ECOSYSTEMS RESEARCH REPORT 16

ISSN 1018-5593

Change in marine benthos: the case for long-term studies

B. F. Keegan, P. J. D. Lambshead, B. C. Coull
M. Overcash, C. Nolan

EUROPEAN COMMISSION

EUR 16965 EN

European Commission

ECOSYSTEMS RESEARCH REPORT No 16

Environment research programme

Change in marine benthos: the case for long-term studies

Symposium proceedings
(Glenlo Abbey, Galway, Ireland; May 1994)

Editors
B. F. Keegan, P. J. D. Lambshead, B. C. Coull
M. Overcash, C. Nolan

Directorate-General XII
Science, Research and Development

1997

EUR 16965 EN

Published by the
EUROPEAN COMMISSION

Directorate-General XII
Science, Research and Development

B-1049 Brussels

Change in marine benthos: the case for long-term studies

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This is No 16 in the **Ecosystems research report series of the Environment research programme** of the European Commission, Directorate-General for Science, Research and Development.
For more information concerning this series, please contact:

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Luxembourg: Office for Official Publications of the European Communities, 1997

ISBN 92-827-7194-7

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Printed in Portugal

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CHANGE IN MARINE BENTHOS: THE CASE FOR LONG TERM STUDIES

EXECUTIVE SUMMARY

The EU co-ordinated COST 647 Project on Coastal Benthic Ecology (1979 -1991) made the case for long term benthic studies. Clearly, this is not solely of European interest, and so a joint U.S. and European symposium was convened at Glenlo Abbey, (Galway, Ireland; May 1994) to compare experiences in this research area. The ultimate aim was to reaffirm the case for long term studies and to address related inadequacies in scientific design and funding policies. Accordingly, delegates included both scientists and representatives of funding and regulatory agencies. Papers were invited not only from benthic specialists but also from investigators who had shown the value of long term studies in cognate fields (e.g. the Continuous Plankton Recorder).

This volume records the proceedings of the symposium, and is arranged in four sections: 1) A Perspective, written by the editors, which provides an overview of the essence of the symposium and recommendations deriving form the formal presentations and attendant discussions, 2) Case Histories, incorporating examples of long term studies which give insight as to the use of their results by environmental managers and policy makers, 3) Protocols, Procedures and Methodologies, dealing with 'ways and means' and new technologies, and 4) Historical Archived Data, examining the value of traditional biological collections in addressing current environmental issues.

The principal conclusions of the symposium follow:

* The time scale for long term studies should accommodate the likely spread of natural variation if it is to permit differentiation between long and short and short term events.
* Only a long term study can determine whether a putative anthropogenic impact is 'real' or merely part of a long term natural cycle. It is critical to isolate the natural from the artificial.
* The time scale is primarily dictated by the life spans of the studied taxa which can extend form weeks to decades. It should be at least twice that of any natural cycle in the data for statistical validation.
* It is not cost-effective to treat long term study as merely a short term study

repeated through time and to use the same intensity of sampling.

* Many short term pollution monitoring surveys are of limited value since they fail to address natural temporal variability.
* With sufficient background on community structure, it may be more cost effective to focus on species which have key roles in communities.
* By concentrating on key components, it should be possible to enhance our predictive capacities in relation to whole communities.
* Rigorous quality controls on acquisition and management will greatly improve the resolution and reliability of data for intercomparability.
* Sampling intervals need to be flexible in the interests of cost effectiveness.
* Adoption of new technologies will greatly augment traditional data acquisition and can, correspondingly accelerate the turn around in reportage while reducing costs.
* Every effort must be made to promote a renaissance of interest in taxonomy.
* Efficient archiving of biological material constitutes a valuable resource for future taxonomic, biological and chemical analysis.
* Scientists and funding agencies need to harmonise their views on what is scientifically realisable, applicable, and financially sustainable from long term studies.

ACKNOWLEDGEMENTS

The organisers gratefuly acknowledge the financial and other support of the Commission of the European Communities (DG XII), the U.S. Office of Naval Research (European Office), The Natural History Museum, London, and The Martin Ryan Marine Science Institute, University College Galway.

PERSPECTIVE

Given their limited mobility or sessile life-styles, benthic animals are particularly apt foci in marine pollution effects monitoring. The EU co-ordinated COST 647 project on Coastal Benthic Ecology (1979-1991) was established to address the problems of accurately evaluating biological change in benthic taxa. Over the ensuing 12 years, the project concentrated on 1) understanding community dynamics and community responses to changes in the abundance of individual species, 2) appreciating the specific causes of biological change to permit prediction of the consequences of natural events, particularly on *key* species, 3) investigating spatial and temporal scales of natural variability, for as long as possible, to ensure that a wide range of climatic / hydrographic events were taken into account. While elements 1 and 2 could be dealt with at a local level, they benefited significantly from the co-ordinated COST approach. Element 3 became the COST hallmark, with simultaneous, intercalibrated studies of select communities (many still in a near pristine state) in a network of stations across the geographic range of each community.

When the project was initiated, the time scales and amplitudes of ecological change in the targeted communities were largely unknown. All the indications were that there might be trends or cycles extending over several years or decades, interspersed with irregular events. This was variously borne out by subsequent research. When the project was brought to a formal close in 1991, the most interesting and informative data derived from the few individual studies that had begun pre-COST. Even these exceptional 15+ year records may not have encompassed the full range of natural variability, but the various insights which they provideed on stability and change, on trends, and on processes and events of short duration, clearly demonstrate the need for long-term data. While the compilation of long term data cannot be accelerated, their interpretative significance can be greatly enhanced when they are part of a series with a wide geographical spread.

Although COST 647 ended formally in 1991, there were compelling arguments for continuing with its long term approach. The primary goal of the Glenlo Symposium was to re-affirm the value of long term studies for scientific /political decision-making such as to influence the funding of environmental research.

'Long term' is a relative concept. To a microbiologist, long term may be hours or days, but in studies of macroevolution or plate tectonics, long term

means thousands to millions of years. Ecological investigations obviously fall between these two extremes, with the duration of the time series being primarily dictated by the life spans of the studied taxa, which can extend from weeks to decades. The time scale must be at least twice that of any cycle in the data to achieve replication for statistical validation. For worthwhile results, the time scale should accommodate the likely spread of natural variation (including catastrophic events) if it is to permit differentiation between long term trends and short term fluctuations. With much of the benthos, the natural ecological cycle is likely to be considerably longer than the standard short term scientific funding cycle. The US National Science Foundation recognised the limitations of short term studies and as long ago as 1980 established the Long Term Ecological Research (LTER) program to address this problem.

The primary aspiration of long term ecological studies is to provide an appreciation of the types and scales of natural variation and to record natural long term trends. This underpins the ability to adjudicate on whether a putative anthropogenic impact is 'real' or merely part of a long term natural cycle. The environment is extremely complex, changing both spatially and temporally, and many changes occur irrespective of anthropogenic activity. From a resource management point of view, it is critical to isolate the natural from the artificial. Because the environment varies on different time scales, it is important not only to distinguish between natural and man-made changes but also between immediate, short and long term variations. We cannot study every location so it is necessary to extrapolate from representative habitats. This clearly requires an understanding of the temporal as well as the spatial processes that control specific kinds of benthic communities.

It is not cost-effective to treat a long term study as merely a short term study 'repeated through time' and attempt to use the same intensity of sampling. Inevitably, such work will always be seen as more expensive than surveys of short duration. It would be naive to expect that the same sampling frequency need be maintained throughout a long term study. To enhance cost effectiveness, the investigator should determine the minimum sampling frequency required to determine cycles, periodicities and events of interest. Resources should be allocated to intensive sampling for a preliminary period (for at least one year) with an appropriate decrease in sampling frequency thereafter. The intervention of stochastic natural or anthropogenic events may warrant a short to medium term return to intensive sampling.

Unfortunately, many short term pollution monitoring surveys are of limited

value since they fail to address natural temporal variability. Indeed, they may lead to false interpretations which could become unjustly costly for an industry when environmental law is wrongly invoked. For example, the unexpected scarcity of 1-2 year old topshells near the oil terminal port at Milford Haven, UK, was wrongly attributed to environmental degradation via oil contamination. However, and fortunately for regulatory authorities, long term and widely spaced data on population age structures showed similar scarcities over much of the species distribution throughout the British Isles. Such events, at such a scale, were caused by adverse climatic influences on larval recruitment and it was inappropriate to implicate industrial activities (Lewis pers. comm.). Another example of the use of long term data is from the pristine North Inlet, South Carolina US LTER site. On property adjacent to the reserve, developers proposed to dredge several canals. A short term study by the developers detected the dominance of the polychaete *Streblospio benedicti* in the macrobenthos which they argued was indicative of polluted waters. So, they suggested that dredging would open the channels allowing increased tidal exchange and rid the canals of the 'pollution indicator'. Long term studies in the North Inlet had shown such tidal creeks regularly became anoxic and *S. benedicti* was a naturally prominent member of the benthic community. In a court case, the judge ruled against the developer because the long term data painted a completely different picture to the short term study.

Benthos are chronically exposed to a bewildering array of contaminants which accumulate at the bottom of almost every aquatic ecosystem in the industrialised world. This is especially true in muddy sediments where toxicants may be sequestered for months to years as the hydrophobic nature of many toxicants results in accumulation. The ecological and trophic importance of benthos is well documented as is the preferably oxidised nature of their sediment microhabitat. Most benthos live in the oxic zone of sediments; few taxa can survive anoxic conditions for any length of time. This benthic habitat preference puts the community at risk to sediment-associated contaminants that are most available in the surficial sediment layers. The relatively immobile benthos are therefore the organisms of choice for environmental assessment, especially in long term studies, because they integrate a comprehensive record of habitat history. Benthos demonstrate a fidelity of association with a habitat, and per force its record of contamination, that is denied to the more mobile organisms inhabiting the water column.

With sufficient background on community structure, it may be more cost

effective to focus on certain species which by virtue of their abundance, size, shape and/or activities have key roles in communities. Key roles operate through the promotion and/or exclusion of other species and reflect the interplay of direct biological and mechanical influences. Many species, including key elements, replace each other within a particular guild or role. Such species are seen as functional equivalents and occupy broadly similar niches. By implication, the diminishing or termination of a key role can be detrimental to the community at large.

The ecological requirements and tolerances of known and suspected key species remain very sketchy. In long term studies, of broad geographic scale, it would be prudent to look to the identification of key species/roles. By concentrating on such key components, at networked sites across natural and imposed distribution gradients, it should be possible to improve our appreciation of their vulnerability to different types and scales of change. This, in turn, would enhance our predictive capacities in relation to the whole community.

Obviously, the goals of any long term study should be clearly defined, and the sampling programme tuned to the realisation of these goals. The imposition of rigorous quality controls on both data acquisition and data management will greatly improve the resolution and reliability of the data. It is also essential to incorporate 'metadata' which describes the sampling and extraction protocols and taxonomy. This allows an assessment of intercomparability between data sets. Benthic ecologists already have an advanced suite of statistical techniques at their disposal. Multivariate statistics are ecologically more sound than a univariate approach and take account of more intrinsic information than most of the traditional community 'indices'. Further, statistical ways and means are now available that allow perceived patterns in data to be interrogated for their robustness.

The application of recent advances in both pelagic and benthic sampling gear to long term studies can greatly increase the spatial and temporal scope of such studies and, thereby, increase confidence in their applicability to regional and even global scales of change. Remote sensing and imaging technologies based on photographic, video and sonic instrumentation provide a suite of techniques which, in combination, can greatly increase the geographic and ecological range of long term studies. For benthic studies, the addition of SPI (sediment profile imagery), together with still / video photography and side-scan sonar of surface biota and topography to the traditional sampling methods can greatly increase the potential information on benthic habitats. The fact remains,

however, that these traditional methods remain essentially less than effective and associated labour intensive processing constitutes a formidable obstacle in long term benthic work. The development of 3-d images of infaunal communities using short frequency sonar is a foreseeable goal which would further extend the breadth of benthic sampling as would the application of certain proven technologies, e.g. bathysnaps, automated sediment traps, remote underwater vehicles (ROVs) and geographic information sytems (GIS).

Long term studies that focus on community structure or key species will require a high level of taxonomic skill in discriminating between and within species. Operating from a strong taxonomic base, it may be more economical and sufficiently effective to determine community responses using higher taxa or ecological guilds. Given the lamentable neglect of taxonomy over the past forty years, special efforts may have to be directed towards provoking a renaissance of interest in this discipline.

Efficient archiving of biological material from long term studies is essential if the total value of such material is to be realised. This goes beyond taxonomic referencing, which remains important with the emergence of new sibling species. The continual evolution of assessment techniques means that historic material constitutes a valuable resource for future chemical and biological analysis. It is, therefore, a capital resource which should be properly evaluated and conserved. Recent techniques which analyse preserved material for biological stress illustrates the value of retaining well documented material for future use. The cost of archiving biological material, together with its qualifying data and metadata, must be accepted as an integral part of any long term study.

Traditionally, the scientific funding cycle has been limited to two to three year contracts and grants. Without assured renewals, this precludes the incorporation of a long term dimension. If significant advances are to be made in detecting and interpreting natural and anthropogenic change, funding agencies must be prepared to redress their policies and funding practises to guarantee a measure of financial stability in long term studies. However, the scientific community must recognise that there will never be adequate funds to perpetuate the typical short term investigation over the long term. The onus is on the scientists to redefine their protocols and priorities towards achieving a more cost-effective approach to work of this kind. In the first instance, scientists and funding agencies need to harmonise their views on what is scientifically realisable, applicable, and financially sustainable from long term benthic studies.

CASE HISTORIES

TEMPORAL AND SPATIAL DATA FROM THE COST 647 ROCKY LITTORAL PROGRAMME

J.R. Lewis

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Robin Hood's Bay, University of Leeds

INTRODUCTION

Fisheries and planktonic data show that marine populations change naturally on various temporal and spatial scales. But when concern arose in the 1960s and '70s over possible anthropomorphic changes among coastal benthos (the marine province most at risk from man-made influences), few data existed for valid comparative judgements, other than in obvious pollution hot-spots. Indeed, despite the fisheries/planktonic evidence, it was uncritically assumed that much of the benthos was sufficiently stable for realistic quantitative "base-lines" to be established quickly as standards against which to assess future changes (i.e. "deterioration").

Nevertheless, a nucleus of European benthic ecologists was becoming aware that the then base-line concept was simplistic, even misleading; and from their deliberations, the COST 647 project came into being in the late '70s. It had the general objective of broadening our understanding of:

(i) the extent to which community dynamics were controlled by physical events/conditions or by biological interactions; and if the latter, how the re-population and mortality rates of key interacting species are related to changes in natural conditions; and

(ii) the temporal and spatial scales of natural variability over as long a time as possible, in order that the effects of a wide range of climatic and hydrographic conditions might be observed.

The project initially comprised four coastal habitat sectors, in which individual ecologists from eleven countries of northern and western Europe participated as appropriate to their expertise. Most sought to adapt or contribute from existing programmes or to extend short-term contracts, while a fortunate few obtained national funding specifically for the purpose. Co-ordination and funding for workshops was provided by the C.E.C. in Brussels.

The separate habitat programmes evolved from existing studies so that, by

the time COST 647 was formally adopted by the C.E.C. and European Governments in 1979, several individual programmes had already started, or had been extended, and could contribute data from the early or mid-'70s.

Most such studies were involved with community structure, local physical factors or biological interactions, aspects that could be dealt with on a local level in the customary benthic manner. The novel feature of 647 was a co-ordinated approach to particular benthic targets, on a scale suitable for revealing the influence of climatic and hydrographic factors across the geographical range of the selected community or species, i.e. on an international scale.

Fuller accounts of the rationale, implementation, present status and results for all habitats are to be found in two C.E.C. publications:

(i) Space and Time Series Analysis in Coastal Benthic Ecology, 1991; and

(ii) Cost 647 - Activity Report, 1988 - 1991.

A symposium, "Long-term changes in coastal benthic ecology" was published in *Hydrobiologia*, volume 42, 1986.

Rocky littoral data

This programme evolved from personal long-term interests and benefited from the fact that this habitat is the most accessible and easily studied, that some individual organisms can be observed throughout their life-spans and that the principle interactions within its low-diversity communities soon became known. So, with a stable substrate, and by avoiding estuarine areas, the pre-COST and COST programmes were able to concentrate upon the effects of climatic and hydrographic variation on a few key species of open coasts, and especially on their reproductive and repopulation rates. As the methods and practical problems peculiar to each type of species have been fully described in Lewis (1991), the following sections deal primarily with some of the results which illustrate different types and scales of temporal and/or spatial data, and the interpretive potential or problems they present.

1. Limpets

The implicit value of long-term records in placing shorter data runs into more realistic perspective are well illustrated by those of *Patella vulgata* in the Robin Hood's Bay area of north-east England. Figure 1 shows three data sets of 10, 9 and 9 years, respectively. By most benthic standards, these sets could be

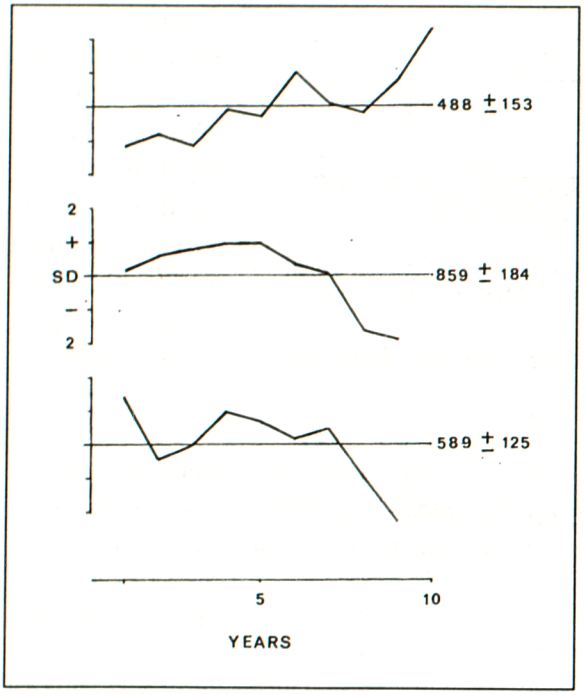


Figure 1. *Patella vulgata*. Three examples of changes in year-end total numbers/m^2, excluding spat, at Robin Hood' Bay, N.E. England

regarded as "long-term", or at least sufficiently long to indicate that both gradual and sharper changes were taking place and that it was unfortunate that recording had not continued a few years more. In actuality, these data are not concurrent at different sites, as Figure 1 would imply. They are parts 1 - 3 of a single site's 28-year record which, with re-calculated mean and standard deviations for the entire period, is shown in Figure 2. The final population in 1993 is, by chance, virtually the same as 1966-68, and the trends and oscillations in Figure 1 are the same, but have smaller amplitudes in the longer context.

This pattern of change, in which the maxima in the late '70s reached levels (up to 1,100/m.sq.) never before recorded on UK shores, requires some explanation. From the outset, data on gonad activity and repopulation rates were collected in expectation of future relevance. A high degree of recruitment synchrony soon emerged across the eight sites used, and these data from '68 to '85 have been published elsewhere (Lewis, 1991). The present Figure 3 shows means of the annual O-class maxima relative to those of year-end populations for three of those sites, with the time scale now extended to 1993*. This mean population curve is very similar to that of the single site in Figure 2, and the O-class data leave no doubt that, despite some heat and predation deaths, the major influence on population size is recruitment. Just as the long-term population record in Figure 2 put the data in Figure 1 into better perspective, so the O-class

* Limpet and barnacle data '87 to '93 exist solely because Miss R.S.Bowman is voluntarily continuing to record at selected sites despite withdrawal of all support for COST 647 by the NERC in '87.

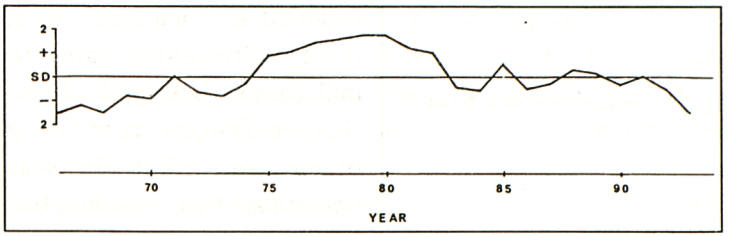


Figure 2. *P. vulgata.* 28 year changes in total numbers, from which the three short-term sequences in Figure 1 were derived.

rating of early years had to be revised later. Thus the 1970 input, which was rated "very good" in 1973, can now be seen as just "above average". The causes of such annual variation are considered briefly in a later section.

2. Barnacles

Changes in barnacle density on open coasts show much less spatial synchrony than does *Patella*, primarily because of differences in settlement. Limpet spat settle (survive?) best in the mid- to upper shore in situations that remain wet during low tide, e.g. clefts, crevices and shallow pools especially, but also between mussels and large barnacles. When the survivors emerge to become established on open rock (variously three to twelve months later), they can usually resist competition from barnacle spat and even modest mussel settlements. Thus, although the physical/biological heterogeneity causes much spatial variation in the absolute numbers of juveniles and adults along or down a shore (Lewis & Bowman, 1975), the relative constancy of the conditions controlling recruitment in each site results in the direction of the annual fluctuations being more or less similar over extensive areas, thus pointing to the operation of broader-scale factors.

