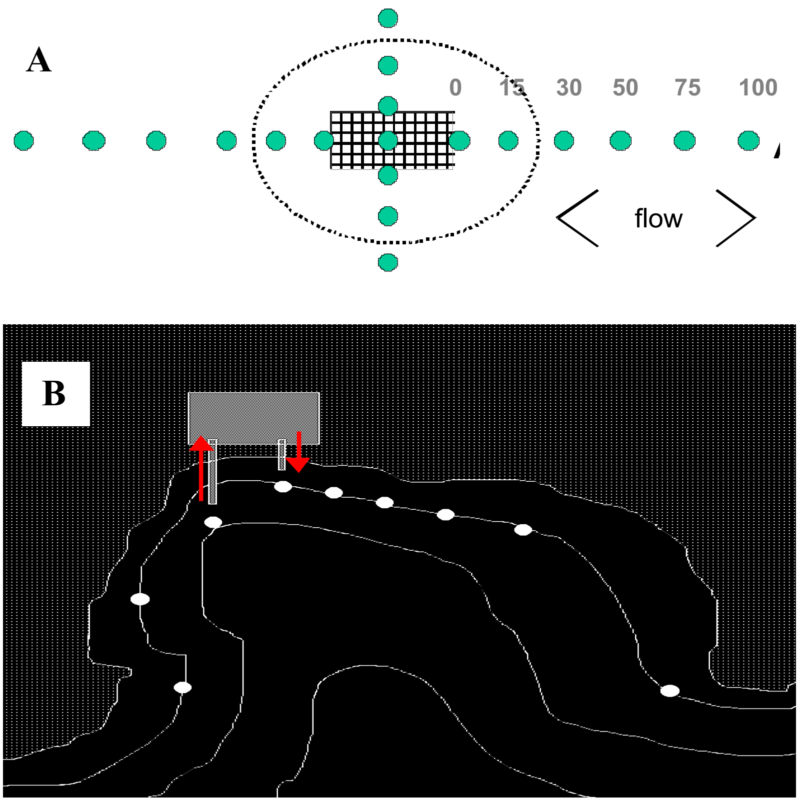

Fig. 3. Example layout for sampling stations for: A, a marine fish cage, and B, a land based facility with marine discharge and intake where samples investigate impacts from discharge and environmental quality at the intake. Positions of sample stations adopt a transect approach which take into account the principle current flows and depth contours. Reference stations should be used at sufficient distance not to be influenced by the discharge but with other environmental conditions being similar.

Samples along these transects may be taken using water samplers such as the Van Dorn and sediment samplers like remotely operated grabs, dredges, trawls or corers or diver operated techniques such as photography, video, corers or REMOT systems. Grabs and coring techniques can be used to take quantitative samples which give accurate and easily comparable temporal and spatial data for physical, chemical and biological analysis. Photography and video methods are qualitative or semi-quantitative but are a good visual record of change.

Recently, with the advent of advanced computer based electronic methods, surveys can be undertaken using sophisticated ship based technology. Such a method is side scan sonar which has been used, with varying success, to characterise sediment types throughout bays containing fish farms (MacDougall and Black, 1999) and for mapping biotopes in coastal regions. Initial findings show that these techniques need further work but they offer promise for the future where surveys will be able to study large areas of seabed quickly and accurately.

An integral part of monitoring is interpretation of results and relating physical and chemical results to the biological effects. For water samples this is often a compromise due to the transient nature of this environment. Most often water quality monitoring requirements are fulfilled by collection of empirical data which can be directly compared to EQSs. For sediments a similar comparative method may be used but, due to the more stable nature of this habitat, more sophisticated techniques can be employed to investigate both gross and subtle changes, such as those that may be due to discharged chemotherapeutants. These techniques use species abundance data to investigate spatial and temporal changes in sediment dwelling communities and relate these to physico-chemical parameters and waste inputs. Such techniques range from statistical comparison of presence or abundance of indicator organisms to univariate measures such as diversity and evenness indices, to classification and comparison of all the community and environmental variables using multivariate analysis.

Univariate analysis

This is characteristation of a complex dataset as a single measure which gives an indication of a particular function of the data. In terms of species abundances, the most commonly used univariate measures are diversity and evenness indices. These characterise species assemblages in terms of domination of those species present and their spread across the whole assemblage (Pielou, 1984). These measures may be empirical or statistically (predictive) based. One of the most popular diversity measures used for assessment of benthic macrofauna is the Shannon-Wiener Index (Hs).

$$Hs = -\sum_{i=l}^{S} p_i \log_2 p_i \qquad p_i \approx \left(\frac{N_i}{N_T}\right)$$

where: S = number of species; N_i = no. of individuals for species "i"; N_T = total number of individuals.

This index measures the uncertainty of predicting the species of the next individual, i.e. the more species and the more even their spread throughout the community, the more uncertain the answer, and the more diverse the community is.

An example of variation in Hs along a nutrient enrichment gradient from fish farm seacages in Scotland is given in Fig. 4. This illustrates the low diversity (high dominance by few species) near to the cages becoming higher with distance away. At this site the diversity attains background levels at approximately 100 m from the cages along the main axis of tidal current flow. Though this would be dependant on physical conditions and fish production for other sites.

Univariate measures may be used in monitoring studies to show changes in community composition by statistical comparison between time point data with baseline and reference values, or by comparing calculated values with an EQS value of diversity set for a particular site by regulatory authorities. If an EQS approach is used, the standard should be site specific and set in relation to the background level, e.g. Hs, as a percentage of background level at any particular time.

Multivariate analysis

This is a branch of mathematics that deals with the examination of many variables simultaneously. Species community data are multivariate because each sample is described by the abundances of a number or species, because numerous environmental factors affect communities, etc. The purpose of multivariate analysis is to treat this data as a whole, summarizing the data and revealing their structure. It therefore serves two basic roles in community ecology; it helps ecologists discover structure in the data, and it provides an easy summarization of the data, which both facilitates comprehension of the data and provides an effective means for communication of results to environmental managers and decision makers.

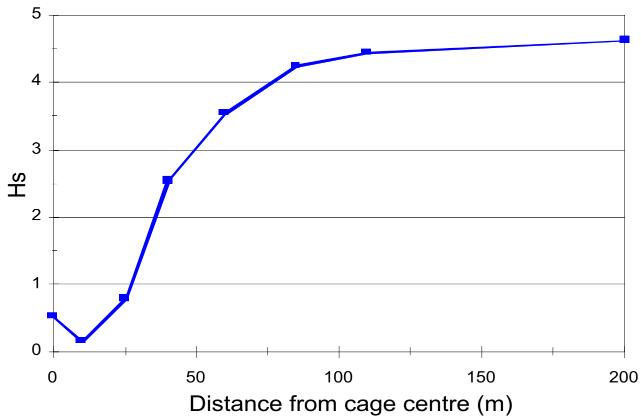

Fig. 4. Variation of the Shannon-Wiener Index of diversity (Hs) along a nutrient gradient from a Scottish salmon cage in the main direction of tidal current flow (Institute of Aquaculture, unpublished data).

There are many types of multivariate analysis and for each type many methods of analysis. Several excellent reviews of these methods are available (e.g. Kent and Coker, 1994) and many computer programs to undertake the complex mathematical analysis to produce the end result. The environmental scientist and environmental managers using these techniques for interpretation of monitoring results, has no need to fully understand the mathematics involved but merely requires an appreciation of what the techniques do and what the outputs, which are usually in the form of a diagram, show.

Two of the most commonly used multivariate techniques for analysis of community data are cluster analysis (a method of classification) and ordination. The former simply involves grouping similar entities, in terms of species composition, together in clusters which are usually presented in the form of a dendrogram. The latter endeavors to represent sample and species relationships as faithfully as possible in a low-dimensional space. The end product is usually a graph in which similar samples or species or both are near each other and dissimilar entities are far apart. Relationships between community and environmental data may be investigated directly within the ordination or using a *post hoc* statistical approach, depending on the ordination method employed.