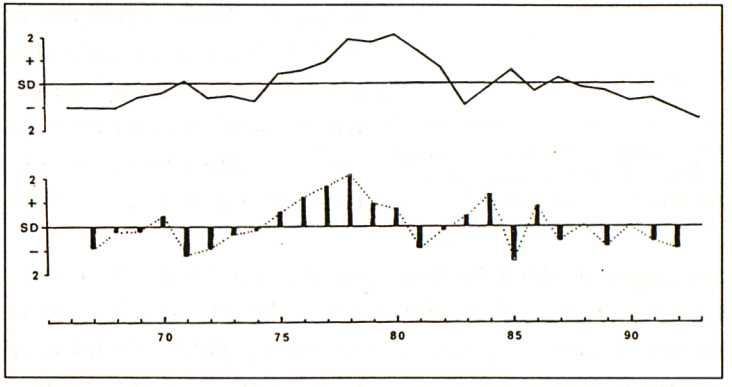


Figure 3. *P. vulgata.* Relationships between recruitment and year-end total numbers. The impact of each year's autumnal spawnings is reflected in the following year's total.

By contrast, spat of the barnacle, *Semibalanus balanoides*, settle within a four- to six-week period in spaces among adults in their drying, open rock habitat and immediately boost the total numbers (see Figs. 4A and B). Within a few months, a rapid decline usually occurs as a result of increasing intra-specific competition for space, dog-whelk predation, or being overwhelmed by mussel settlements. Thus, to explain the sequences of barnacle density in Figures 4A and B involves consideration of the space available locally before each spatfall, the initial density and annually varying growth-rate of the spat, the constantly changing abundances of other interacting species, and so on.

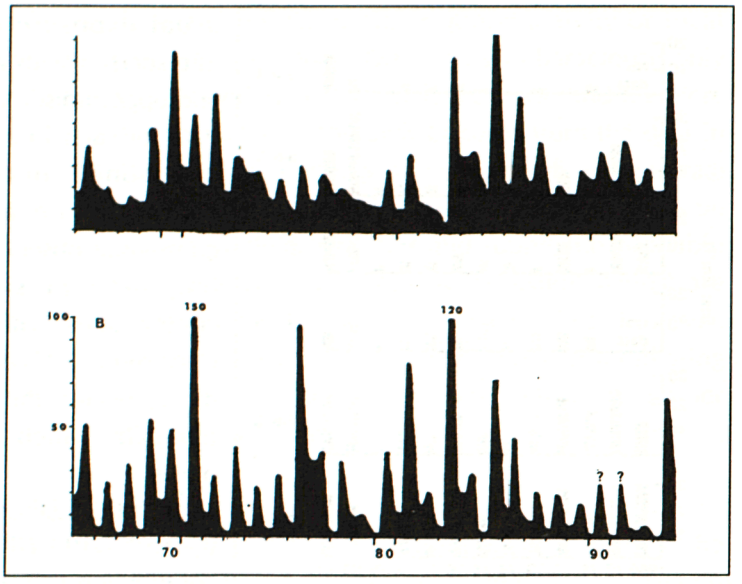


Figure 4. *Semibalanus balanoides.* Continuous record of total density (1,000s/m^2) on two sites in the upper (A) and mid (B) shore at Robin Hood' Bay, N.E. England.

The markedly different amounts of persistent barnacle cover between sites 4A and B is a direct consequence of different intensities of the interactive processes. Site 4A is in the upper shore, where generally lower rates of recruitment and growth in both barnacles and mussels result in less intra- and interspecific competition for space than in the midshore site B, which additionally is subject to dog-whelk predation. Hence site A is considerably more stable than B, the over-wintering cover of *Semibalanus* may be as high as 50-60% and individual barnacles may survive for up to six to eight years.

This tide-level gradient of an increasingly dynamic open coast system (which I first suggested in 1964 and compared with the U.S. Pacific coast situation in 1977), culminates at levels below site B in virtually unpredictable mixtures, patches or carpets, for weeks, months, or one to two years, of all the

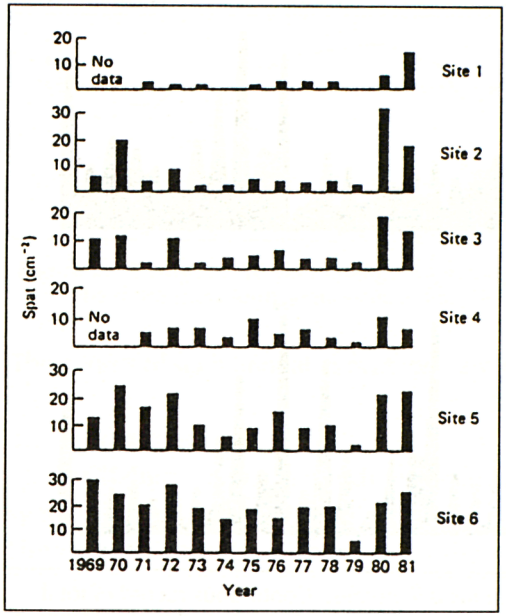
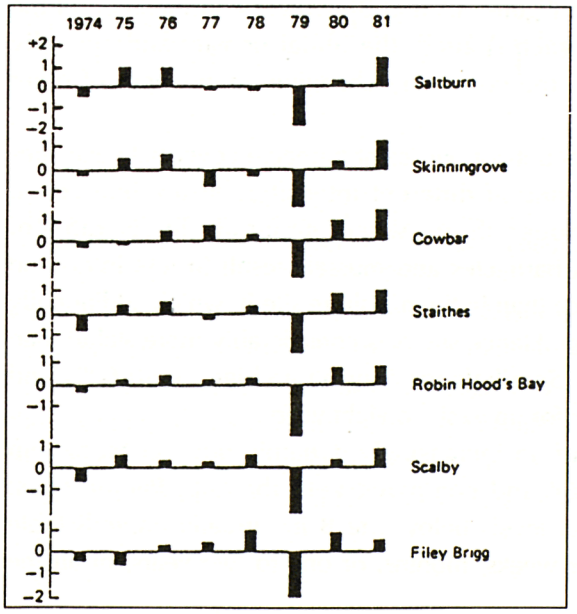


Figure 5. *S. balanoides*. Annual recruitment maxima in Robin Hood' Bay, on sites cleared before onset of settlement. Sites arranged in descending order of shore height (From Kendall *et al.*, 1985).



usual exposure-tolerant species interspersed with areas of bare rock and opportunistic algae. Quantitative data for such lower-shore sites were abandoned once the dynamic character became clear, but continuing observations confirm the long-term persistence of these communities, with the permanent(?) loss over 30 years of only one macrospecies: the alga, *Himanthalia elongata*, which was scarce at the outset.

Even at the tidal levels of Figs. 4A and B, and with 28 years' data, the contribution that annual recruitments make to the total population is obscured by the frequent lack of synchrony between sites. This is because numbers per natural site reflect the space available as much as, or more than, the overall recruitment density. To obtain the latter requires the use of experimental settlement areas, or plates, which are cleared of all barnacles just before each spatfall. Results thus obtained (Fig. 5) confirm the tide-level gradient of settlement density, and show 1979 to have been the worst recruitment year during this 13-year study.

Figure 6. *S. balanoides*. Annual recruitment maxima at sites over 100 Km of the coast of N.E. England (from Kendall *et al.*, 1985).

Inability to relate early years' results to either gonad activity or local influences upon larvae prompted the question: "Do our data characterise only this local area or are they repeated widely on the adjacent coast, and therefore reflect the operation of broad-scale factors?" The answer came from the data in Figure 6, which were being collected early enough to convincingly demonstrate how widespread was the failure of 1979. The detailed labour-intensive studies on settlement which by chance took place astride '79 and found the probable explanation for this event (cyprids driven off-shore by persistent winds) are described fully in Kendall *et al.* (1985) In the context of this workshop, however, the significant aspect of this study is the value of spatial data in facilitating distinction between the operation of local and broad-scale factors, the former possibly man-made and the latter probably natural.

3. The Geographical Component

While spatial data over a modest distance serve primarily to confirm the uniqueness or generality of local events and thereby assist interpretation, data on a much larger scale, e.g. regions hundreds of kilometres apart, permit observation of the effects of weather patterns that may be temporarily out of phase or are part of a recognisably different climatic regime. Moreover, the seasonality of reproduction in temperate zone species, whose overall distribution correlates broadly with latitudinal temperature gradients, suggests that repopulation data towards species' geographical limits might provide clues to the cause of fluctuations elsewhere. To this end, species reaching their northern limits in the UK were added to the programme.

A ten year record of such data for the Lusitanian barnacle, *Chthamalus montagui*, is shown in Table 1 for sites commencing at virtually the northern limit in Scotland, and extending 300 km to the south. These data, when associated with a very low mortality rate (8% in 4 years at and near Sites 1-3) and the ability of *Chthamalus* to survive and reproduce when transplanted well beyond its northern limit, all point to that limit being set primarily by failure at the larval or juvenile stage, rather than by population wipe-out or gonad failure.

In another case, that of the trochid gastropod, *Gibbula umbilicalis*, several years' poor recruitments were recorded about 600 km from the species' northern limit in Scotland at a site (Dale in South Wales) close to several oil terminals. With no other data, the obvious inference of oil pollution would be reached, but set in the context of Figure 7, the data from Dale are probably the southernmost,

YEAR	DOUNREAY	CLASHNESSIE	STORR	SANNA	BEASDALE
1974	0	0.04	0.01	0	1.6
1975	0.2	0.6	0.5	0.8	14.4
1976	0.01	0.01	0.05	0.4	20.0
1977	0	0.01	0.2	0.3	27.0
1978	0.04	0.1	0.2	0.06	2.8
1979	0	0.03	0.02	0.1	35.0
1980	0	0.15	0.02	0.1	1.7
1981	0	0	0	0.02	1.8
1982	0.1	0.04	0.1	0.2	16.0
1983	0.5	0.9	0.8	3.6	30.0

Table 1:
Chthamalus montagui. Densities per square cm of recent settlers in November of each year, between locations ranging from *ca* 30 km (Dounreay) to *ca* 300 km (Beasdale) from the species' northern limit of distribution in northern Scotland. The Beasdale figures probably also reflect the funnelling of larvae by wind and coastal configuration into an embayed, warmer situation.

if less dramatic, components of an extensive natural picture, the spatial and temporal scales of which must surely reflect climatic events.

The limpet, *Patella vulgata*, in the UK is far from its geographical limits (Norway and Portugal), and the regional data for this species contained less dramatic, more subtle, information. Synchronous recruitment within individual regions of Scotland was confirmed strongly in some cases (Figure 8), rather less so in another, but even so, was still detectable between regions at least 300 km apart (Grant, 1991). Figure 9 shows a summary of Scottish recruitments relative to those for Robin Hood's Bay (up to 1985). But the most valuable regional data contributing towards an understanding of the controlling processes was the emergence of latitudinal patterns in development and duration of gonad activity, date and frequency of spawning(s), and times of successful settlements.

As these and other data became available, firstly from S.W. England and then from Spain and Portugal (through COST colleagues*), it has become clear that the six species involved (5 gastropods and *Chthamalus*) will be characterised

* See Bode et al., Guadencio & Guerra, Guerra & Guadencio, Ibanez et al., and Myares, all 1986.

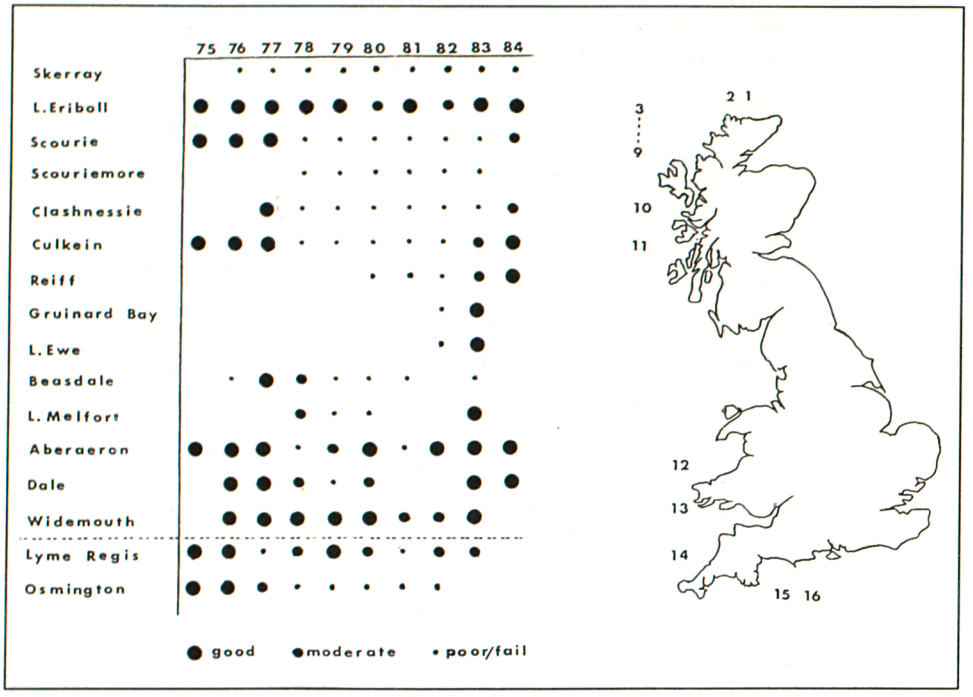


Figure 7. *Gibbula umbilicalis*. Assessments, based on late spring samples, of the strength of annual recruitment around British coasts between 1975 and 1984. Skerray, Site 1, approximates to the northern limit of distribution and Osmington, Site 16, to the eastern limit of the south coast. The unique regularity of recruitment of Site 2, Loch Eriboll, reflects an unusual combination of physical factors, including summer sea temperatures at least 1° - 2°C higher than other localities in northern Scotland (based on Kendall & Lewis, 1986).

to greater or lesser extents by: short mid-summer breeding, intermittently very poor recruitment but long life-span and large size to the north of their range; and, to the south, by a switch to autumn/winter breeding periods of much longer duration, the near certainty of at least one successful spatfall annually but short individual life-spans and small size. Thus population stability rests on individual longevity northwards and high recruitment southwards.

Hypothesising about the significance and underlying causes of such latitudinal patterns led on to very detailed observations and experiments (where possible) into gonad cycles, spawning frequency and environmental triggers, larval and juvenile tolerances, growth rates and survival, all relative to annually varying temperatures of both sea and air (for littoral species). These facets and their outcome (Lewis, 1986; 1991) are not relevant to this workshop, but it is appropriate to draw attention to the following:

(i) Seeking regional data to confirm that climatic factors were involved led to the recognition of the latitudinal gradients which, more than anything else, focused attention upon what are proving to be the weakest links in the repopulating process, i.e. the limited temperature tolerances of settlers and very young juveniles.

(ii) Despite limited success with laboratory experiments, such understanding and predictive ability as were gained came mainly from intensive field observation, and being therefore dependent upon an annual succession of random "natural experiments", it was essential to have continuity in the same locality. Thus, long-term data not only set the grosser events into better perspective, they may also be essential when seeking to identify the causes of those events.

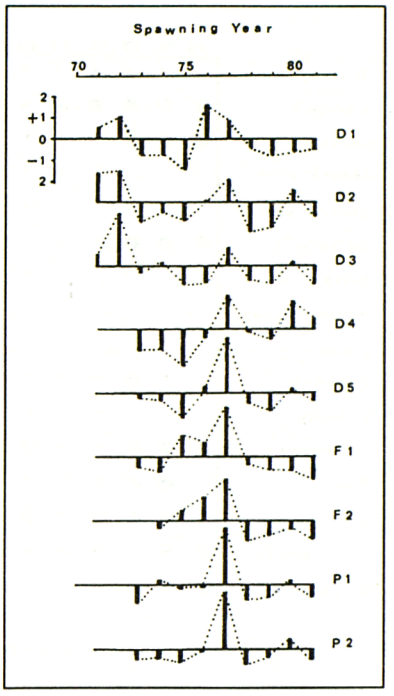


Figure 8. *Patella vulgata.* Recruitment at stations along approximately 14 km of the north coast of Scotland (Caithness).

(iii) The temperature sensitivity of settlers and juveniles and the implication that geographical limits, especially the northern, are set primarily by inadequate repopulation rates, provide us with a potentially very sensitive indicator of the scale of climatic change. A sustained rise in temperature in the northern hemisphere could lead to more regular and higher rates of repopulation near northern limits, followed rapidly by obvious changes in age structure and thence to progressive extensions of range.

Postscript: interpreting a pollution incident

Wherever possible, regional sites were established in areas deemed unlikely to experience human impacts, but one area at Dounreay in northern

Scotland unexpectedly led to a "before and after" pollution study which illustrated the potential for misinterpretation. The biological consequences of this small oil-spill from a small shore-line naval establishment in February 1977 have been fully described in Bowman (1978): firstly, as if through the eyes of a visiting assessor and, secondly, through those of one with experience on these shores since 1971.

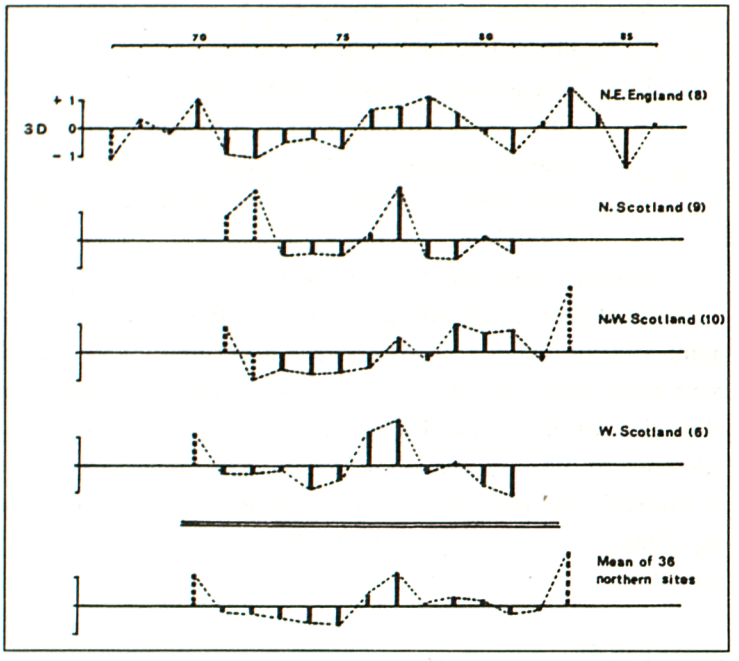


Figure 9. *Patella vulgata*. Summaries of the mean recruitment variations in N.E. England and three Scottish regions (numbers in brackets indicating the individual sites in each region) plus the balance of all the above sites (and three more isolated Scottish sites). A broken column indicates an incomplete total of sites. Dates relate to spawning year (from Lewis, 1991).

The two versions have a few conclusions in common: the deaths of about 1,000 seabirds and of littoral snails physically engulfed in oil. But most of the other shoreline mortalities that appeared attributable to oil or dispersal were scaled down appreciably or fully discounted in the second version for diverse reasons:

i). Considerable and very unusual mortality had occurred in the upper half of the shore on open rock and in shallow pools during the previous very hot summer ('76). This was still evidenced by the presence of many oiled but empty barnacle shells, and by white encrustations of dead calcareous algae with conspicuously vacant limpet 'scars';

ii). Heavy predation in the lower shore of medium to large limpets

(except those in deep pools) had been regularly caused by a large local flock of oyster-catchers;

iii). The scarcity in March of the '76/77 class of limpets reflected, for one species, a similar scarcity elsewhere in northern Scotland that season, and for the other species, slow growth of juveniles and their late emergence from settling niches as a result of adverse winter conditions.

Having prior data for an affected site clearly allows more reliable assessment than is usually possible, and the local bird predation is a case in point. But the major source of putative misinterpretation in this instance would have been ignorance of the effects of the preceding summer and winter. Since climatic events are not highly localised, neither are their consequences, so reference to other shores in the region would have largely compensated for lack of pre-spill site data at this particular location. The more so if reinforced by experience of the biological interactions prevailing and the subtleties of limpet recruitment.

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COMPARATIVE LONG-TERM ECOLOGICAL RESEARCH OF A RELATIVELY PRISTINE ESTUARY AND A MAN-IMPACTED ESTUARY

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Key words: Long-term research, North Inlet estuary, Murrells Inlet estuary, resource management, comparative ecosystem studies, urbanization effects.

ABSTRACT

The importance of long-term studies to the development of environmental sciences has long been stressed, but the utilization of the results of these studies by environmental managers and policy makers has received less attention. The objectives of the investigations described in this study are to provide scientific bases for resource managers to make decisions relating to coastal environments.

Two estuarine systems in South Carolina, USA, have been studied extensively. Both are located in the same geographic area and have similarities (i.e. size, geological history, species composition, habitat types, climatic conditions). However, they both vary in the degree of upland development. North Inlet estuary, the more pristine system, has been part of the National Science Foundation's Long-term Ecological Research Program (LTER) since 1979. The past four years the environmental dynamics of the Murrells Inlet estuary, which has been subject to intense utilization of its uplands and water as a site for construction of recreational housing (cottages, condominiums), restaurants, and marinas, has been studied and compared to those of North Inlet. Thus, in a general sense, North Inlet serves as a "control site" and Murrells Inlet may be regarded as an "experimental site."

As background to this case study, the national LTER program is briefly reviewed and the database and data management programs for North Inlet are described in general. Although Murrells Inlet has been studied for a shorter period of time, similar sampling and analytical procedures are used and the comparative data on a temporal and spatial basis from these two estuaries are incorporated

into a Geographical Information System.

Although long-term studies have advanced our ecological understanding of how systems function, numerous problems need to be overcome in order to bridge the communication gap existing between environmental policy makers and environmental scientists in order to utilize LTER data in formulating better science-based resource and environmental protection policies.

A number of examples of how the results of long-term ecological research have helped answer questions of temporal variability were presented. In addition, comparative studies involving Murrell's Inlet and North Inlet demonstrated the impact of urbanization on system characteristics.

INTRODUCTION

Over the past 25 years, there has been an edver-increasing awareness of the often destructive impact of human populations on the environment. Degradation of the environment has occurred not only on a local scale but also on a regional and global scale. Over the past 25 years spatial and temporal measurements of pollution effects have been documented in both the scientific literature and the popular media (Vernberg *et al.*, 1981; Vernberg *et al.*, 1987; Beukema *et al.*, 1992; Kennish, 1992). Although progress has been made in understanding the scientific bases of the causes, effects and fate of pollutants at various levels of biological organization, the complexity of the environment urgently demands a more comprehensive, integrative approach to be taken to protect and manage the earth's resources. One trend in addressing this complex problem is to develop a management strategy focusing on the ecosystem rather than on the management of one or two species (Costanza *et al.*, 1992; Slocombe, 1993). To focus on only one species inevitably results in overlooking other segments of the total ecosystem which are of great importance.

At the same time that the scientific basis for delineating pollution effects on the natural environment is being studied, regulatory agencies are attempting to develop regulations and plans designed to protect and manage the environment. The interactions between the scientific community and the environmental managers have been good in certain areas, but a continuing need for greater integration and understanding is required. This need is becoming more widely recognized. One of the principal purposes of this meeting is to examine the influence of long-term ecological studies both on science and on policy.

It is recognized that the environment is extremely complex, changing both

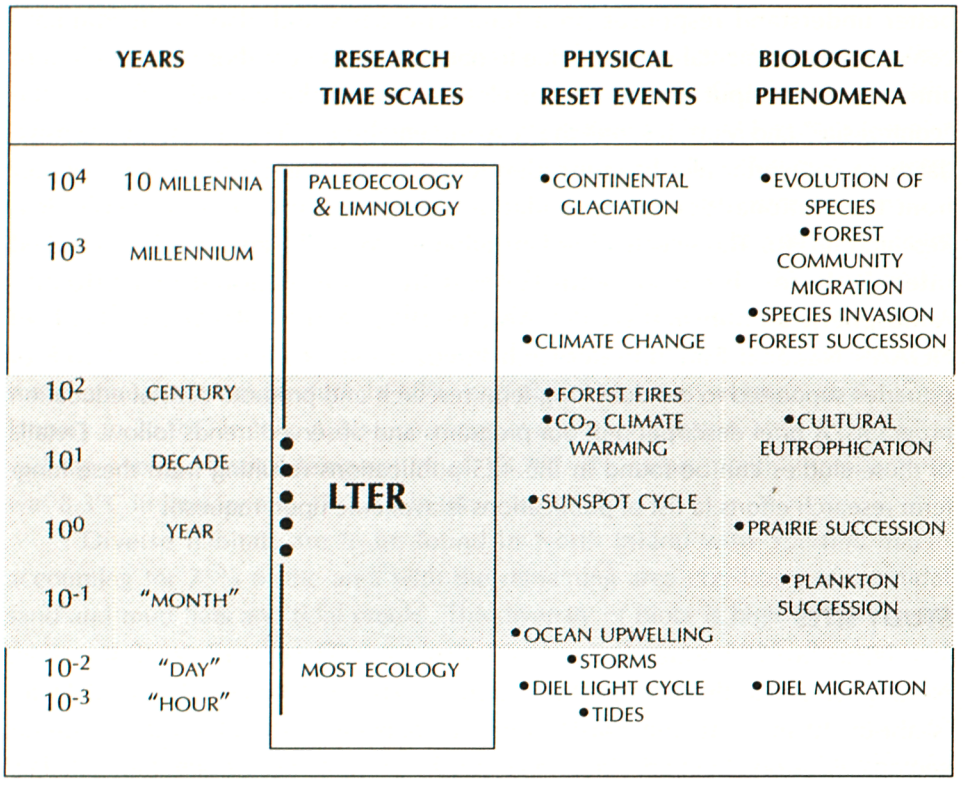

Figure 1. The long-term ecological research program in relation to time scales relevant to various physical events and biological phenomena (modified from Magnuson, 1990).

spatially and temporally. Many of these changes would occur whether humans are present or not. Hence it is important to be able to isolate natural fluctuations from those man-induced ones, especially from a resource management viewpoint. Because the environment can vary on different time scales ranging from less than minutes to thousands of years (Fig. 1), it is important not only to distinguish between natural and man-induced changes but also understand differences between immediate, short- and long-term variations.

One of the objectives of this paper is to present a case study comparing responses to environmental changes over a period of time in two similar estuarine ecosystems. These two systems are geographically located near each other and the principal difference between the two is that one estuary (Murrell's Island) has been impacted by human activities while the other (North Inlet) is relatively pristine. Using this comparative ecosystem, research approach permits us to

better understand responses on a long-term basis and also to discriminate between environmental variation due to natural causes from those that result from anthropogenic input. In this sense, North Inlet can be considered to be the "control site" and Murrell's Inlet the "experimental site". Since 1979, an extensive database for North Inlet has been developed which was obtained with support from the National Science Foundation's Program in Long-term Ecological Research (LTER). The effects of urbanization on Murrell's Inlet has been studied intensively for five years with support from the National Oceanic and Atmospheric Administration (NOAA). In 1992, North Inlet became part of NOAA's National Estuarine Research Program (NERR), a national network of estuaries supported to conduct long-term research and promote coastal education programs. A brief description of our programs and observed trends follow. Details of these studies can be found in the 425 publications resulting from these long-term research efforts (a list of publications is available upon request).

STUDY SITES

The two estuarine systems are located on the coast of South Carolina: North Inlet is near the city of Georgetown (33°20', 79°10' W) and Murrell's Inlet is about 20 miles to the north. Both are bar-built estuaries with a similar geological history. Both are similar in size (about 3,200 ha) and are dominated by extensive stands of *Spartina alterniflora* which are dissected by many tidal creeks. These two systems are representative of many similar estuaries located in the southeastern region of the United States. It is estimated that there are more than 320 small, high-salinity inlets, creeks and estuaries in the area between Cape Fear, North Carolina and Cape Canaveral, Florida (Vernberg *et al.*, 1992). Nearly half of these habitats are located in South Carolina. The total area of these small-sized estuaries exceeds the total combined area of larger South Carolina estuarine systems (Winyah Bay, Santee River delta, Charleston Harbour and Port Royal Sound). However, these areas, which have received little scientific attention, represent important habitats for natural resources (i.e. fisheries) and are prime sites for development of accommodations for tourists and permanent residents. Hence, because these areas are important resources and little is known about their ecosystem dynamics, there is a pressing need to develop strategies to manage them before irreversible damage takes place resulting from urbanization.

North Inlet

In general this is a high salinity estuary with a mean monthly concentration ranging from 29.5 parts per thousand in May to 34.4 ppt in October. It is a well-mixed body of water with a mean semidiurnal tide range of 1.6 m. Mean water depth of the major tidal creeks is 3 m (the greatest depth is 7.4 m) and water velocities seldom exceed 2.3 m/s^{-1}. Because of limited freshwater input, water movement within North Inlet is dominated by tidal pumping and water level variation. The watershed drains primarily forested uplands to the west and a moderately developed watershed to the north. To the east, the North Inlet is bounded by sandy barrier islands and to the south is located Winyah Bay. The mean annual air temperature is 18°C and the range is an average of 8.4°C in January to 26.9°C in July. A 10-year range of water temperature was 4°C to 32°C with an average annual temperature of 18.7°C (the mean monthly temperature was 8.3°C in January and 27.22°C in July).

Diverse habitats are to be found in North Inland with *Spartina* marsh accounting for 75% of the area with the remaining area consisting of intertidal sand and mud flats and tidal creeks. The diversity of biota is high in the coastal regime of South Carolina (Zingmark, 1978; Fox & Ruppert, 1985; Ruppert and Fox, 1988). For example, 832 species of phytoplankton have been identified, 358 species of benthic marine algae, 66 species of saltwater vascular plants, 123 species of Cnidaria, 385 species of marine mollusks, 68 species of copepods, 272 species of decapod crustaceans, 344 species of Osteichthyes and 430 species of birds.

The uplands land use within the North Inlet Estuary basin are primarily forested or undeveloped land (89.6 km^2) with wetlands occupying 52.6 km^2. Residential areas are 1.1 km^2 in surface area and are restricted to a small region to the north. Most of the upland surrounding North Inlet is owned by the Belle W. Baruch Foundation or the Yawkey Foundation and these foundations have established their lands in perpetuity for research and education and not to be developed.

Murrell's Inlet

Murrell's Inlet has very similar characteristics as those of North Inlet. The principal difference is that the uplands surrounding the 13 km^2 border of the marshlands have been highly developed to meet residential and tourist demands. In addition, portions of the waterways have been dredged, bulkheads constructed,

DATA SET TITLE	INITIATION DATE	NO. OF PARAMETERS	SAMPLING FREQUENCY
Climate/water	6/3/82	9	Continuously
National weather service (2 stations)	12/1/86	4	Continuously
Nutrient chemistry	9/1/78	11	Daily
Chlorophyll/ Phaeophytin	9/8/78	2	Daily
Suspended sediments	2/12/81	5	Daily
Rainfall chemistry	5/26/83	13	Variable
Sediment & erosion	6/1/90	4	Monthly
Spartina production	5/1/84	1	Seasonally
Macrobenthos	1/20/81	56	Biweekly
Meiobenthos	9/1/72	12	Biweekly
Motile epibenthos	1/20/81	91	Biweekly
Fishes, shrimps, crabs	4/15/83	188	Biweekly
Zooplankton	1/20/81	65	Biweekly
White Ibis	6/1/84	3	Spring
Feeding/nesting	5/1/79	2	Summer

Table 1 North Inlet long-term data sets.

marinas have been built, and a jetty constructed at the mouth of the inlet. The watershed draining into Murrell's Inlet is less extensive than that of North Inlet due to upland modifications such as highway construction and ditching. In addition, the water quality of upland run-off waters have been influenced by human activities including run-off of hydrocarbons from roads, herbicides, nutrients and pesticides from home owners' use, and from septic tanks.

DATABASE CHARACTERISTICS

Although a comprehensive program of collecting data on numerous components of the North Inlet estuary was initiated and maintained only after our program became an LTER site in 1979 and later an NERR-NOAA site, some individual data sets were in existence from 1970. The existence of a long-term data set on a limited number of components of an ecosystem is valuable but, because of the complexity and interconnectivity of various segments of an ecosystem, a comprehensive database is needed. Unfortunately, environmental scientists are not always sure of the parameters needed for measurement or the frequency these measurements should be made. Table 1 lists the available long-term data sets and includes the initiation date, the number of parameters measured, and the frequency of sampling. The frequency of sampling varied from continuous recording of various chemical and physical factors (i.e. salinity, air and water temperature, and wind speed and direction) by sensors in the meteorological station, the daily water sampling, biweekly faunal sampling and irregular events such as Hurricane Hugo in 1989. These data sets are available to those scientists and regulatory agencies who have a need for them by contacting the Baruch Institute. An essential feature of a database which is meaningful and useful is to have a well developed data management system.

The North Inlet Database Management Facility represents an integral component of the LTER research effort which supports the following activities: (1) data entry (full screen entry program development and supervision of data entry); (2) quality assurance of the database; (3) data archival (tape, mass storage, etc.); (4) data documentation and database security; (5) intrasite communciation (coastal LAN file exchange with campus, etc.) and intersite exchange (BITNET, tapes, etc.); (6) hardware and software maintenance; (7) personnel training and consulting services (visitors, students, etc.) and (8) ancillary activities necessary for maintenance and accessibility of LTER data.

Data management activities related to data entry include the development of full screen entry programs, hardware and software support for automatic data acquisition systems (e.g. the meteorological station, Technicon auto-analyzers, etc.) and supervision of data entry personnel. Full screen entry programs are designed by data management personnel in conjunction with the investigators and technical staff. Data entry screens mirror the field and laboratory data sheets used by technicians to record observations. Full screen entry programs have greatly reduced the time required for both data entry and verification.

Quality assurance includes many of the activities routinely associated with data entry (maintenance, testing, full screen entry program development, etc.). Additional quality assurance procedures are associated with both the biological and physical/chemical data sets. All data entered at computer terminals or microcomputers are manually verified. Numerous quality assurance checks are built into the full screen entry programs. Additional quality assurance programs have been written for all core LTER data sets. These programs provide a printout of the data set which mimics the field or laboratory data entry sheet as well as checks for outliers. When possible, checksum techniques are employed to calculate categorical sums and compare with those values calculated and entered by the primary technicians. These techniques have been particularly valuable in flagging errors which are not identified by visual verification. Post-entry graphics and statistics programs are also employed to identify potential outliers.

Particular attention is paid to data archival throughout the process from data entry to analysis. All field and laboratory data sheets are xeroxed and the originals are stored in flame-proof cabinets. Data sets being entered via the microcomputer full screen entry programs are routinely backed up onto floppy disks. Once verified for correctness and completeness, all data sets are transferred to the Baruch Database which resides with the University of South Carolina's Auxiliary Disk Storage Facility and backed up onto standard 9 track 6250 bpi tapes. Tapes are read once per year to verify redundant archival. Database security includes redundant backup and password protection of accounts and storage access.

Data set documentation is an integral part of any data management system developed for long-term studies. The database catalog designed for the LTER project's various data sets has two levels of documentation. Level I documentation contains information about the project or experiment which generated a particular data set (i.e. data set title, principal investigator(s), project abstract, keywords, core research questions being addressed, temporal and spatial resolution and proprietary limits). All Level I documentation is accessible to interested individuals for their examination. If more information is desired, the Level II documentation can be retrieved and a hard copy generated. Level II documentation contains detailed information about a particular data set. This documentation is designed to provide secondary users with enough information to fully understand the conditions under which the data set was generated as well as information necessary to access and utilize the data. Any individual or

institution may access data sets collected under auspices of the North Inlet LTER Project after receiving written authorization from the principal investigator.

A review of the scientific literature on long-term databases for coastal and estuarine environments indicates that the North Inlet database and the Appalachicola River Basin, Florida have two of the most comprehensive in existence (Callahan, 1984; Livingston, 1984; Holladn & Kjerfve, 1985; champ *et al.*, 1987; Edwardsx & Coull, 1987; Allen & Barker, 1990; Franklin *et al.*, 1990; Service & Feller, 1992).

LONG-TERM SYSTEM RESPONSES OF NORTH INLET

Within the scope of the present paper, it is not possible to present a detailed discussion of long-term variability of the North Inlet estuarine system. Hence the following are a few examples to illustrate some temporal trends exhibited by different ecosystem components.

Dame and Kenny (1986) studied the total primary production (above and below-ground production) of *Spartina* in a southeastern U.S. estuary (North Inlet, S.C.) over a four-year period. Monthly samples were taken from three habitat types: creekside (tall growth form), midmarsh (medium height form) and highmarsh (short growth form). The three areas exhibited seasonal patterns. Above-ground, live biomass was most abundant in late summer and early fall, and the maximum amount of live below-ground biomass was found in the fall. Net above-ground primary production was highest at the creekside site (2069 g/m^2 per year), next highest in the highmarsh (1113 g/m^2 per year) and lowest in the midmarsh (649 g/m^2 per year). Year-to-year values varied about 25% for the creekside site, 12% for midmarsh and 3% for highmarsh. Creekside live biomass was higher during the years following depressed winter-spring salinities, which appears to be correlated with increased rainfall. Although Dame and Kenny pointed out the difficulty in comparing production values for different estuaries because of the differences in sampling techniques, these data demonstrate the existence of the potential for monthly and annual variation. When attemptin to study the influence of human disturbances on wetlands, it is important to consider that differences in production values may be due to long-term variations in normal environmental factors that influence production and may not be entirely the result of human-induced perturbations.

Additional studies by Morris and Haskin (1990) further supported the results of Dame and Kenny (1986) that marked interannual variation exists in

above-ground productivity of *Spartina* in North Inlet. Morris and Haskin found a statistically significant relationship between stem age and cumulative leaf loss when used to estimate leaf turnover. They reported positive correlations of primary production and mean sea level and/or rainfall and the effect of these factors on sediment salinity was suggested to be the proximate determinant of interannual variation in production.

Some environmental changes occur on an irregular basis and can dramatically influence estuarine dynamics. Physical oceanographers have reported that along the Atlantic and Gulf coasts of North America anomalies in mean sea level can occur seasonally, resulting in temporary fluctuations of 30 cm. Morris *et al.* (1990) suggested that, if the anomalies occur during the growin season, the above-ground productivity of *Spartina* increases by a factor of two and that the commercial landings of two estuarine dependcent species (shrimp and menhaden) increased. They suggested that increased mean sea level flooded more of the tital marshes and increased the amount of habitat for organisms dependent on marsh for food and predator avoidance. In addition the pore water salinity of the upper marshes decreased; this serves as a stimulus to *Spartina* production.

Gardner *et al.* (1989) analyzed a nearly continuous time series of organic and inorganic suspended sediment measurements taken daily over almost five years at three separate sites in the North Inlet estuary. To assist in the interpretation of these data, they also examined synchronous daily measurements of POC, water temperature, salinity, tide height, Secchi disk, air temperature, wind speed and direction and rainfall. Using power spectrum analysis of these data, they found that most of the explainable variance in the inorganic suspended sediment, POC, and Secchi disk data was related to a yearly cycle strongly correlated with water temperature, i.e. high tubidity was associated with frequencies that could be related to the semidiurnal tide. Simple correlation analysis indicated that turbidity was more closely associated with water temperature than with tide height or salinity. From their results, they hypothesized that temperature-regulated bioturbation was the main factor controlling turbidity variations in the system. The lack of a strong inverse correlation between turbidity and salinity suggested that river runoff had little immediate impact on the suspended sediment of near-shore coastal waters in ecological systems similar to the North Inlet. They speculated that this marsh/estuarine system acts like a lung, exhaling suspended sediment into the coastal ocean during the summer and

inhaling it during the winter.

Another example of LTER studies is the work of Spurrier and Kjerfve (1988) who developed midels to estimate the net flux of nutrients between a salt marsh and a tidal creek on a tidal cycle basis and an annual basis. When considering a year as a finite population of tidal cycles, they found that the marsh was a statistically significant sink for nitrogen (dissolved nitrate plus nitrate) from adjacent tidal creeks.

Nitrogen fixation is a dynamic process influenced by various environmental factors such as light, temperature, redox potential, carbon substrate availability, and inorganic nitrogen concentrations. Because of the number of variables, field estimates of nitrogen fixation rates have been difficult to make. Whiting and Morris (1986) developed a temperature-controlled chamber for the *in situ* determination of nitrogen fixation (acetylene reduction) in a vegetated salt marsh (North Inlet estuary, SC). They found a positive correlation between seasonal temperature values and the rates of acetylene reduction activity (ARA) in three zones of a vegetated salt marsh. Spatial variability in ARA within the salt marsh was observed, suggesting differences in the variables influencing nitrogen fixation in these three zones.

Zingmark (in Vernberg, 1989) reported the following long-term trends in phytoplankton dynamics. Chlorophyll-*a* correlates highly with carbon-14 uptake during all seasons and is thus an excellent predictor of phytoplankton productivity in the North Inlet estuary. Reasonably accurate estimates of annual phytoplankton productivity can be modeled by considering the rate of photosynthesis as a function of light, the depth of the euphotic zone, and the diurnal variations in solar irradiance during the year. Five years of daily sampling indicates diurnal and seasonal variations in phytoplankton biomass (chlorophyll-*a*) that predict similar changes in productivity. Although phytoplankton productivity varies seasonally, the annual rate has remained similar from year to year. Depth-integrated (areal) productivity was correlated primarily with light and temperature rather than with nutrients and salinity. Thus it was suggested that most of the time the production of phytoplankton is not nutrient limited.

Eleven years of monthly (or fortnightly) meiofauna abundance and physical variable data at 2 subtidal estuarine sites (sand and mud) in South Carolina, USA, suggest that complex interactions control faunal abundance (Coull, 1985). At the mud site, abundance peaked in late winter/early spring, reaching over 1800 meiofauna 10 cm^{-2}; seasonal abundance was correlated with salinity changes. In

sand, abundance peaked in mid-summer and was positively correlated with temperature (an negatively with RPD). Variability in abundance at the mud site was approximately twice that of the sand site, and year to year variability was greater at both sites than the inherent seasonality. There were no long-term cycles in the fauna or temperature/salinity at either site; 12 mo was the period recurrent through the data set. The period 1975 - 1977 had the highest abundances at both sites, but these peaks were not correlated with any of the measured (or obtained) physical variables. Grain size at the sand site decreased in the 1980's and there was a concomitant decrease in the abundance of copepods and an increase in the nematode/copepod ratio.

Analyses of seasonal and yearly samples of subtidal macrobenthic fauna collected biweekly at a sandy site and a muddy site for five years show large fluctuations in abundance and high variability between replicate samples (Service & Feller, 1992). Despite seasonal and interannual variability, the fauna at both sites exhibited long-term stability in abundance. Allen and Barker (1990) studied interannual variation in larval recruitment of 45 fish species to epibenthic habitats over the period 1981-1985. Samples were culled biweekly. For every major taxon, date of arrival, duration of recruitment period and size distribution were similar among years. Although the arrival of early stage larvae was continuous within each annual period, patterns of abundance were not consistent. They suggested that factors controlling larval fish recruitment and fluctuations in abundance operated on a large spatial scale and that the magnitude of utilization of epibenthic habitats was important.