Both approaches may be used simply to show how samples indicate impacts from fish cages at a particular time or may be used to investigate temporal variations of community composition in relation to environmental changes, including inputs from fish cages. These methods may highlight subtle changes within community structure which may have implications for multiple environmental effects, e.g. effects due to chemotherapeutants over a "background" of nutrient enrichment impacts.

An example of an ordination output, using detrended correspondence analysis (Hill and Gauch, 1980) on spatial and temporal data collected from a Scottish fish farm, is given in Fig. 5 (Institute of Aquaculture, unpublished data). This illustrates both spatial and temporal changes where the main gradient along Axis 1 has a strong correlation to nutrient enrichment with the left end stations being highly enriched and the right end stations no enrichment. Changes of the same sample station with time in the ordination space are indicated with arrows. In this case, these changes with time can be strongly correlated to biomass of fish contained in the cages. The cycle shown by the reference station (to the right of the ordination plot) illustrates community seasonality.

Multivariate analysis is useful in monitoring for interpretation purposes but also to allow environmental managers to gauge acceptable impacts in the form of AZEs. An environmental standard may be set as a community parameter or discrete grouping within a plot, thus stations appearing within this group should fall within the AZE for the site to conform to an acceptable environmental effect on sediments. Again there should be caution as though multivariate analysis is a very powerful interpretive tool to help in the decision making process, interpretation may be at least partially subjective. Therefore it should always be used in conjunction with other methods such as direct measurements and univariate analyses.

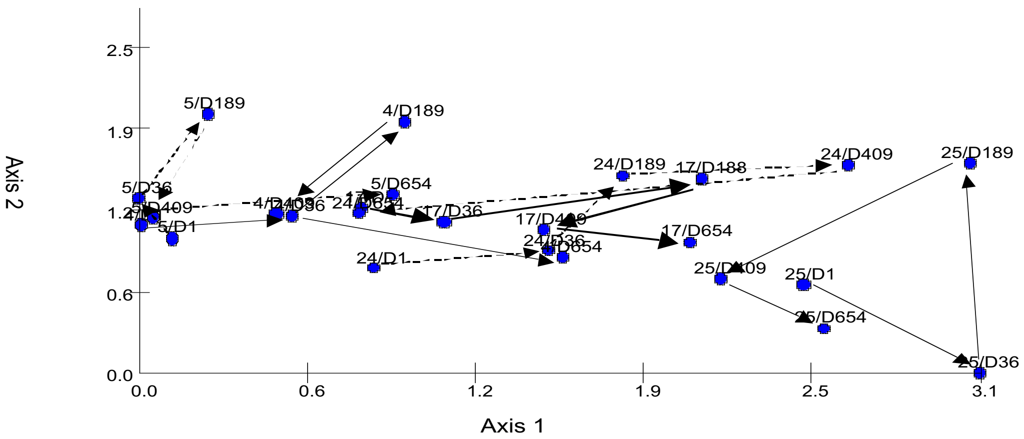

Fig. 5. Ordination plot of spatial and temporal data to investigate changes in macrobenthic faunal communities along an enrichment gradient with time. The arrows indicate the movement, within the ordination space, of the same sampling station with time. The axes give the two most significant trends shown in the data by the ordination method and may be related to environmental variables using statistical techniques.

Conclusion

A well conceived and designed monitoring programme is a highly effective method of measuring environmental change and relating these changes to inputs from fish cages; in effect, investigating impacts from these inputs. However, there are no set ways of monitoring and interpretation of the data obtained. These are dependant on the purposes and aims of the study, the size if the development, site characteristics, etc.

Monitoring is an important part in environmental management of mariculture, and in integral part of an EIA, and should be included in any mariculture regulation programme or coastal zone management plans.