In 1989, the eye of Hurricane Hugo passed over the North Inlet estuary providing an opportunity to examine salt marsh ecosystem responses to a system-wide perturbation. In general, the salt marsh ecosystem demonstrated its resilience to disturbance. Primary and secondary productivity patterns in the marsh observed prior to Hugo remained unchanged or were quickly re-established after the hurricane passed. However, the structure of both the barrier island complex and the adjacent coastal forest was significantly altered. In particular, the systems were affected by wind damage, salt water inundation, and increased susceptibility to biotic disturbances. Results suggest that portions of the salt damaged forest will not recover and will probably be permanently converted into high marsh, the first stage of marsh development.

COMPARISON OF NORTH INLET ESTUARY AND MURRELL'S INLET ESTUARY

Because the thrust of the present paper is to emphasize long-term studies, only a few examples of distinctive differences between North Inlet and Murrell's Inlet are presented which demonstrate the influence of urbanization on estuaries. In general, the following data were the results of analyzing samples from a total of 60 sites in the two estuaries.

Nitrate and phosphate concentrations in water were statistically higher in Murrell's Inlet than in North Inlet (Vernberg *et al.*, 1992). Although the nitrate concentration was elevated in Murrell's Inlet, it was not sufficiently high to result in eutrophication. The source of the excess nitrate and phosphate was probably from surface run-off from the adjacent developed land and from septic tanks. By contrast, the ammonium concentration at the landward collection sites in North Inlet were higher than from similar sites in Murrell's Inlet. This difference appears to result because of greater stream run-off from the forested highlands surrounding North Inlet while much of the run-off from Murrell's Inlet enters impoundments before entering the estuary. In the impoundments, vegetation removes much of the ammonium. At high tide, the dissolved oxygen concentration at Murrell's Inlet was lower than that in North Inlet. Of particular interest is the finding that at low tide the dissolved oxygen concentration in certain undisturbed regions of North Inlet may be extremely low. This observation brings into question the advisability of using low oxygen concentration as an indicator of poor water quality resulting from human activities when it can occur as a normal response in estuarine waters.

A number of differences in chemical contaminant levels in water and animal tissues (oysters) between the two estuaries were noted. For example, total polycyclic aromatic hydrocarbons (PAH), chemicals associated with automobiles and fossil fuel emissions, were found in higher concentrations in both water and oyster tissues collected from Murrell's Inlet. Those oysters in Murrell's Inlet found closest to regions of land run-off had higher levels of PAHs than those located in more distant sites. Similar results were observed when analyzing samples for copper. Both PAHs and copper have been shown to have lethal and sublethal effects on organisms and their accumulation in animal tissues assists in transfer to other trophic levels in estuarine food webs.

Estimates of total annual biomass of macropelagic fauna showed marked interestuarine differences: Murrell's Inlet had lower biomass values than North Inlet. This difference could be the result of several factors acting independently or

in concert. Chemical contaminant loads in Murrell's Inlet are higher than those in North Inlet, although these loads are generally below laboratory-established lethal levels. Another strong possibility is related to the greater amount of habitat loss in Murrell's Inlet resulting from dredging and filling of *Spartina* dominated salt marshes.

Utilizing long-term data sets for North Inlet coupled with comparative sampling of the two estuaries provided a basis for suggesting that the observed differences were due to the impact of urbanization on Murrell's Inlet and not the result of natural, interannual variation in environmental conditions.

Although still in the developmental phase, spatial and temporal data is being utilized to produce a Geographic Information System (GIS) based non-point source (NPS) pollution surface run-off model for the watersheds within Murrell's Inlet and North Inlet. After an assessment of approximately 30 available NPS pollution models, the Agricultural Non-point Source (AGNPS) model was selected for use in this study. The goal is to have a model which can readily be used by policy makers and resource managers. For a general discussion of GIS, see the excellent paper of Professor Clark in this volume.

RELEVANCE OF LONG-TERM ECOLOGICAL RESEARCH TO SCIENCE AND POLICY MAKING

Although the importance of studying the environment over a long-term has been recognized by the scientific community, continuous data sets for marine environments are few in number (Holland & Kjergve, 1985; Champ *et al.*, 1987). Various reasons for the scarcity of these data sets have been suggested with the most common being the lack of long-term financial support from funding agencies or agency commitment to their own monitoring activities. To help meet this need, the National Science Foundation established a program to support long-term ecological research (LTER). Funds were provided to support core research at a specific site over a long period of time to develop a long-term data base. The resultant data sets were not only analyzed by the core research team but were available to provide a basis for short-term individual investigator-supported projects designed to study some ecological aspect of the site. In 1979, the initial cohort of six diverse ecosystems was funded. Since then, the program has expanded to include approximately 20 sites ranging from the South Pole to Alaska and from the mountains to the sea.

Investigations at the various LTER sites were science driven, however, one

justification of the program was that the data were to be available to a spectrum of users from state and federal regulatory and resource management agencies to academic researchers to the private sector. As the program expanded to include other sites, greater emphasis was placed on intersite comparisons of ecosystem dynamics. Five core research questions were to be addressed at each site: 1) Dynamic patterns and control of primary production in relation to natural and induced stresses of disturbances; 2) Dynamics of selected populations of organisms in relation to time as well as natural and induced stresses or disturbances; 3) Patterns and control of organic accumulation (biomass) in relation to time or natural and induced stresses or disturbances; 4) Patterns of inorganic contributions and movement through the ecosystem in relation to time and natural or induced stresses or disturbances and 5) Patterns and frequency of apparent disturbances over space and time that may be a product of, or induce, long-term trends. The NSF LTER Program has stimulated interest in long-term research by other national agencies and by the scientific community (Franklin *et al.*, 1990). For example, the National Estuarine Research Reserve Network of NOAA, consisting of 22 estuarine systems, has initiated a project to manage the data collected at the various sites to provide a long-term database. Also two volumes of *Estuaries* were dedicated to long-term ecological studies of estuarine and coastal marine systems (Holland & Kjerfve, 1985; Champ *et al.*, 1987).

Long-term data sets are not only of significance in addressing scientific questions but in recent years more attention is being focused on how to utilize research and monitoring of the environment so that the data will be useful to policy-makers when making management and regulatory decisions. Wolfe *et al.* (1987) identified five scientific objectives for utilizing long-term estuarine and coastal data sets which would be of potential importance to decision-makers. They were: 1) Field calibration of laboratory test results; 2) Field validation of model predictions; 3) Detection and analysis of long-term trends; 4) Definition of long-term variability regimes and 5) Generation of testable hypotheses on observed patterns and relationships.

More recently, Slocombe (1993) reviewed and synthesized the literature dealing with the theory and practice that facilities implementing ecosystem-based management of resources. In particular, he stressed the importance of both research and participatory, consultative efforts involving scientists, resource managers and people in communities in describing, planning and managing ecosystems.

In the case study presented in this paper, scientific results discussed in numerous published papers involving the LTER database have contributed to the development of ecosystem science. However, the rate of knowledge transfer to regulatory agencies and resource managers has not been as rapid. This difference between the rate of impact on science and on policy is not unexpected, since results of scientific study synthesized before detailed discussions with policy makers could be held. To remedy this situation, we have had scoping meetings involving local, state and federal agencies at which scientific results were presented and wide-ranging discussions were held on various topics, including the implications of these results to management and regulatory practices, fostering future research/policy interactions, involvement of the public, and defining various scenarios concerning the environment and sustainable development.

Data from our long-term studies have been used in the legal procedure necessary to reach the decision to prohibit dredging in salt marshes. Further, our studies on the dynamics of a relatively pristine marsh provide a baseline essential in developing procedures for bioremediation of degraded marine habitats. What are the criteria for stating that a marine environment has been restored to its former natural state?

Of particular significance is the use of long-term datasets to develop ecosystem and landscape models based on spatial and temporal variability. The utilization of tools of Geographic Information Processing (GIP) is being tested and adopted by estuarine researchers and resource managers to address ecosystem, landscape and global issues related to estuarine resource management (Michener *et al.*, 1989; Haddad & Michener, 1991; Dunlap & Porters, 1993). GIP is an integration of the technologies of remote sensing, Global Positioning Systems (GPS), Geographic Information Systems (GIS) and computer cartography (Dunlap & Porter, 1993). When combined with appropriate human intervention, GIP provides for the integration of historical and acquired data from disparate sources into an analytical system, the GIS. The GIS provides powerful tools for examining and evaluating a multitude of estuarine resource issues. This is accomplished by integrating biological, chemical, physical and socio-economic data as related to a specific issue. This integration provides for more rapid and precise assessment of existing conditions and relationships.

CONCLUSION

This paper emphasizes the importance of long-term ecological research by presenting a case history of the comparison of two estuarine systems which are very similar in many ecological characteristics except that one (North Inlet estuary) is relatively pristine while the second (Murrell's Inlet estuary) has been subjected to human perturbations.

North Inlet has been extensively studied on a long-term basis (25 years) and since 1979 it was part of the National Science Foundation's program on Long-term Ecological Research. The history of this program was discussed. In addition, a semi-detailed description of the program at the North Inlet site was discussed. A long-term database exists which includes data on the physical, chemical, geological and biological characteristics of this system. The data management system is an important aspect of this program. Some examples from the 425 papers resulting from this program were presented. Seasonal and interannual variation was observed for primary production of the dominant vascular plant, *Spartina alterniflora*. Various causes of this variability were proposed. Although phytoplankton productivity varied seasonally, the annual rate was relatively constant on an annual basis. Using power spectrum analysis of measurements of organic and inorganic suspended sediment taken daily over five years, yearly cycles were strongly correlated with water temperature with only a small fraction of the variance being related to the semidiurnal tide. Nitrogen fixation proved to be a highly dynamic process influenced by various environmental factors such as light, temperature, redox potential and carbon substrate availability. Seasonal and interannual variability of different assemblages of animals was observed, including meiofauna, subtidal macrobenthic fauna and larval recruitment of fishes. The interactions of various environmental factors were proposed to explain fluctuation in abundance.

Murrell's Inlet estuary had higher levels of various chemical contaminants, including polycyclic aromatic hydrocarbons, heavy metals, and herbicides/pesticides, than did North Inlet. The biomass was less in Murrell's Inlet. Environmental perturbations, including dredging, dock construction, salt marsh destruction, marinas and bulkheading and land use patterns associated with urbanization contribute to the degradation of Murrell's Inlet relative to North Inlet.

Results from this comparative study of two estuaries has added significantly to the scientific literature, however, the interaction of investigators of long-term

phenomena with policy makers has not been high. A few examples of how ecosystem management can be advanced were discussed.

ACKNOWLEDGEMENTS

The research cited in this paper was supported by grants from the National Science Foundation (BSR DEB 80 12 165, 8514326, BSR 9011664), the National Oceanic and Atmospheric Administration (NA 90 AA-D-SG672), and the South Carolina Coastal Council. Support from the United States Office of Naval Research enabled us to attend the workshop, "Long-term Study Influences on Science and Policy" held in Galway, Ireland, at which portions of this paper were presented. We acknowledge the invaluable work of many researchers involved in the grants cited above. This is contribution number 1024 from the Belle W. Baruch Institute.

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LONG-TERM INVESTIGATIONS PROVIDE FUNDAMENTAL INSIGHT INTO NATURAL AND HUMAN-INDUCED CHANGE IN THE SAN FRANCISCO BAY (U.S.A.) ESTUARY

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Key Words: San Francisco Bay, long-term, pollution, introduced species, river flow, monitoring

ABSTRACT

Human-induced effects on the benthos of the San Francisco Bay estuary were noticeable decades ago. For example, untreated human and industrial sewage (and the attendant reduction of dissolved oxygen) were recognized in the 1950's as causes of reduced numbers of species and abundances in the vicinity of waste discharges. Concern, here as elsewhere, about effects of contamination on water quality and biota resulted in the development of modern waste treatment facilities during the 1960's and 1970's. At the same time, scientific studies of the estuary were providing an ever-increasing awareness of other natural and human-induced factors that contribute to ecosystem variability and change in San Francisco Bay. These studies have demonstrated, for example, that effects of contaminants on benthic communities can often be overshadowed by changes resulting from such stressors as multi-year climatic variability, human manipulation of freshwater inflow, and the introduction of exotic species. It is clear that long-term study of estuarine benthic community dynamics in the context of all sources of stress to individual species is essential to distinguish and quantify the specific effects of contaminants. Monitoring and assessment programs to guide management decisions in complex estuarine systems like San Francisco Bay should be designed to distinguish among the causes of both short- and long-term changes in benthic communities.

INTRODUCTION

A fundamental question for scientists and managers working in moderately

urbanized and industrialized estuarine environments is: How do we know when the biota at a particular location are being affected by a specific human activity. For example, are they being affected by the contaminants that are present? We may recognize that something is wrong when we find diseased animals, a few pollution-tolerant species, or when we find no animals at all. Careful studies may point to cause and effect after a dramatic event such as an oil spill. However, dramatic evidence of contaminant effects is typically not present except at local "hot spots" or if the event is extreme. Scientists are rarely studying the right location before and after critical changes. In many cases we find contaminated biota and habitat, but we are not sure about responses at the population and community levels. Answering the question about effects of disturbance on populations and communities in estuaries can be exceedingly difficult because any particular stressor such as contamination is typically only one of a number of stressors affecting biota. For example, continuous long-term studies in estuarine, coastal and marine environments document that estuarine biological communities (1) change with time (over seasons, years, and decades) due to natural causes, and (2) are subject to aperiodic "events" (e.g., floods, droughts, storms, cold winters, hot summers and the like) that can result in quite rapid and unpredictable changes in community structure (e.g., Heip *et al.,* 1986). In the context of such variability, the short-term study of a particular environmental impact can lead to either vague or incorrect conclusions about cause and effect. Nonetheless, governmental agencies charged with managing or regulating aquatic environments and their biological resources are required to try to identify and measure the effects of human impacts, particularly those resulting from pollution.

In this report, we briefly review the factors that contribute to ecosystem variability and change in the San Francisco Bay estuary. This review will demonstrate that we need to understand the underlying causes of natural variability and change, and to integrate that understanding with our knowledge of the possible role of human-induced stressors, if we are to clearly recognize human-induced effects and begin to identify specific cause and effect relations. The experience in San Francisco Bay suggests that achieving this understanding is possible only through sustained, multi-disciplinary investigations. Alternative hypotheses must be rigorously examined in order to uncover those that make the most sense in explaining the changes that are observed.

In using the San Francisco Bay example, we wish to make the following points:

1. While the chemistry and biology of the estuary do exhibit reasonably predictable seasonal and interannual patterns of variation, these patterns are routinely disrupted by episodic events such as floods, droughts, or the arrival of exotic species. The effects of such events, superimposed on the normal patterns of variability, are typically seen in rapid, unpredictable changes in the estuary's biological communities. The important conclusion is that the chemistry and biology of the estuary at any point in space and time is highly dependent on antecedent events.
2. Our understanding of the relations between human-induced stressors (pollution, freshwater diversion, introduction of exotic species) and changes in ecosystem structure and functioning in San Francisco Bay, and particularly the detection of trends, has come from sustained multidisciplinary studies, not from one-time or short-term (on the order of one or two years) studies.

SAN FRANCISCO BAY: A HISTORY OF CHANGE

Throughout history, estuaries have been the focus of human activity. The rapid influx of people to California following the discovery of gold in the Sierra Nevada in 1848 brought rapid and permanent changes to the California landscape and to the San Francisco Bay estuary (Nichols *et al.*, 1986). At the end of the nineteenth century severe contamination of the estuary with raw domestic and industrial sewage was readily apparent. As recently as the 1950's, no living invertebrates were found on the bottom of South San Francisco Bay during summer presumably because of anoxia caused by the widespread disposal of untreated domestic and industrial sewage. Today, the bay supports a reasonably diverse estuarine biota due to vastly improved waste treatment. However, the bay's sediments and organisms remain contaminated by a wide variety of organic and inorganic wastes (Luoma & Phillips 1988).

The estuary was altered by other activities as well. Its native fisheries were heavily exploited during the latter half of the 19th century, and most commercial operations were halted to protect sports fisheries. At the same time the estuary's fresh and salt water tidal marshes in the Delta (Fig. 1) and around the perimeter of the bay were diked and/or filled to create agricultural land, salt evaporating ponds, and land for urban and industrial expansion. By the 2nd decade in this century, 95% of the original 2,200 km^2 of marshland had been eliminated from tidal action (Nichols *et al.*, 1986). This change represented a huge loss of habitat

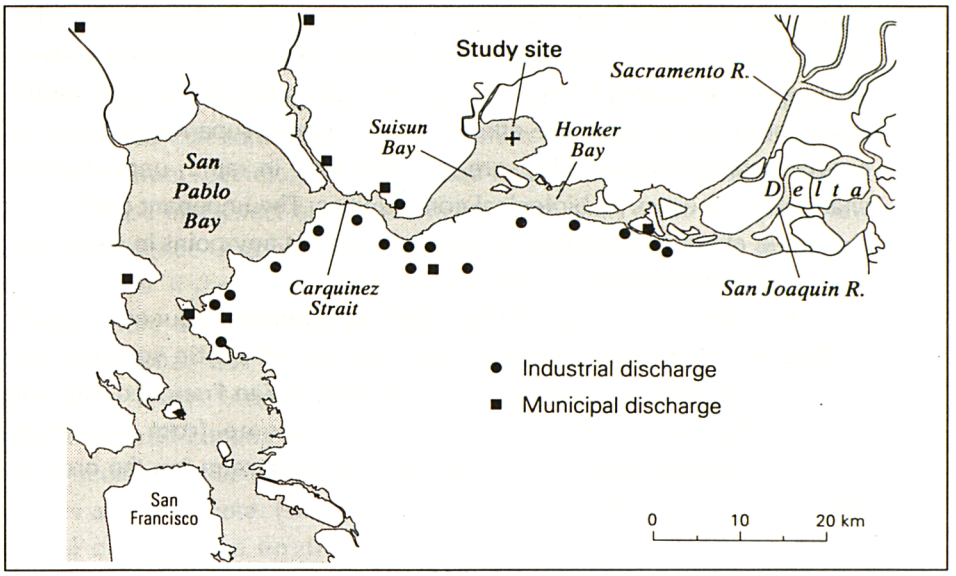

Figure 1. Upper San Francisco Bay Estuary with locations of waste discharges and the site of long-term sampling by the California Department of Water Resources and the U. S. Geological Survey.

for fish and wildlife species and presumably a reduction of organic matter input to the estuary.

Simultaneously, large numbers of exotic species were intentionally or accidentally introduced into the estuary, including numerous fish species (Herbold *et al.*, 1992) and more than 100 invertebrates, some of which are pest species (Carlton, 1979; Carlton *et al.*, 1990). Introduced species now dominate the bay's fish, plankton and benthic communities (Herbold *et al.*, 1992).

By the 1960's most of California's major rivers had been dammed and a large complex of aqueducts constructed to provide water for the rapidly growing population and the conversion of desert into irrigated farmland. This water storage and delivery system, one of the largest in the world, has greatly reduced the flow of freshwater into the estuary, particularly during spring (Nichols *et al.*, 1986; Peterson *et al.*, 1989).

Historical records about the effects of these past events on the San Francisco Bay estuary are sparse and scientific interest in the Bay is relatively recent. Thus, it has been difficult to identify and quantify the specific environmental effects of each change. The modern challenge is to distinguish among changes caused by (1) human encroachment on the estuary and its

watershed, (2) pervasive contamination, (3) the continued arrival of exotic species, and (4) changing ecosystem functions as a result of changes in freshwater inflow.

We will use the example of the upper estuary (Fig. 1) to show how all of these factors play roles in determining how this ecosystem functions.

UNPREDICTABLE AGENTS OF CHANGE

River inflow is the predominant agent of estuarine variability.

The San Francisco Bay region has a mild Mediterranean climate with two seasons: a dry summer/autumn season when river flow to the estuary is typically less than 500 $m^3 s^{-1}$, and a wet winter season when river flow ranges from 1,000 to 10,000 $m^3 s^{-1}$ (Fig. 2). During winter high flow periods, salinity in Suisun Bay drops to near zero, inputs of river-borne sediments, nutrients and organic materials are highest, the abundance of benthic invertebrates and macroalgae are lowered, and pelagic organisms including zooplankton and fish are redistributed. During summer low flow periods, seawater intrudes to the eastern end of Suisun

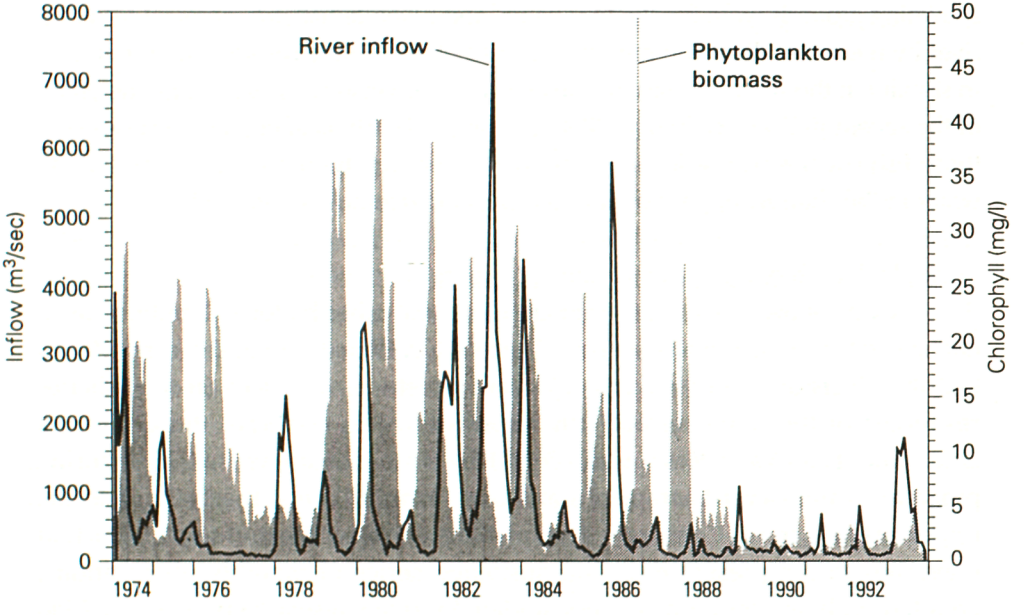

Figure 2. Monthly mean river inflow to northern San Francisco Bay from the Sacramento and San Joaquin Rivers and monthly or semimonthly measures of near-surface chlorophyll *a* in Suisun Bay (data from the California Department of Water Resources and the U. S. Geological Survey).

Bay and biological productivity increases in the warmer, clearer, slower moving water. This highly seasonal pattern of river flow strongly influences all physical, chemical and biological processes within the estuary (Cloern & Nichols, 1985).

Superimposed on the seasonal pattern of river flow is the strong interannual pattern of variability (Fig. 2) in response to (1) large-scale, long-term changes in precipitation patterns and trends and (2) the patterns of diversion of water from the Sacramento and San Joaquin River system that vary in response to demand and changing water policies (Peterson *et al.*, 1989).

Determining the effects of reduced flows in San Francisco Bay has been difficult because (1) environmental research began long after most of the water delivery system was built, and (2) interannual climatic variability and coincident human perturbations (overfishing, introduction of exotic species, shoreline modification, and waste disposal) greatly complicate the resolution of river diversion effects. Nonetheless, some relations between freshwater inflow and estuarine processes are clear.

The most obvious consequence of water diversion has been the reduction of anadromous fish stocks in the rivers because fish migration routes and spawning grounds were blocked by dams, and juvenile fish are removed from the river by the water diversion pumps (Herbold *et al.*, 1992). The long-term increase in salinity in the upper estuary because of water diversion, exacerbating the effect of the recent prolonged drought (Peterson *et al.*, 1989), is affecting the survival of those fish species whose juveniles are dependent on the presence of low salinity water in the shallow upper estuary during spring (Herbold *et al.*, 1992).

Phytoplankton biomass - an indicator of change.

River inflow is a key determinant of several other biological and chemical changes taking place in the estuary. Concern developed during the early 1970's that the diversion of freshwater could have a detrimental effect on the fisheries resources of the upper estuary. In response to this concern, the California Department of Water Resources (DWR) began a comprehensive monitoring program in the lower Sacramento and San Joaquin Rivers, the Delta, and the upper estuary (e.g., California Department of Water Resources, 1981) that continues to the present day. This sustained series of monthly observations, coupled with shorter-term process studies by other researchers, has provided invaluable insight into the factors that contribute to variability and change in the San Francisco Bay estuary. For example, early results demonstrated the close

relation between river flow and phytoplankton biomass in the upper estuary: peak blooms occur each year during low flow periods (Fig. 2) when the estuary's "null" or entrapment zone is positioned adjacent to the shallow reaches of Suisun Bay (Cloern *et al.*, 1983). A model for studying effects of reduced flows, developed for the State of California in the early 1970's, suggested that low river inflow would result in lowered turbidity and the development of nuisance summer algal blooms. However, during one of the driest periods on record (1976-77), the opposite occurred: the typical summer increase in phytoplankton biomass failed to occur at all (Fig. 2). This unexpected observation remained unexplained until several years later when an analysis of data from the benthic invertebrate samples collected at the DWR monitoring site in Suisun Bay (Fig. 1) revealed the occurrence of a broader-scale ecosystem change during the 1976-77 period of sustained low flow. The increased salinities that accompanied the low river inflows permitted the colonization of the region by estuarine benthic invertebrates (Fig. 3). These "dry period" species, largely filter feeders, consumed the phytoplankton as fast as it could be produced (Nichols, 1985).

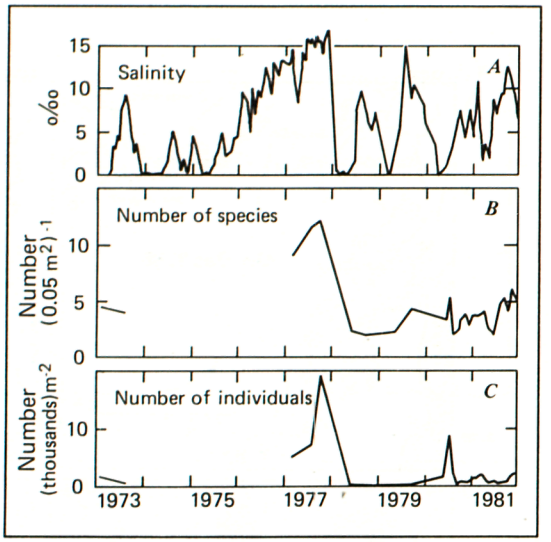

Figure 3. (A) Salinity, (B) mean number of species per sample, and (C) mean number of individuals m^{-2} at the Suisun Bay study site between 1973 and 1981 (adapted from Nichols 1985, Fig. 3; data from the California Department of Water Resources).

In summary, the long-term data revealed that interannual patterns in river flow strongly determine benthic community structure in the Suisun Bay region of the estuary and, thus, subsequent ecological changes. During years of normal river flow, the benthic community consists of a few fresh and brackish water species that are incapable of controlling phytoplankton biomass. During dry years, large numbers of estuarine invertebrates become established and subsequently control phytoplankton abundance.

Prior to 1986, the only exception to this complex set of interactions occurred in 1983 when prolonged high river inflows prevented the development

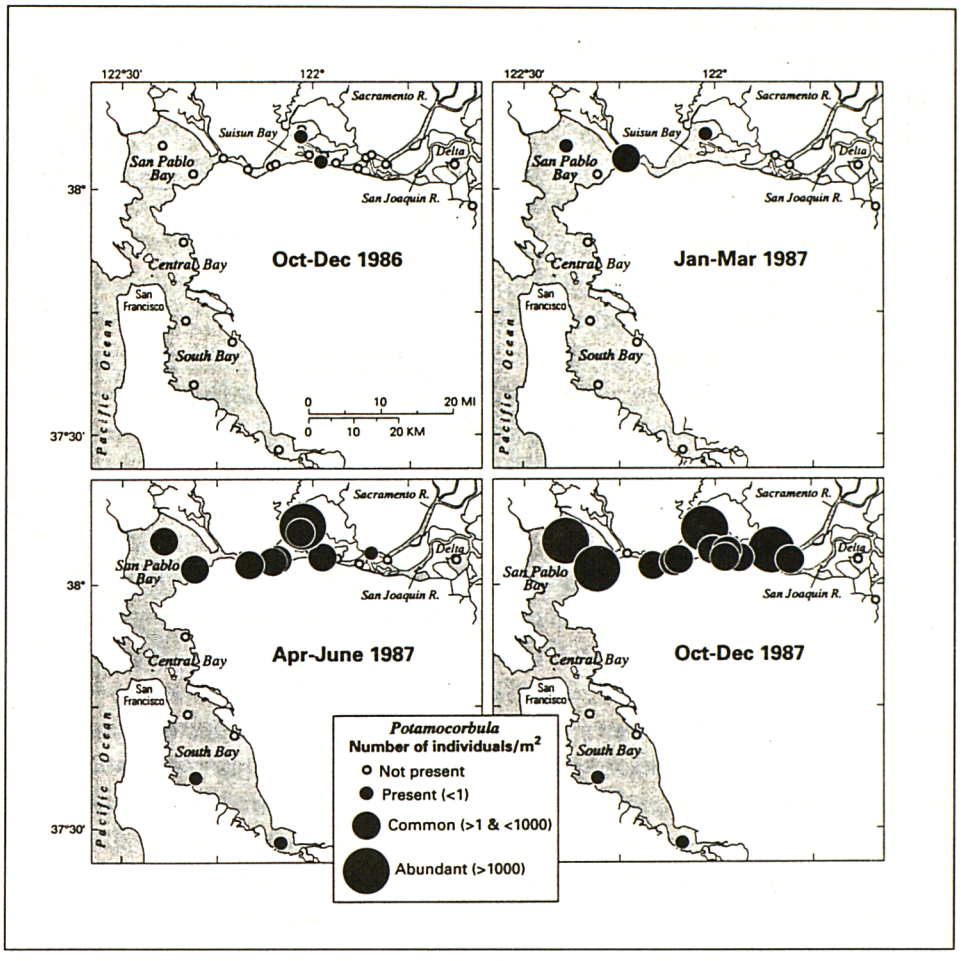

Figure 4. Distribution and relative abundance of *Potamocorbula amurensis* in San Francisco Bay during the first year after its arrival (Carlton *et al.*, 1990, Fig. 3).

of a summer phytoplankton maximum (Fig. 2) because hydraulic retention was too short relative to population growth rate (Alpine & Cloern, 1992). In 1986, the otherwise well-established patterns were disrupted by the arrival of a new exotic species.

Introduced species change the estuary.

By the mid-1980's enough had been learned from the sustained research and monitoring about the connections between river flow and lower-level food

chain processes to influence the development of strategies for the protection of the estuary. In 1986, however, the recognized patterns of variability and change in the biota of the upper estuary were dramatically and, perhaps, permanently changed by the introduction of *Potamocorbula amurensis*, a bivalve from Asia (Fig. 4; Carlton *et al.*, 1990). The availability of consistent data collected at the DWR study site in Suisun Bay (Fig. 1) since the mid-1970's provided the opportunity to document the changes that occurred as a result of this introduction.

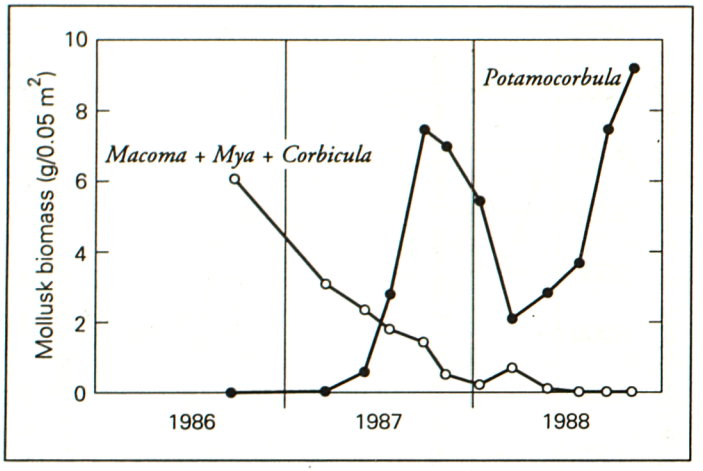

Figure 5. Wet weight biomass of mollusk species at the Suisun Bay sampling site (Nichols *et al.*, 1990, Fig. 6e).

Near the beginning of the longest drought period in this century (1986-1992), a single brief flood during February of 1986 eliminated most estuarine benthic species from the upper estuary (Nichols *et al.*, 1990). The first specimens of *Potamocorbula* were discovered in fall 1986, presumably a few months after being released into San Francisco Bay in ship ballast water. By the time that salt levels had increased to levels seen in the 1977 drought, *Potamocorbula* had displaced previously abundant clams (Fig. 5), and was sufficiently abundant to permanently prevent the reestablishment of the "dry period" community species such as *Mya arenaria* (Fig. 6).

Potamocorbula, tolerant of very low salinities (< 1 ppt), continues to be the most abundant benthic invertebrate throughout the upper estuary. As a direct result of its filter-feeding capacity, phytoplankton abundance has remained extremely low (Figs. 2, 5). Moreover, *Potamocorbula* also consumes the nauplii of resident zooplankton, contributing to a decline in copepod abundance since 1987 (Kimmerer *et al.*, 1994). It is possible that these changes in the lower trophic levels of the estuary's food chain have been important in the simultaneous declines of some the fish species that inhabit this region of the estuary, although

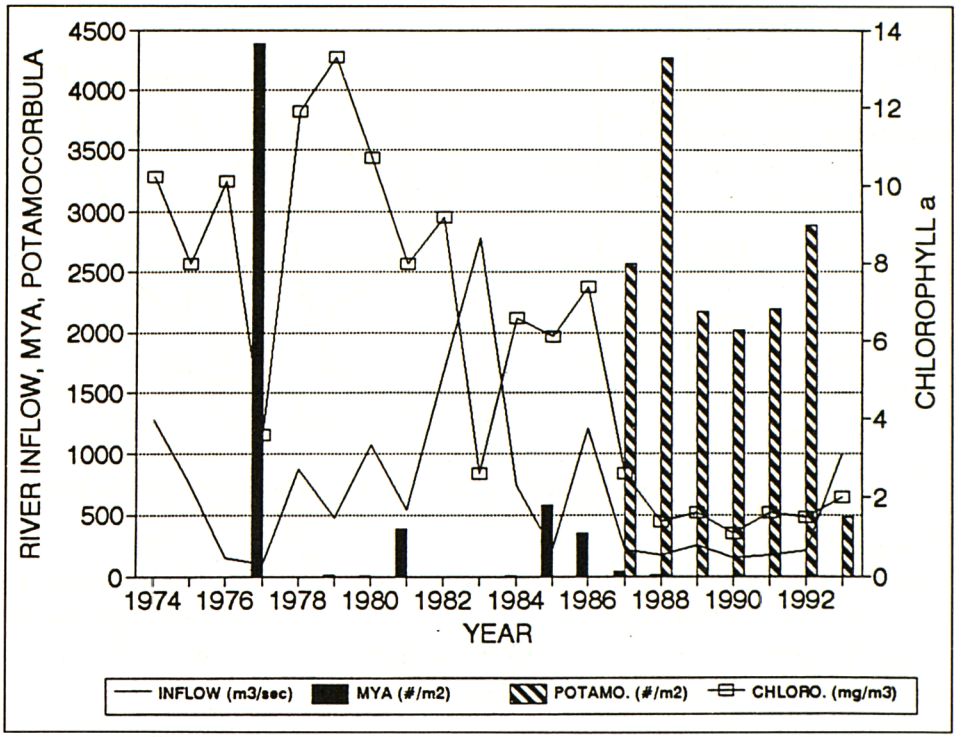

Figure 6. Annual mean chlorophyll concentrations, river inflow, and abundances of *Mya arenaria* and *Potamocorbula amurensis* since 1974 (adapted from Alpine & Cloern 1992, Fig 5).

direct food-chain linkages have not yet been demonstrated. Only continued research and monitoring will permit us to develop the needed level of understanding of these key food web interactions.

Effects of contamination are unclear.

Wastes from the nearly 6 million people of the San Francisco Bay metropolitan area continue to enter the bay from numerous "point" sources (waste treatment facilities) and "non-point" sources (local runoff and river inflows). The effluent from domestic and industrial waste treatment facilities alone represent 4% of the average freshwater flow into the Bay (Russell *et al.*, 1982). Modern waste treatment facilities have largely eliminated oxygen depletion and reduced enteric bacterial contamination of bay waters. The effects of trace contaminants continue to be of great management interest, however, and has been the subject of numerous studies. Despite substantial investment in such

studies, there remains great uncertainty about the role of contaminants in San Francisco Bay. An important reason for that uncertainty, here and elsewhere, is the predominance of the short-term, simplistic studies that do not consider the environmental context of the estuary.

Waste managers have typically requested studies of toxicant effects that yield "immediate results", and that focus very specifically on toxicants. Immediacy requires that most such studies are of short duration and involve sampling at one or a few times. Too often, the characteristic estuarine processes described earlier are not considered.

Efforts to combine contaminant levels, bioassay results, and community information show promise as an approach to demonstrate contaminant effects. Unfortunately this approach is also typically used in the single sampling mode, and other environmental characteristics are ignored. Under such circumstances, the approach is successful only at the most extremely impacted sites. Worse, the insensitivity of the measurements, compounded by ignorance about environmental conditions, can lead to erroneous conclusions. For example, Chapman *et al.* (1987) used this "triad" approach at three sites in San Francisco Bay to describe the relative effects of contaminants on benthic invertebrate community composition. They concluded that aspects of community composition showed relation to contaminant levels: the composite index of the three Triad components showed that a severely impacted slough on the San Francisco waterfront was 58 times more degraded than and open water San Pablo Bay site while an Oakland harbor site was 1.4 times more degraded than the San Pablo Bay site. However, experience gained from sustained study of the benthic invertebrates of the estuary (Nichols & Thompson, 1985) suggests that it is probable that species composition, at least in Oakland Harbor and San Pablo Bay, reflected variations in salinity during the months prior to the sampling for this study. This problem reflects the fact that there are no true reference locations in complex estuarine environments such as San Francisco Bay. Each area of the estuary is subject to different natural and human-induced stressors. In short, conclusions drawn from comparisons of different areas within the estuary that focus on toxicity alone, and do not take other confounding variables into consideration, can be inappropriate or inaccurate with regard to species distributions and abundances.

It is unfair, however, to criticize short-term toxicity studies simply because they have not conclusively proven that contaminants have adverse effects in the

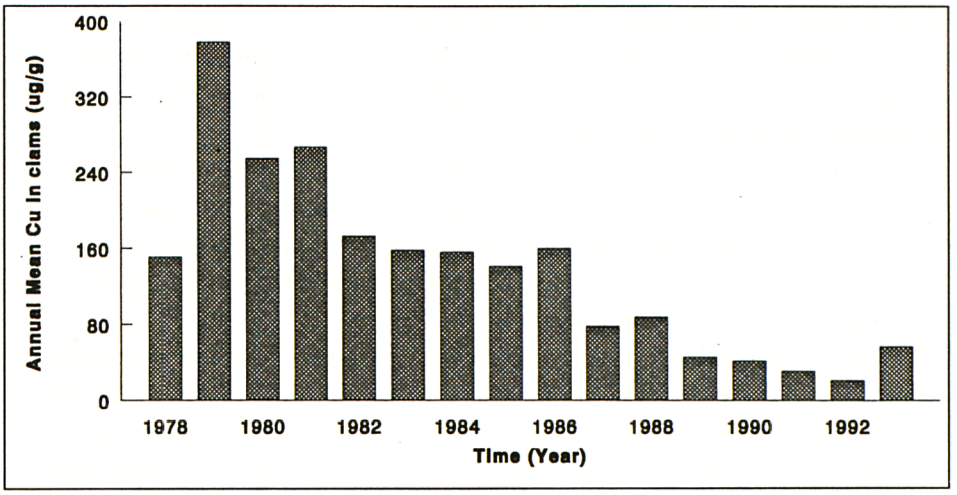

Figure 7. Annual mean copper concentrations in clams from an intertidal South San Francisco Bay site near a waste treatment facility.

estuary. Determining how contaminants influence populations or communities of organisms is inherently difficult in any moderately contaminated ecosystem (Luoma & Carter, 1993), and no approach has yielded indisputable evidence about the effects of contaminants. It can be argued, however, that longer-term, multi-disciplinary studies of contaminants have been of greater benefit to estuarine management than studies purporting to yield immediate results, especially when the longer-term studies are interpreted within the context of biological, chemical and hydrologic processes. The understanding of the basic characteristics of San Francisco Bay benthic community structure was achieved only through a sustained study that documented the patterns of variability and change (Nichols & Thompson, 1985). Similarly, persistence and carefully designed monitoring have demonstrated that a 30-year investment in waste treatment was able to lower the threat of contaminants in the Bay. Metal concentrations in sediments and the tissues of a local bivalve, measured at near monthly intervals at a site near a sewage treatment plant in South Bay revealed high levels in the late 1970's that were unprecedented for this species worldwide (Luoma & Phillips, 1988). As the treatment plant continued to improve waste treatment and management, concentrations of copper in clams dropped (Fig. 7).

The long-term observational approach to studying contamination does not demonstrate "effects", but it produces irrefutable data demonstrating benefits from a public investment. It also demonstrates that natural processes will facilitate

recovery from extreme contaminant exposures in local environments if source inputs are reduced. Waste managers are using these data to encourage reduced release of wastes by local industries (source controls). Moreover, regional water quality managers are implementing similar monitoring schemes at selected other locations.

Sustained contaminant data collection has also provided demonstrations of the complex interactions among river inflow (hydrodynamics), contaminant inputs, metal concentrations in clam tissues, metal tolerance and periodic physiological stress in clam populations, and disruption of the accumulation of reproductive reserves in clams (Luoma & Phillips, 1988). Such complexity may be typical of the manner in which contaminants interact in ecosystems. Because unpredictable, high-frequency fluctuations also characterize community composition (Nichols & Thompson, 1985), the linkages among complex contaminant dynamics and complex community dynamics will require a sophisticated understanding of contaminants, hydrology, and ecology that will probably only be obtained by the type of long-term, multi-disciplinary study that few institutions have been able to sustain. The upper region of San Francisco Bay is the recipient of wastes from many domestic and industrial outfalls (Fig. 1) and from river-borne contaminants. Not surprisingly, the levels of trace elements in clam tissue reflects regional scale contamination. Thus, the biota of the region of the estuary most influenced by altered river flow and introduced species is potentially affected by contaminants as well.