This paper has been very general illustrating concepts of monitoring the marine environment in relation to aquaculture and suggesting survey and data analysis approaches. The examples call upon experience from salmon farming in northern Europe, though the general approaches given are valid for aquaculture in the Mediterranean Sea with little or no adaptation.

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References

Bergheim, A. and Asgard, T. (1996). Waste production from aquaculture. In: *Aquaculture and Water Resource Management*, Baird, D.J., Beveridge, M.C.M., Kelly, L.A. and Muir, J.F. (eds). Blackwell Science, Oxford, pp. 50-80.

Beveridge, M.C.M. (1996). *Cage Aquaculture,* 2nd edn. Fishing News Books, Oxford.

Cromey, C.J., Nickell, T.D. and Black, K.D. (2000). DEPOMOD software. A model for predicting the effects of solids deposition to the benthos from mariculture. LINK Aquaculture, UK Conference SECC, Glasgow (UK), 31 March 2000. Abstract.

Davies, I.M., Smith, P., Nickell, T.D. and Provost, P.G. (1996). Interactions between aquaculture and benthic microbiology in sea lochs. In: *Aquaculture and Sea Lochs*, Black, K.D. (ed.). Scottish Association for Marine Science, Oban, pp. 33-39.

Edwards, A. and Griffiths, C. (1996). Fish farms and the physical environment in west Scotland. In: *Aquaculture and Sea Lochs*, Black, K.D. (ed.). Scottish Association for Marine Science, Oban, pp. 33-39.

GESAMP (IMO/FAO/Unesco-IOC/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on Scientific Aspects of Marine Environmental Protection) (1996). *Monitoring the ecological effects of coastal aquaculture wastes*. Rep. Stud. GESAMP 57, 38 pp.

Gowen, R.J. and Bradbury, N.B. (1987). The ecological impact of salmonid farming in coastal waters: A review. *Oceanography and Marine Biology Annual Review*, 25: 563-575.

Gowen, R.J., Smyth, D. and Silvert, W. (1994). Modelling spatial distribution and loading of organic fish farm waste to the seabed. In: Modelling benthic impacts of organic enrichment from marine aquaculture, Hargrave, B.T. (ed.). *Can. Tech. Rep. Fish. Aquat. Sci.* 1994: xi + 125 p.

Hill, M.O. and Gauch, H.G. Jr (1980). Detrended correspondence analysis, an improved ordination technique. *Vegetatio*, 42: 47-58.

Karakassis, I., Tsapakis, M. and Hatziyanni, E. (1998). Seasonal variability in sediment profiles beneath fish farm cages in the Mediterranean. *Marine Ecology Progress Series*, 162: 243-252.

Kent, M. and Coker, P. (1994). *Vegetation Description and Analysis. A Practical Approach*. John Wiley and Sons, Chichester.

MacDougall, N. and Black, K.D. (1999). Determining sediment properties around a marine cage farm using acoustic ground discrimination; RoxAnn^{TM}. *Aquaculture Research*, 30: 451-458.

Midlen, A. and Redding, T. (1998). *Environmental Management for Aquaculture*. Chapman Hall, London.

Pearson, T.H. and Stanley, S.O. (1979). Comparative measures of redox potential of marine sediments as a rapid means of assessing the effects of organic pollution. *Marine Biology*, 53: 371-379.

Pielou, E.C. (1984). *The Interpretation of Ecological Data*. John Wiley and Sons, New York.

SEPA (1999). *Regulation and Monitoring of Marine Cage Fish Farming in Scotland. A Procedures Manual Version 1.0*. Scottish Environment Protection Agency, Stirling.

Telfer, T.C. (1995). Modelling of environmental loading: A tool to help fish cage management. *Aquaculture News*, 20: 17.

Underwood, A.J. (1991). Beyond BACI: Experimental designs for detecting human environmental impacts on temporal variations in natural populations. *Australian Journal of Marine and Freshwater Research*, 42: 569-587.

Walthern, P. (1988). *Environmental Impact Assessment: Theory and Practice*. Routledge, London, 332 pp.