Studies of selenium levels in clams, for example, show that concentrations approach levels sufficient to be toxic to fish and diving ducks when eaten as food (Johns & Luoma, 1988; Luoma *et al.*, 1991). These long-term selenium studies have influenced development of waste management criteria for the estuary. Another ongoing study of contamination in this region (C. Brown, unpublished) has demonstrated, over a four-year period, a consistent negative correlation between a bivalve "condition index" (dry weight of tissue) and the concentration of trace metals in the tissues of clams from along the axis of the estuary, with the lowest condition index found in the Suisun Bay region. Other evidence (F. Parchaso, unpublished) demonstrates that the reproductive cycle of *Potamocorbula amurensis* in Suisun Bay differs from the reproductive cycle of this species elsewhere in the bay. Of course, a lowered condition index and differences in reproductive cycle may also reflect confounding influences of environmental factors other than (or in acting in conjunction with) contaminants,

e.g., reduced salinity and lowered phytoplankton biomass (see above).

Because of the many confounding variables present in any estuarine environment, sustained multi-disciplinary study seems to be the only approach that will resolve questions about specific human impacts. The more we know about the basic physical, chemical and biological processes in an estuary, the more likely is conclusive understanding.

CONCLUSIONS

In the study of the San Francisco Bay estuary, we have been confronted with obvious questions:

1. What are the relations between river flow and the biological populations of the estuary? For example, can we distinguish the seasonal, annual and interannual factors that control the abundance, growth and survival of fish or clams?
2. What are the relations between river flow and the pollutant chemistry of the estuary? For example, can we quantify and thus predict the relations between flow conditions and the delivery of contaminants to the estuarine biota and sediments?
3. What are the specific contaminant effects on individual organisms?
4. How can we clearly distinguish the effects of contaminants on benthic populations and communities from effects of the many natural influences that can be responsible for much of the observed variability and change, particularly when there are no truly appropriate "reference" locations?

Because estuaries are influenced by a variety of factors that contribute to variability and change, it is no surprise that one-time or short-term studies that emphasize the study of one factor have been ineffective. Rather, it is clear from a review of the record of research and monitoring in the San Francisco Bay estuary that most of the fundamental understanding of the processes controlling ecosystem variability and change has come through diverse, multi-year efforts. The results of each study, while providing incremental understanding, invariably raised new questions, permitted the development and testing of new hypotheses and, thus, allowed for the enhanced level of understanding necessary to draw conclusions about cause and effect relations. As a key example, it is the sustained studies of the effects of natural variations in river inflow that have provided the level of understanding necessary to characterize and predict the estuary's

responses to diversions of river inflow. On the contrary, the usefulness of the dozens of short-term environmental impact studies conducted over the past two decades has been largely limited to one-time descriptions of chemical conditions and toxicity tests often unrelated to the well-being of local fauna. Both studies of contaminant effects and of invertebrate communities typically ignored many potential causes of any effects seen, including such obvious factors and hydrologic seasonality.

The key environmental questions faced by water resource managers, regulators, and policy makers (see San Francisco Estuary Project Management Committee, 1994) can, for the most part, be best approached through sustained time-series field studies of basic estuary processes - that is, using key variables to follow chemical and biological responses to ecosystem changes and trends through time. Only through sustained multi-disciplinary study, both in the field and in the laboratory, can we draw sensible generalizations, generate testable hypotheses, formulate and test predictive models, and provide reasonable strategies for managing the estuary's biological resources.

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THE USE OF LONG-TERM SURVEYS AND MONITORING OF INTERTIDAL AND SUBTIDAL BENTHOS IN PREDICTING CHANGES IN THE MARINE ENVIRONMENT

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ABSTRACT

This paper presents selected findings from surveying and monitoring both intertidal and subtidal macrobenthic populations

One set of findings is taken from the COST (Coopération Scientifique et Technique) 647 Project on Coastal Benthic Ecology. This project was coordinated by the EU and dealt, *inter al.*, with natural changes *versus* anthropogenic changes in certain soft-bottom communities. Local case studies are described from the French coast of the English Channel; the baie de Somme and the baie des Veys. These studies are based on the bio-sedimentary approach proposed in the early 1980s by GEMEL (Groupe d'Etude des Milieux Estuariens et Littoraux) study group. Processing of up to 20 year data series reveals the value of the method in predicting changes at the ecosystem level. An international intercomparison exercise was also carried out within the COST 647 framework and mainly dealt with bivalve molluscs such as *Cerastoderma edule, Macoma balthica* and *Scrobicularia plana.*

A second set of results has been extracted from the North Sea Benthos Survey and shows how some data has been used by the North Sea Task Force to predict temporal changes at the North Sea level. The North Sea Benthos Survey took place in 1986; some stations were revisited in 1990 and 1991 as part of the Monitoring Master Plan of the North Sea.

It is concluded that a more comprehensive description of biotic and abiotic factors is needed in studies such as those presented here in order to better understand the role of natural variability in observed changes. Finally, a plea is made for a real harmonisation of field techniques and for a spatial and temporal co-ordination of sampling and data processing at the European level.

INTRODUCTION

Recently, Elliott & Ducrotoy (1991) have written on the need for long-term studies of the marine environment in order to better manage its resources. Stressing that many studies in oceanography, sedimentology and biology have implications for the management of coastal and estuarine areas in Europe, they recommended that inter-comparative studies between sites be carried out on an international basis because of the increasingly widespread nature of anthropogenic problems. In 1994, the North Sea Task Force (Oslo and Paris Commission and International Council for the Exploration of the Sea) produced the Quality Status Report of the North Sea (North Sea Task Force, 1994). In the report it was stipulated that even the offshore environment of the English Channel and the North Sea was directly or indirectly at risk because of specific human activities.

In this paper, local examples of long-term studies on intertidal and subtidal benthos are presented. The work on intertidal habitats was co-ordinated within the Groupe d'Etude des Milieux Estuariens et Littoraux (GEMEL). GEMEL is an association of research workers dealing with the coastal environment. Some members of GEMEL have been working on several estuaries along the French coast of the English Channel since the early 1970s and the GEMEL team contributed significantly to the COST 647 initiative which ran from 1981 to 1991 (Souprayen, 1992b). The project was targeted on macrobenthic benthic animal communities (including subtidal communities), investigated the factors influencing natural variability and endeavoured to distinguish between natural and man-induced variability (Souprayen *et al.*, 1992a). Special attention was given to the standardised statistical analysis of the quantitative data collected within the project, from many sites in several countries throughout Europe (Keegan, 1992). As a result, the influence of biological controlling processes such as recruitment, competition and predation on the primary state variables of marine ecosystems, such as density and biomass of species or communities, are now better understood.

To assess the scale of the observed changes at some subtidal sites in the North Sea, data collected as part of the Monitoring Master Plan (MMP) of the North Sea (Ducrotoy *et al.*, 1991a) in 1990-1991 were compared with data collected in 1986 by the Benthos Ecology Working Group (International Council for the Exploration of the Sea, 1993). This preliminary comparison is described further below (Portmann, 1991).

LOCAL STUDIES

Channel estuaries

General presentation

GEMEL has been studying ecosystem functioning and the impact of human disturbances on macro- and mega-tidal estuaries on the French coast of the English Channel since the beginning of the 1970s. These studies took a bio-sedimentary approach and monitored the macrobenthos and environmental parameters to assess the quality of the environment (Ducrotoy *et al.*,1989). Benthic population mapping was based on stratified random sampling of sedimentary plus biological characteristics and incorporated the notion of 'biofacies'. Survey of pilot-stations produced data on abundance, richness and biomass several times a year on all macrobenthic species. Further information was collected on key-species with regard to size, age, population structure, sexual maturation and data returned from chemical analysis of their tissues.

The above approach is demonstrated further hereunder using examples from the baie de Somme (Picardy) where such a survey was initiated in 1978 (Dupont, 1981) and routinely serviced from 1981 (Ducrotoy *et al.*, 1987). These studies were initially developed to understand the collapse of the local fisheries; dramatic changes in species composition and abundance were recorded in the course of the research programme.

Spatial changes in biofacies

At the historical level, changes in the morphology and physiography of the estuary have taken place on a wide scale. A few centuries ago, the estuarine complex of the Somme included several rivers and encompassed an area over 500 km^2. The present baie de Somme was created by the embayment of 2 rivers behind a shore-bar and the current tidal area is some 70 km^2 (Ducrotoy & Elkaim, 1992).

In 1984, Ducrotoy *et al.* (1986) suggested that hydrodynamic factors played a major role in structuring the communities and their habitats. They promoted a survey of the estuarine communities based on the notion of biofacies (Figure 1).The facies derive from the interaction between environmental factors integrated through the sediments and the macrobenthic infauna, i.e.

- hydrodynamic parameters controlling dynamic processes in the estuary;
- physico-chemical parameters, governed by the former conditions where a) salinity is controlled by the river input and the comparative extent of the

inner estuarine area, and b) the impact of pollution depends on the concentration of introduced materials (chemicals), fresh-water flow and the other continental inputs (runoff, etc.);

- the geomorphology of the estuary, producing some sheltered areas;
- the regional sedimentary characteristics governing the types of deposit;
- the regional biological environment including the recruitment of estuarine

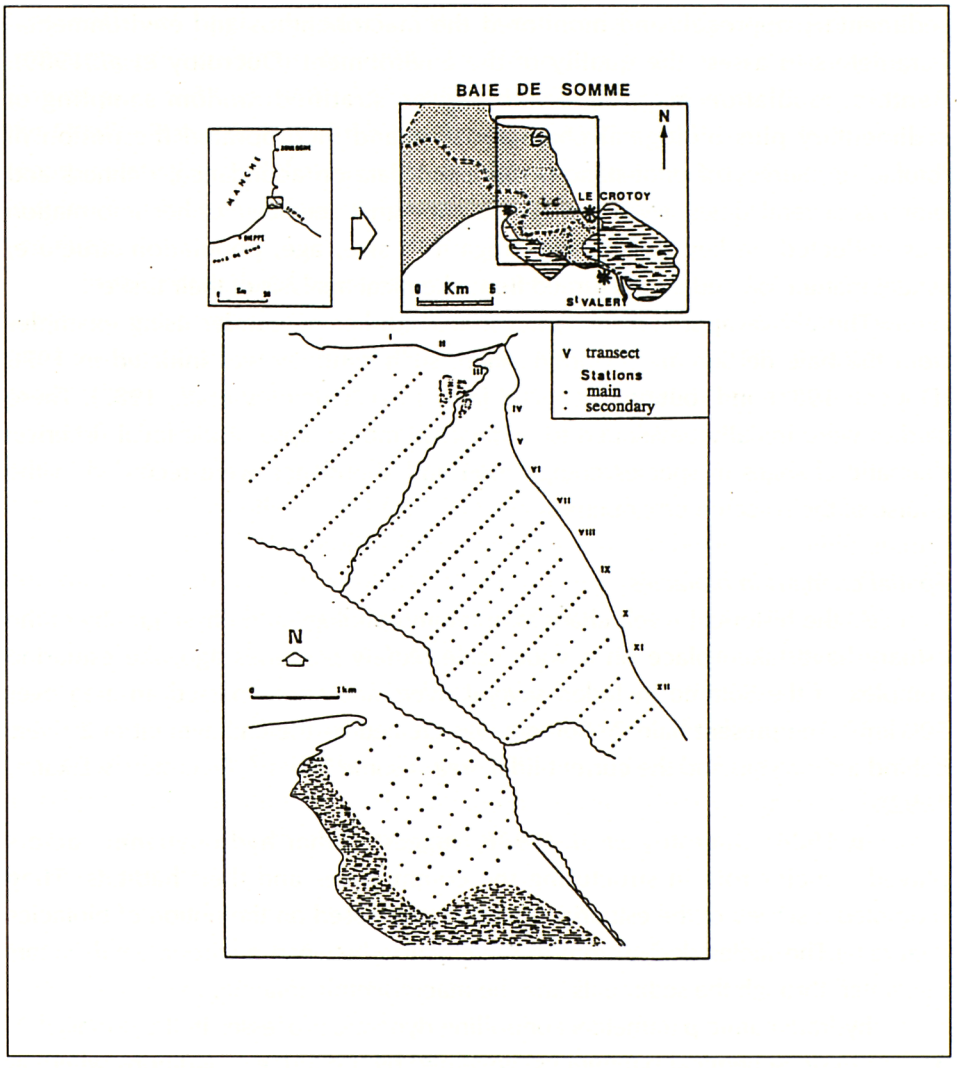

Figure 1. Sampling area and sampling grid used in the baie de Somme for the study of the macrobenthic infauna (after: Ducrotoy & Elkaim, 1992)

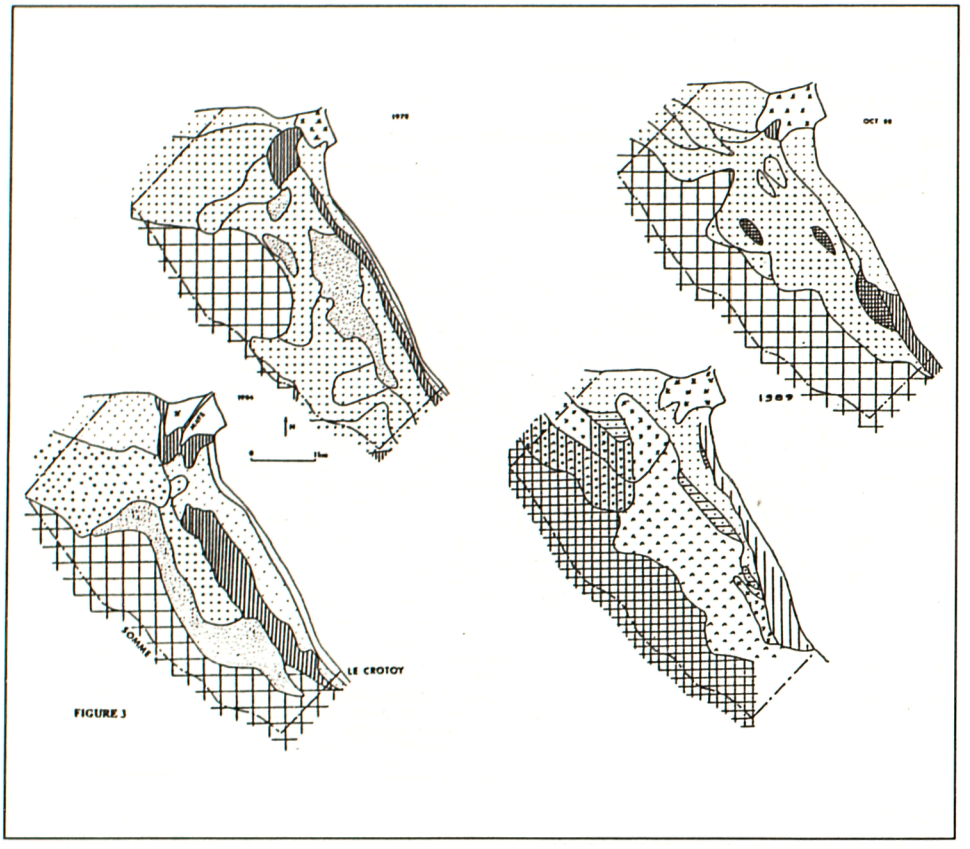

Figure 2. Bio-sedimentary facies in the northern study area of the baie de Somme
a) Spatial distribution of the facies in 1978, 1984, 1988 and 1989

organisms as governed by local conditions (station concept) (Ducrotoy *et al.*, 1989).

Biofacies and benthic communities were surveyed in 1978 by Dupont (1981) and from 1984 up to the present. The 1978 mapping exercise was derived from the work of Dupont (1981) with the subsequent work following the method described in Ducrotoy & Elkaim (1992). Maps showing changes in the distribution of the bio-sedimentary facies in the northern study area are given in Figure 2a.

Mortalities of benthos over relatively large areas were observed in 1982, 1983 and 1989 and affected the local cockle (*Cerastoderma edule*) fisheries. From 1984 to 1988, *Pygospio elegans* beds expanded dramatically while cockle

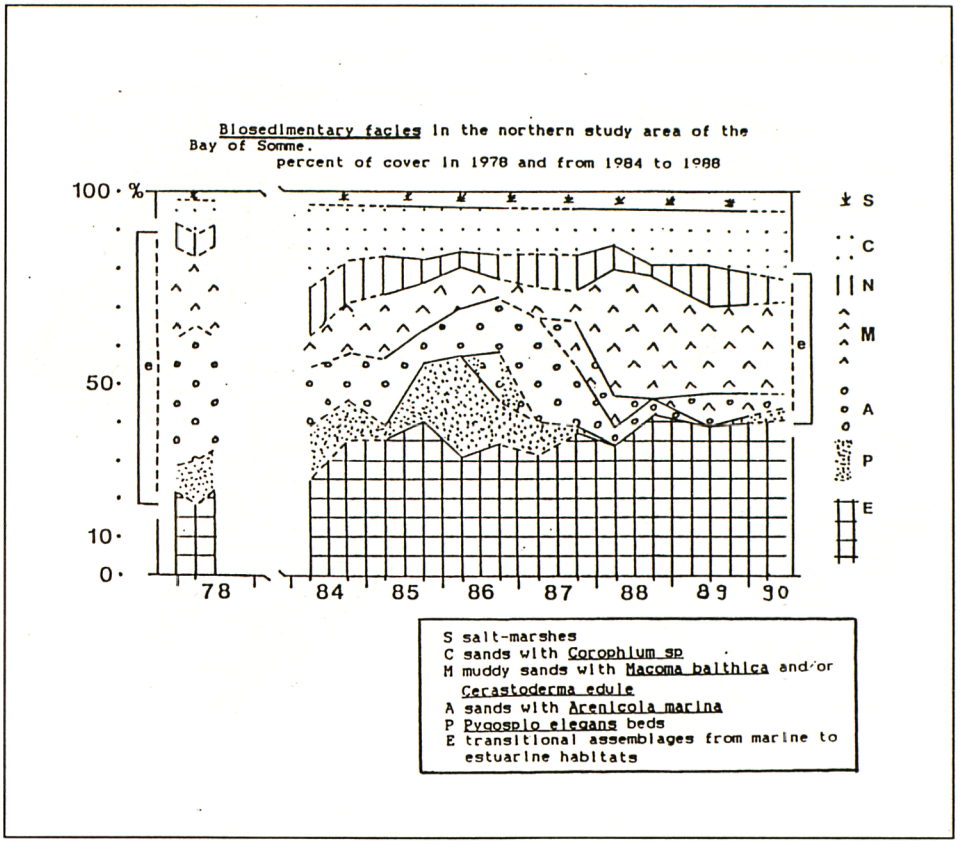

Figure 2. Bio-sedimentary facies in the northern study area of the baie de Somme
b) Percentage of cover of facies in 1978 and from 1984 to1990

A Sands with *Arenicola marina*
C Sands with *Corophium* sp
E Transitional assemblages from marine to estuarine habitats
M Muddy sands with *Macoma balthica* and/or *Cerastoderma edule*
N Muddy sands with *Nereis diversicolor* and *Hydrobia ulvae*
P *Pygospio elegans* beds
S Salt-marshes
(after: Ducrotoy & Elkaim, 1992)

populations showed a collapse in numbers. Desprez *et al.* (1993) showed that the mortality of the benthos was a direct result of anoxia in the water column promoted by phytoplankton blooms of *Asterionella glacialis*. Blooms were attributed to high nitrogen levels. Nitrates originated from river and land run-off while it was demonstrated that the ammonia was made available through the metabolism of the estuarine bivalves. By 1989, the *Pygospio* knolls had

disappeared from the estuary at large (Souprayen *et al.*, 1992b).

The above study, which produced a typology of facies, allowed a better understanding of changes/trends in time and space. As a result of the benthic mortalities, the estuarine facies were reduced in extent while the salt-marshes doubled in area in 10 years. Facies under marine influence also showed a seasonally regulated expansion. (Figure 2b).

It is worth mentioning that the 10 year time span of the study was sufficient to include certain catastrophic events whose effects could be considered with respect to the management of natural resources in the baie de Somme. This type of research work revealed some notion of the time base and the amplitude of ecological changes in estuarine communities (Ducrotoy, 1984; Ducrotoy, 1986). It gave a better understanding of what constitutes stability (and the supporting processes and events) in such ecosystems and, in turn, allowed a greater appreciation of the complexity of, and of the importance of natural variability in, estuaries (Rybarczyk *et al.*, 1990).

Pilot-stations

Changes in populations were also recorded when sampling pilot-stations. A pilot-station was defined as representative of a specific community according to the nature of the biofacies. They were sampled (i) to quantify the temporal variability of populations in an attempt to understand population dynamic, (ii) to detect any consequences of disturbances, and (iii) to identify species whose biological cycles appeared to integrate the variations in the environmental factors at different levels.

Results from two of the pilot-stations surveyed in the baie de Somme were given in Desprez *et al.* (1986) and Souprayen *et al.* (1992b). From 1981 to 1993, 25 species were recorded at these stations. Though there was a lack of synchronisation between changes in the numbers of certain species at the two stations, the overall changes reflected the trends observed for the estuary as a whole. The asynchrony between sites, and the possibility of a human impact on the communities, required a regular estuary-wide survey to set the results into context. The high degree of unpredictability in estuarine ecosystems indicated that short-term monitoring is not sufficient to permit differentiation between sub-catastrophic pollution effects and natural variability. Recently, Rastall and Ducrotoy (1994) proposed a new approach to interpreting long-data series on estuarine benthos from the Somme. They used a modified Fibonnacci Series with

incorporated constants to accommodate population growth, population decay and the carrying capacity of the environment. While certain values for constants gave predictable cyclical numbers, sometimes seemingly chaotic fluctuations were revealed. It is hoped that this mathematical approach will facilitate more ready interpretation of the variations in the numbers of macrobenthic species.

Key species

The changes which occurred in the estuarine community may be summarised in the long-term changes shown by the two species *Pygospio elegans* and *Cerastoderma edule*. The first effects of eutrophication were demonstrated through a mapping of cockle populations when high mortalities led to a collapse of the fisheries in the baie de Somme. *Pygospio elegans* opportunistically occupied the space vacated by *Cerastoderma edule*. Batten (1994) suggested that changes in the community structure could also be reflected in the physiological status of certain organisms. She measured fluctuations in the biochemical composition of estuarine animals, correlated them with environmental changes and showed that physiological responses may be predictive of subsequent population changes.

Changes were also apparent higher in the food chain. Desprez *et al.* (1993) have linked changes in benthic communities to changes in the diet of the two main predators of *Cerastoderma edule*, the oyster catcher (*Haematopus ostralegus;* Caudron *et al.*, 1983) and the common gull (*Larus canus*; Sueur *et al.*, 1989).

Initial conclusions

The above long-term studies are highly valuable inasmuch as they led to an understanding of the causes of the observed disturbances and, as a consequence, enabled local authorities to take remedial action. The conditions for benthos kills, the subsequent collapse in cockle fisheries and outbursts of opportunistic species are now better understood. A high input of nutrients from the continent, the production of ammonia by estuarine species combined with warm calm weather produced phytoplankton blooms with attendant high oxygen consumption during the degradation process. This resulted in benthos kills. These mortalities only affected localised parts of the estuary and could not explain entirely the drastic changes which were observed in 1985-1987 and 1991. Hydrodynamic conditions and the sedimentary regime of the bay also seemed to

be affected (Ducrotoy *et al.*, 1986).

The asynchrony noted between the fixed sampling sites points to the need for regular estuary wide surveys. Seasonal patterns at single sites must be interpreted with reference to changes in species distribution and biological parameters. Ecophysiology studies, the use of mathematical models and the analytical approach complemented each other.

The study of spatial and temporal variations in key-species can have a high predictive value. Where the habitat was claimed to be pollution free and clean before the start of the studies, they have helped to identify the supposed causality of the observed disturbances (i.e. nutrient enrichment from municipal outputs and agriculture).

Oil Rigs: North Sea Task Force stations

Biological monitoring around offshore oil production platforms of the North Sea started in the 1970s. In the interim, there have been changes in governmental and international legislation relating to drilling activities. There has been a corresponding evolution of approach to associated monitoring activities (Reiersen *et al.*, 1988; Kingston, 1990). Efforts to better understand pollution effects linked to the oil industry culminated in 1990-1991 when the Monitoring Master Plan (MMP) of the North Sea was put into effect by the North Sea Task Force (Ducrotoy *et al.*, 1991a; Ducrotoy, 1993).

Effects were shown to be mostly due to the impact of oil contaminated drill cuttings discharged by the offshore industry. The scale of the impact was dependant upon current regimes and the depth of the seafloor at the oil rig and was outlined as follows in the Quality Status Report of the North Sea (North Sea Task Force, 1994):

- species increase in abundance (subtle effect),
- reduction in number of sensitive species,
- increase in abundance of some opportunists,
- increased mortality,
- overall reduction in abundance and diversity.

It was also possible to associate a particular oil concentration to one or more effects. No signs of macrobenthos recovery was observed at highly contaminated sites after 6 years. In moderately affected areas, recovery did not take more than two to three years. These types of studies clearly demonstrate the pertinence of benthic investigations in monitoring pollution effects.

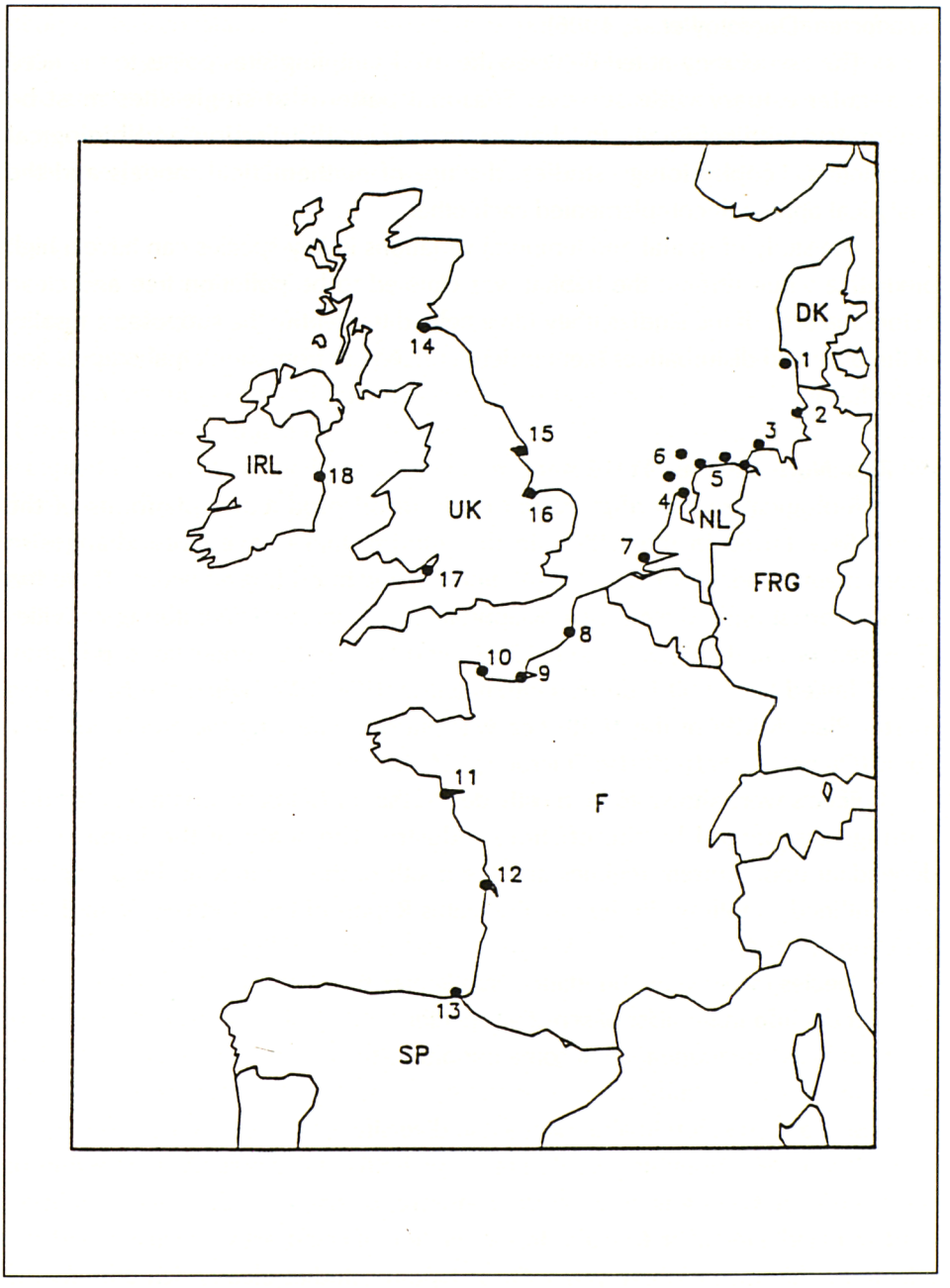

Figure 3. Sampling localities in the intertidal and shallow subtidal "*Macoma* community" in the framework of the COST 647 programme from 1981 till 1992

INTERCOMPARISONS

The aim of intercomparisons is to set data in a geographical context so as to determine whether observed changes are due to local conditions or are part of a broad scale natural pattern. A more meaningful analysis can then be achieved and variations in parameters be interpreted. As long as the studies in different areas are carried out with sufficient quality assurance and standardisation of methods, then individual investigations can be conducted on a smaller scale and yet be worthwhile (Elliott & Ducrotoy, 1991). This was achieved by the Groupe d'Etude des Milieux Estuariens et Littoraux from 1981 up to the present, particularly in the context of the COST 647 initiative. Figure 3 shows the sites that were sampled for the study of the '*Macoma* community' within the COST project.

Latitudinal trends in reproduction, recruitment and population characteristics of estuarine bivalves

The COST 647 framework has provided an opportunity to collect and compare long series of data on benthic estuarine species in order to understand how climatic and hydrographic factors operate on the recruitment, survival and reproduction of selected species. Data was collected for a wide range of animals and in particular on bivalves including *Scrobicularia plana* da Costa (Essink *et al.*, 1991) *Cerastoderma edule* Linnaeus (Ducrotoy *et al.*, 1991b), *Macoma balthica* Linnaeus (Desprez *et al.*, 1991) from sites in Ireland, Great Britain, Germany, the Netherlands and France.

Scrobicularia plana is a long-lived (up to 16 years) deposit-feeding tellinid bivalve which showed a decline or even disappeared from several European sites in the 1980s. Latitudinal variations in reproduction patterns were demonstrated, from 1 cohort in northern Europe to 3 in southern localities. This information was valuable in order to understand the natural variability of local population dynamics. For example, recruitment failures were observed for up to 4 years after a severe winter, and high densities did not endure for more than 2 years after a successful recruitment. This means that the populations were particularly vulnerable to climatic events and that any changes due to human activities could be all the more dramatic where they operate in concert with climatic events(Ducrotoy & Desprez, 1986). In the baie de Somme and the Loire estuary in France, population densities decreased due to occasional sediment instability. In the German Wadden Sea, the animals were gradually disappearing or had already disappeared from some locations before the start of the COST 647

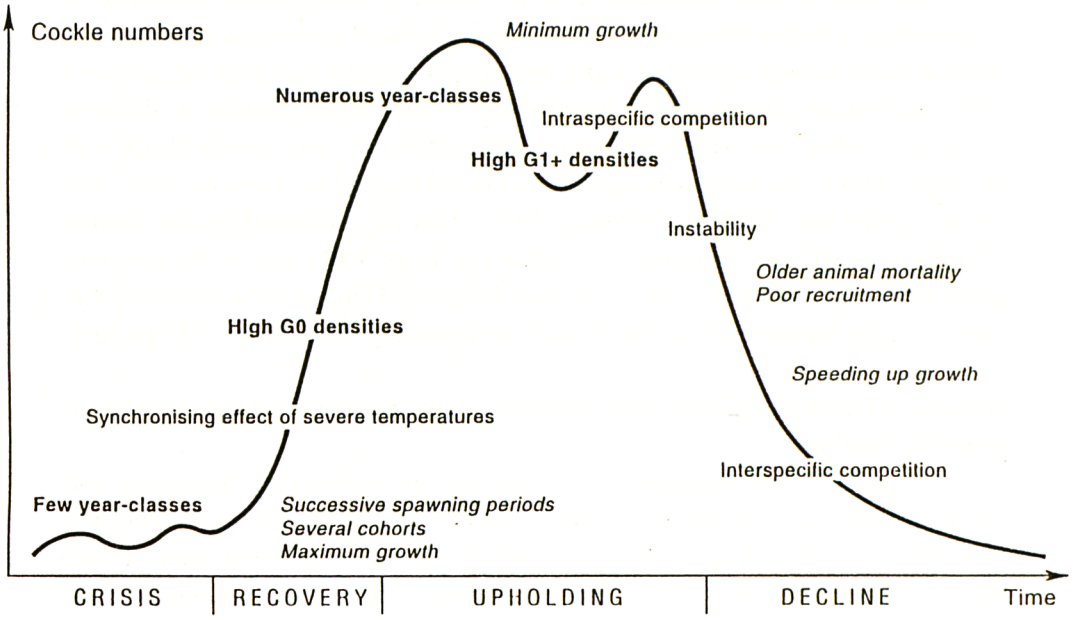

Figure 4. Summary diagram of population fluctuations in Cerastoderma edule in north-west Europe (after: Ducrotoy *et al.*, 1991b)

studies. It is not understood whether the inability to recolonize the substrate after severe winters was due the species being at the north of its range or whether man-made disturbances were also at work.

Cerastoderma edule is a short-lived suspension feeding bivalve. Known as the cockle to fishermen, populations are commercially exploited on a large scale in the Netherlands, Britain and France. The turnover of exploited populations is rapid and fluctuations in local fisheries have led to economic problems. The COST 647 studies helped to give perspective to the role of climate along a combination of north-south and west-east gradients in these regards. In comparing population characteristics, a simple model of population fluctuations was proposed (Figure 4) and the background to the success or failure of recruitment can now be explained (Guillou *et al.*, 1990). The inhibiting effect of adults on recruitment was shown through field surveys and manipulations of

adult densities *in situ* (Bachelet *et al.*, 1992). Mortalities of the bivalve were variously shown to be linked to the trophic capacity of the habitat, pollution and/or nutrient enrichment, the direct influence of climatic or biological factors such as parasitic infestations.

Macoma balthica is a deposit and suspension feeding bivalve with a moderately long life-span. Spatial and temporal surveys within the COST 647 project showed the influence of environmental factors (temperature, granulometry, emersion time, chlorophyll-a content of the water) on the species population dynamics, mainly through recruitment processes. While the number of cohorts was shown to be linked to phytoplankton blooms, direct pollution effects were not demonstrated (Ducrotoy *et al.*, 1985).

One of the most significant achievements of the COST 647 project was the archiving of data on several species up to 1992. There was better data management in the latter part of the project and it is hoped that the resultant databases can be expanded in the future.

Community changes in estuarie

Ducrotoy & Sylvand (1991 and in prep.) described and compared changes in the bio-sedimentary characteristics of the baie des Veys and the baie de Somme. Despite their differing geographical positions on the coast of the English Channel, the two sites showed similar morphological, sedimentary and faunal characteristic, e.g. the presence of a tidal deltaic area, high hydrodynamics and a low species diversity with high biomass.

Anthropogenic influences are also similar, e.g. land reclamation, the canalisation of rivers, pollution and nutrient enrichment. The macrobenthic assemblages reflected local environmental conditions and the typical estuarine communities were deemed to be at risk due to human activities and, possibly, climatic changes. One consequence is the loss of the productive muddy areas which are of more benefit to waders and fish than the poorer sandy areas and unused salt-marshes. Eutrophication may increase the productivity of estuarine communities but the attendant oxygen depletion can kill invertebrates in specific areas. Thanks to these studies, a scenario for future changes in the baie des Veys up to the year 2000 has been proposed by Sylvand & Savini (1991).

Changes in the distribution, biomass and diversity of subtidal assemblages

The Monitoring Master Plan of the North Sea included the sampling of

macrofauna as a voluntary requirement (Portmann, 1991). While most of the sampling stations were visited, difficulties arose in processing samples and/or collecting data. A comparison based on the 1986 North Sea Benthos Survey (Künitzer, 1990; Heip *et al.*, 1992) gave a reasonable idea of the regional-scale of differences in the various assemblages. This preliminary temporal comparison showed that changes observed at certain stations were dependant upon the type of assemblage involved (North Sea Task Force, 1994). Nevertheless, it was possible to define the role of local effects:

- changes in surface productivity,
- sediment redistribution,
- bottom shear stress,
- impact of fishing gear,
- low level pollution ,
- anoxia (localised and short lived).

This information has been very valuable and has proved to be a strong base for policy-making (Ducrotoy, 1996). Ten years is seen as a worthwhile separation between successive intercomparisons and it is hoped that further benthic survey of the North Sea might be carried out in 1996 or shortly thereafter.

CONCLUSIONS

The studies described above have shown that a satisfactory understanding of natural variability in marine ecosystems may be attained through the assessment of the bio-diversity of benthic species and the ecology of opportunistic species. Understanding the role of environmental factors can then help in discriminating between natural and man-made disturbances (Ducrotoy & Elliott, 1991). The predictability of benthic systems remains problematic as illustrated by the difficulties in managing the cockle resource in the Somme estuary (Lemoine *et al.*, 1988). Recruitment of benthic species is difficult to predict but the notion of "catastrophes" is very helpful in allowing predictions for whole communities in the medium term (Elkaim *et al.*, 1992).

To improve the usefulness of the bio-sedimentary approach, sampling methodologies and strategies need to be harmonised at an international level. Standard procedures and continuity in sampling strategy are essential. Intercalibration exercises need to be promoted in the interests of a common approach. Sampling frequencies need to be addressed and the long term changes of benthic communities at individual stations (treated as separate entities; notion

of pilot-stations) targeted. It is further recommended that spatial surveys of estuaries be carried out at various scales and at regular time intervals as they give a good idea of changes at community level. The location of pilot stations should be reviewed from time to time.

There is no valid basis for comparing the richness of a series of communities using a single index or a single method. A combination of methods, as suggested in the bio-sedimentary approach, could be adopted internationally. The recent Quality Status Report of the North Sea (North Sea Task Force, 1994) has emphasised the need for long-term time series of ecological data, especially those relevant to climate change and/or those giving indications of trends in anthropogenic effects (Ducrotoy, 1994). Therefore, the use of data on the environment, including information on climate and water/sediment chemistry, should be encouraged and used as appropriate.

Finally, a good interaction should be developed between scientists and policy-maker in order to define and take into account the relative importance of human activities versus the natural variability of marine and coastal benthic systems. Long-term studies are increasingly held to be of high scientific and decision-making value; they should be facilitated where possible.

ACKNOWLEDGEMENTS

The GEMEL-Picardie was supported primarily by a grant from the Région de Picardie. The author wishes to thank colleagues who have contributed to this research. Dr. B. Keegan kindly assisted with the final stages in writing this paper.

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PROTOCOLS

THE ENVIRONMENTAL MONITORING AND ASSESSMENT PROGRAM: A PARADIGM FOR LONG-TERM RESEARCH, MONITORING AND ASSESSMENT[1,2]

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ABSTRACT

The Environmental Monitoring and Assessment Program (EMAP) is an ambiguous initiative for ecological research, monitoring and assessment designed to report on the condition of ecological resources in the conterminous United States and identify stressors associated with estimated condition. One of the principal goals of the program is to provide decision makers with tools and data for assessing and managing environmental risks.

The specific objectives of EMAP are (1) to estimate with known confidence the current status of and trends in selected indicators of the condition of ecological resources, (2) to estimate with known confidence the geographic coverage and extent of those resources, and (3) to seek associations between selected indicators of natural and anthropogenic stresses and indicators of condition of ecological resources. Providing annual statistical summaries and periodic assessments of the ecological resources at regional and national scales also is an important program objective.

The program has adopted a probability-based approach to sampling in order to achieve representativeness with known confidence. The statistical survey design poses a convergence of temporal and spatial components. Ecological resources are sampled in proportion to their occurrence without intentional stratification. Collection of data over several years decreases the uncertainty of spatial estimates. Similarly, detection of temporal changes and trends requires multiple years of observation.

1. Presented at the International Workshop on Long Term Study Influences on Science and Policy, May 27-29, 1994, Galway, Ireland
2. Although the research described in this article has been funded by the U.S. Environmental Protection Agency, it has not been subjected to Agency review and therefore does not necessarily reflect the views of the Agency and no official endorsement should be inferred.

Geographic coverage and extent estimates are made through the use of existing data, including information from remotely sensed sources. Condition indicators are usually biological or ecological entities which provide measures relevant to societal values. Most condition indicators are critically selected to represent assessment endpoints having biological integrity, productivity or aesthetic implications. Indicators of natural and anthropogenic stress include the more traditional measurements of physical, chemical, climatic and habitat characteristics. Land use and land cover attributes supplement anthropogenic stress information.

Ecological resources studied include agricultural lands, rangelands, estuaries, forests, Great Lakes, surface water (both lakes and streams), and wetlands. In addition to these individual ecological resource classes, EMAP has an integrated landscape ecology component to address landscape-level configurations of multiple resources. Data produced by the program since the inception of field work in 1990 have demonstrated the utility and validity of the approach.

INTRODUCTION

Land and natural resources have continually provided life support for civilization on this planet. Ecological resources such as wetlands, farmlands, fisheries, and forests can be depleted through overuse, misuse, and pollution. In the past two decades, in the United States, pollution control efforts have improved the air quality in many cities, improved the quality of thousands of miles of rivers and streams, and restored thousands of acres of lakes. However, these efforts have not addressed the serious ecological impacts associated with long-term exposure or the subtle changes in our environment.

Addressing the environmental problems of the Twenty-first Century requires a scientific research program that focuses on sustaining our ecological resources. While the site-specific and pollutant-specific risk assessment issues remain critical, many threats such as cumulative pollution impacts and global climate change require the integration of traditional data bases with enhanced ecological assessment approaches.

The Environmental Monitoring and Assessment Program (EMAP) is a research, monitoring, and assessment program designed to determine the condition of our Nation's ecological resources. The multimedia approach of EMAP is designed to assist in verifying the cumulative effectiveness of

environmental policies and in identifying emerging ecological problems. The ultimate goal of the program is to provide decision makers with sound scientific data on which to base environmental risk management decisions.

OBJECTIVES

EMAP has three strategic objectives:

(1) Estimate with known statistical confidence the current status, trends, and changes in selected indicators of the condition of the Nation's ecological resources on a regional basis.

(2) Estimate with known statistical confidence the geographic coverage and extent of the Nation's ecological resources.

(3) Seek associations between selected indicators of natural and anthropogenic stresses and indicators of the condition of ecological resources.

Publishing annual statistical summaries and periodic assessments of the ecological resources studied by EMAP is an important aim of the program.

HISTORICAL BASIS FOR EMAP

EMAP was initiated in 1990 as part of a redirection of the EPA research program towards conserving the integrity and sustainability of our ecological resources. The need for EMAP became apparent in the late 1980s because we lacked the necessary information to describe the condition of the environment. In addition, we needed a way of verifying the cumulative effectiveness of our environmental policies. Although the United States spends between 2 and 3 percent (over $100 billion) of its Gross Domestic Product on environmental protection (EPA, 1990), we have had no systematic way of measuring our performance. No monitoring system has existed to evaluate over the long-term the overall condition of the Nation's ecological resources.

Furthermore, in 1988 the EPA Science Advisory Board (SAB) published *Future Risk: Research Strategies for the 1990s* and recommended that EPA initiate a long-term program to monitor ecological status and trends (EPA, 1988). Other groups including Congress and the scientific community also highlighted the need for a carefully planned and executed ecological research program.

Plans for EMAP began in 1988-89 and concentrated on developing a focussed approach to answer questions such as:

- What is the current status and geographic extent of ecological resources?

- What resources are degrading or improving, where, and at what rate?
- To what levels of stress or pollution are the resources exposed, and in which regions?
- What are possible reasons for resources degrading or conditions improving?
- What resources are at current or future risk?
- Are affected resources responding to control and regulatory programs?

These six questions are central to EPA's current risk-based strategy. Priority attention is given to problems posing the greatest risks. EMAP is designed to support these resource management efforts by identifying high risk environmental problems and by monitoring to determine whether changes in management strategies achieve desired results.

THE EMAP APPROACH

EMAP takes a multimedia or holistic perspective of the environment to provide system-level information about ecological condition (Kutz & Linthurst, 1990). Traditional single contaminant or single site approaches contribute to this; however, this approach lacks the comprehensive biological associative concept. The EMAP strategy represents a major technical and administrative shift in environmental management and protection by monitoring throughout the Nation over long time periods.

EMAP's approach combines a statistical sampling design with the use of biological, chemical, and physical indicators. This design uses a systematic sampling grid which allows for consistent spatial representation of all ecological resources in the Nation. EMAP's randomized design also ensures that each ecological resource is sampled in proportion to its geographical presence. Specified locations are sampled within an ecological resource to produce estimates of the condition and spatial extent of ecological resources on regional and national scales with known statistical confidence.

EMAP combines this probability-based sampling strategy with ecological indicators to determine the "health" of ecological resources. Traditionally, monitoring programs have measured pollutants in the environment to determine good or poor condition. EMAP takes a different approach: it focuses on the condition of plant and animal communities and ecosystem processes through ecological and biological indicators. Ecological resources are affected by multiple

stressors but are transported via multiple environmental media (water, air, and soil). These stressors can produce effects on entire populations and communities. EMAP measures two types of physical, biological or ecological indicators: condition and stressor. Condition indicators include measurement of ecological structure, composition, and function that are important to society. EMAP also measures the exposure of organisms to chemicals and other stressors. EMAP data provide the basis for determining associations between human-induced or natural stresses and ecological condition. In turn, EMAP assessments translate scientific results into information useful for decision makers.

Environmental Values and Indicators

Risk assessment is the formal process used by various governmental and private organizations to estimate risks to public health and the environment. It is a relatively new and rapidly developing science. At present, about seven Federal agencies are intimately involved with risk assessment; most of these agencies were in fact created within the last three decades (NRC, 1993). Although initially applied in the public health area, the risk assessment paradigm is now used for estimating ecological risks at various spatial scales.

Ecological risk assessment estimates the effects of human action on a natural resource and interprets the significance of those effects in light of the uncertainties identified in each component of the assessment process. The ideal output of the risk assessment process is an estimated probability that an event of a certain magnitude will occur, e.g., a 90% probability of loss of fish populations in 20% of the lakes in a region (Suter, 1990). The key components of risk assessment include (1) selection of endpoints, (2) qualitative and quantitative description of the stresses, including the origins (e.g., locations and emission levels for pollutant sources), (3) identification and description of the environments within which effects occur or are expected to occur, (4) estimation or measurement of spatiotemporal patterns of exposure, and (5) quantification and characterization of the relationship between exposure in the modified environment and effects on biota (Hunsaker & Carpenter, 1990). The adaptation of the standard risk assessment paradigm to accommodate ecological risk at different time and space scales has been accomplished (NRC, 1993).

Although the sequence of activities in traditional risk assessment moves from source(s) to exposure assessment and then to effects assessment, an epidemiological approach to ecological risk assessment is also appropriate (Suter,

1991). It is the latter step in the risk paradigm - effects-driven assessment -that is under development for EMAP. In effects-driven risk assessments, an effect is observed, and one then works toward identification of the hazard or stressors by using exposure information. The degree to which EMAP indicators can be used in a truly diagnostic manner is probably limited to associative relationships.

It is paramount to the success of a monitoring program that the characteristics of the environment being monitored be appropriate for the purpose of the program's assessment goals (NRC, 1990). The indicators of EMAP share some common characteristics with "endpoints," components of the risk assessment process. Two types of endpoints are used commonly in risk assessments. Assessment endpoints are "formal expressions of the actual environmental value that is to be protected." They should have unambiguous operational definitions, have social or biological relevance, and be amenable to prediction or measurement (e.g., a decrease in biodiversity, probability of a >10% reduction in game fish production, or the proportion of raptors killed within a region of pesticide use). The quantitative results of the measurements taken to characterize assessment endpoints are termed measurement endpoints. Measurement endpoints must correspond to or be predictive of assessment endpoints. Examples of measurement endpoints include the percentage of trees that exhibit visual symptoms of foliar damage due to oxidants, or the fraction of streams that exceed the LC_{50} for a toxicant to largemouth bass. Many of the criteria for good measurement endpoints for regional assessments proposed by Suter (1990), were used as criteria for EMAP indicators. In EMAP, the proportion of sites subnominal with respect to particular response indicators within a region are the proposed assessment endpoints.

Assessment endpoints by definition must relate to the environmental values identified for each resource category. Therefore, the measurement endpoints for EMAP are ideally response indicators. Exposure and habitat indicators are not our measurement endpoints because they do not integrate effects of multiple stresses. Occasionally, as in the case of wetland extent, a habitat indicator can serve as both a measurement endpoint and an assessment endpoint, for example, "no net loss of wetlands." Exposure or habitat indicators also can be used to identify possible threats to ecosystems.

It is important to keep the purpose of EMAP in mind when considering a risk assessment framework (EPA, 1992). EMAP response indicators (measurement endpoints) are monitoring tools that need to be primarily anticipatory or

representative of environmental effects rather than predictive. EMAP indicators must meet specific criteria associated with annual surveys conducted on probability samples of sites.

The type of risk assessment that EMAP could accomplish is likely to be an initial or "screening" assessment, i.e., EMAP indicators could comparatively risk some possible reasons for poor ecological condition. Additional research and more focused risk assessment would then be required to determine discrete cause-and-effect relationships.

Indicators Concepts Expanded

Ecological indicators represent broad categories of measurements used to signal environmental conditions and changes important to society. These changes may result from anthropogenic disturbances or represent natural variations. Indicators of both categories are needed to comprehend environmental changes, abate pollution, ascertain risk and restore damaged ecosystems (McKenzie *et al.*, 1992).

Many categories of indicators can be defined; for the purposes of this paper, these categories are response or condition, exposure, habitat and stressor. Table 1 presents these categories with examples of each. Response or condition indicators are characteristics of the environment measured to provide quantification of the biological or ecological condition of a resource at various levels of organizational integration. Exposure and habitat indicators are measured in conjunction with response indicators and provide characteristics of the environment measured to provide evidence of the occurrence or magnitude of a response indicator's contact with a physical, chemical, or biological stress. Habitat indicators are physical attributes measured to characterize conditions necessary to support an organism, populations, or community. Stressor indicators are characteristics measured to quantify a natural process, environmental hazard, or a management activity that effects changes in exposure and habitat. EMAP does not preport to produce all indicator information itself, but is using information from other monitoring and data collection efforts to provide some portion of particularly stressor information. Consequently, EMAP can be viewed as a geographically referenced organizational umbrella for a wide variety of environmental data of varying scales.

TYPE OF INDICATOR	EXAMPLES
Response or Condition Indicators	Community Structure Population Dynamics Gross Pathology Biomass Ecosystem Processes
Exposure - Habitat Indicators	Biomarkers Pathogens Bioassays Tissue Concentrations of Contaminants Ambient Concentration of Contaminants Habitat Structure Landscape Structure
STRESSOR INDICATORS	
Hazard Indicators	Atmospheric Deposition Census Data Regulatory Permit Information Land Use/Land Cover
Natural Process Indicators	Climatic Fluctuations and Events Pest-Plant Disease Relationships Predator-Prey Relationships Successional Stage
Management Indicators	Dredging/Filling Fire Management Harvest Rate Hydrologic Modification Landscape Pattern Pest Control

Table 1: Some examples of indicator classes

EMAP uses response indicators to describe ecological condition. Exposure and habitat indicators are used to provide plausible hypotheses for observed differences and changes in response indicators, and stressor indicators are used to identify possible associations with changes in exposure and habitat indicators. Analyses rely on correlative empirical approaches and, thus, cannot prove causality. The use of correlative approaches, however, can identify hazards that are geographically widespread, most intense, or associated with most rapid deterioration. Once EMAP identifies a geographic area with a high proportion of a resource in unacceptable condition, other projects can be designed and implemented to investigate causes and, thereby, provide insight into solutions.

EMAP also must seek to present its results in ways that are readily interpretable by the public and decision-makers. Assigning a threshold value to response indicators that will enable decision-makers and the public to distinguish "good" ecological condition from "bad" ecological condition is not possible *a priori*, because public concerns about ecological "health" can differ from region to region and can change with time. Also, ecological condition may reflect exposure to a multitude of environmental stresses including those that are related to human activities and those that are natural. Which indicators to implement in a long-term monitoring program that will provide the most cost-effective information on the status and trends of ecological condition must be carefully evaluated, and the effective use of relevant data collected by other operational monitoring programs clearly requires careful consideration.

Several other issues related to interpretation and summary presentations of indicator data require examination. These include addressing situations when resource sampling units in poor condition are associated with multiple exposure or habitat indicators. The use of indices, which are mathematical combinations or indicator measurements, provides a means to rank resources on an acceptable-to unacceptable continuum based on multiple measurements. Research is needed to select the most appropriate mathematical schemes to combine data that will summarize results without losing critical information.

Geographic information systems have the capability to overlay patterns in exposure, habitat, or stressor indicators onto patterns in response indicators across broad geographic regions to provide plausible hypotheses on ecological condition. EMAP also uses multivariate statistical techniques to analyze regional data sets. Finally, retrospective analysis techniques are used to evaluate current ecological condition at single sites and over larger areas, relying on archived remote sensing or other data that are available.

Resource Monitoring, Research and Assessment

During its first three years, EMAP has evolved three functional components: resource monitoring, research, and integration and assessment. EMAP is assessing the condition of seven ecological resources (defined within EMAP as: agriculture lands, range lands, estuaries, forests, Great Lakes, and surface waters). In addition, EMAP also has an integrated landscape ecology component called landscapes.

A program as ambitious as EMAP requires the participation of many organizations. Collaboration has been established among 12 Federal agencies, 27 States, and more than 50 universities. EMAP aims to integrate -- not duplicate -- the efforts of EPA offices, Federal agencies, States, the scientific community, and geographic initiatives such as the Chesapeake Bay, Great Lakes, South Florida, and Gulf of Mexico Programs.

Since its creation, EMAP has exercised leadership in coordinating large-scale assessment and reporting activities that include participation of agencies and institutions outside EPA. EMAP field studies are generally conducted through interagency teams. For instance, in EMAP-Forests, the major participants are the USDA Forest Service, the USDA Soil Conservation Service, EPA, Tennessee Valley Authority, and State forestry agencies.

SUMMARY

EMAP is dedicated to making its monitoring data and assessments widely available to resource managers, environmental decision makers, other scientists and the public. Once data have been properly validated, EMAP is expending considerable effort to ensure that all potential users are fully informed of the data content, limitations, unique characteristics and significance, as well as how to obtain the data. Reports are publicly available (Macauley *et al.*, 1994; Weisberg *et al.*, 1992; Schimmel *et al.*, 1994 & Summers *et al.*, 1992 & 1993). Use of EMAP data by the scientific community is being facilitated by on-line access to EMAP's Information Management System.

EMAP has a lot to offer. The primary interest is in EMAP's assessments of status and trends which will become stronger as baselines and databases expand in future years. Ultimately EMAP's success depends on its ability to interject high-quality, long term information into the environmental and natural resource decision-making process.

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IMPROVEMENTS TO LONG TERM BENTHIC STUDIES

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ABSTRACT

The relative stability and immobility of benthic organisms have resulted over the past thirty years in their becoming targets for many long-term studies of the effects of natural and anthropogenic change in marine ecosystems. Until recently such studies have tended to be individualistic and localised, but recent moves towards national and regional monitoring and surveillance schemes have focused attention on the inconsistencies and differences in both the design and execution of such surveys from area to area. Suggestions are made for improvements to the scope, resolution and quality of the data obtained from studies of long-term changes in marine benthic populations and communities. It is postulated that the geographic scale of long-term studies could be increased by the careful design and integration of local, regional and national survey grids. The scope of infaunal survey data might be increased by the development of sedimentary sonar scanners to map burrow structures and cavities in sampling areas. Such developments, combined with the increased use of SPI, video and still photography and side-scan sonar to map topographic features and epifaunal distributions in areas around infaunal sampling points, could provide a broader synoptic picture of the benthic system. The simultaneous assessment and subsequent integration of such comprehensive data on benthic communities should increase confidence in the interpretations made about the scale and implications of any temporal and spatial changes observed.and biological variables can be improved by greater use of multivariate analytical techniques such as Correspondence analysis and Canonical correspondence analysis and that data derived from such analyses might be used to develop predictive response models of the interactions of benthic organisms and environmental variables.

It is emphasised that standardisation of field collection, laboratory analysis and data handling techniques and the application of agreed quality control directives are essential if the best use is to be made of long-term survey data. Without such standardisation and quality guarantees, full confidence in the

comparability and replicability of data sets can not be maintained.

INTRODUCTION

The relative stability and immobility of benthic organisms have resulted over the past thirty years in their becoming targets for many long-term studies of the effects of natural and anthropogenic change in marine ecosystems. Until recently such studies have tended to be individualistic and localised, but recent moves towards national and regional monitoring and surveillance schemes have focused attention on the inconsistencies and differences in both the design and execution of such surveys from area to area. Thus, if effective and efficient survey data is to be collected and compared by different organisations working over extensive geographic areas, then considerable efforts have to be made to improve the scope, resolution and quality of the techniques and organisation of data collection and analysis. In this brief overview of the problems and possibilities in effecting such improvements, each of these general areas will be examined and suggestions made as to where improvements to present practices or the introduction of new techniques might improve the quality of long-term data acquisition and analysis.

Improvements to the scope of long-term studies

Integrated field survey designs

Nearly all long term benthic studies reported to date have been undertaken in relatively restricted local areas, e.g. the studies of changes in the benthos of soft sediments off the Northumberland coast over a fifteen year period reported by Buchanan *et al.* (1986) and Buchanan & Moore (1988). Many such studies have been concerned with the effects of pollution discharges of one sort or another (Pearson & Barnett, 1987). Such pollution studies have usually included at least one reference station situated in an area outside the influence of the pollutant effects. In the past decade, there have been moves in both Europe and North America to initiate and develop regional and/or national monitoring and surveillance schemes in coastal areas which will collect data on the sedimentary environment and biota at designated stations. It is suggested that, as these schemes are developed, they should be integrated with ongoing pollution monitoring surveys as far as is practicable or possible to improve both the scope and extent of the long-term surveillance exercise and to ensure that the individual pollution monitoring schemes can be predicted on an extensive background data

base. Such integration could be achieved by including the local monitoring survey reference stations in the developing regional or national networks. As an example of how such a development might be implemented, the present and possible future structure of monitoring surveys around oil installations in the Norwegian sector of the North Sea can be considered.

Modifications to the overall design of the North Sea surveys to take into account the possible impacts from any increase in the discharge of production waters is at present under discussion. It must be assumed that the sediments will be the ultimate sink for contaminants discharged in production waters, but that sedimentary accumulation of production water contaminants discharged to the water column will have a long-term, far-field, rather than a short-term, near-field, effect. It will be difficult to predict what areas might act as recipients for the long-term accumulation of such contaminants or, indeed, what their ultimate effects might be. However, a wide-scale monitoring programme will be essential if the impact of any such effects is to be assessed. As the sum of the present monitoring surveys, which extend over an area of 6° of latitude and 2° of longitude in the northern North Sea, is indeed an ongoing wide-scale monitoring programme, it seems logical to adapt the present survey design to the additional detection of far field effects. This could be done by combining the reference station(s) from each Field presently being monitored into a network, the data from which would be assessed jointly for appropriate environmental and faunal parameters deemed to be potentially sensitive to the subtle effects of low level contaminants of the type being discharged in production waters. It has been suggested elsewhere (Dinneen *et al.*, 1993; Mannvik *et al.*, 1993) that, where a number of fields are adjacent, or indeed even over lap, e.g. the Ekofisk and Frigg areas, then the spatial design of monitoring surveys should be modified to treat the entire area as a single unit. If the Norwegian sector of the North Sea were regarded as a single unit for monitoring purposes and a nested box design was adapted to contain sampling stations appropriate to every individual field within that area, then the requirements for both unified station networks to cover adjacent fields and for a far-field network could be most parsimoniously fulfilled. Thus a three tier design has been suggested. The first, or national level, would cover the entire Norwegian continental shelf area. The second, or regional, level would include a series of boxes each encompassing groups of adjacent, contiguous and/or overlapping Fields. Such regions are already recognised by the Norwegian Oljedirectoratet and seven have been defined to date along the southern and central areas of the

Norwegian coast. The third, or Field level would relate to single operational Fields within each area, i.e. the level that is addressed by the current survey design. A national level survey grid might consist of pairs of stations at differing depths sited at 0° 30' latitude intervals covering the area along the Norwegian coast between 57° and 72° N. Each regional area would be covered by a grid of stations positioned at 0.15' intervals of latitude and 0.10' intervals of longitude to coincide with the intersections of the concession blocks designated by the Oljedirectoratet. Where regional and national grids coincided, then those stations would be dedicated to both survey tiers. Each field area is surveyed at present by sampling a series of stations sited along transects radiating out from the central Field installations. It has been suggested that future Field grids might consist of a reduced number of stations chosen from the existing set and including the present reference station. This existing reference station should be also dedicated as a regional tier station. In this manner, a tiered survey design would provide integrated information at successively larger scales from local areas (0 - 10 km) through regions (10 - 100 km) to the entire Norwegian coastline (1600 km). The stations dedicated to all three levels provide the essential links for interpreting changes related to environmental variables influencing the system at these different scales.

Improvements to field sampling and observational technique

The scope of infaunal survey data might be increased by the development of sedimentary sonar scanners to map burrow structures and cavities in sampling areas. Appropriate technology exists to develop penetrative sonar scanners capable of imaging cavities, burrow structures and organisms to depths of several centimetres in marine sediments. Investment is required to adapt and develop short range, high frequency sonar technology to such ends. Such developments, combined with the increased use of sediment profile imaging (SPI), video and still photography and side-scan sonar to map topographic features and epifaunal distributions in areas around infaunal sampling points, could provide a broader synoptic picture of the benthic system. The simultaneous assessment and subsequent integration of such comprehensive data on benthic communities should increase confidence in the interpretations made about the scale and implications of any temporal and spatial changes observed.

Improvements to the resolution of long-term data

Improvements to the collection and interpretation of field data

The information gained from long term survey data could be greatly improved and increased by integrating data collected at different spatial scales in the survey area. Faunal and environmental data should be acquired using a variety of broad and narrow scale techniques. Thus the abundance and distribution of infaunal organisms and variations in local sedimentary factors can be assessed from core or grab samples supplemented by SPI and surface imaging of the areas sampled. More extensive information about the sampling area and the distribution and abundance of the larger epifaunal and demersal organisms in the vicinity should also be obtained using an appropriate selection of sledges and trawls. These should be deployed with video equipment to obtain simultaneous video records of the surface topography and more mobile fauna in the collection path and side-scan sonar should be used together with sonar assessments of comparative surface roughness, e.g. the ROXANNE system, to gain information on broad scale patchiness in the sedimentary environment of the survey area. Informative collation, integration, validation and interpretation of all such records, following detailed analytical assessment of the appropriate data in each scale of reference, can be greatly aided by the development and use of Geographic Information System (GIS) technology. The final assessment of such synoptic survey data should result in broader and more confident interpretations and predictions of the consequences of environmental change.

Improvements to the analysis of survey data

Marine ecosystems are structured on differing spatial and temporal scales by a range of environmental variables resulting from the interactions *inter alia* of meteorological, oceanographic, geological and biological factors. However, in recent years, their resultant natural variability has been extensively modified by man's activities in many coastal and shelf areas. It is critical, therefore, to distinguish anthropogenic from natural changes in the analysis of data series from long-term surveys. Such distinctions are dependant on the accurate collection, collation and statistical analysis of biological and environmental data. At present marine environmental surveys do not apply statistical methods which can detect environmental changes over time in a precise manner, and can not relate changes in biological communities directly to changes in environmental factors. Moreover, present survey designs are frequently inadequate to detect significant

levels of change in the environmental variables measured. However, the application of some recently developed multivariate statistical techniques to the analysis of marine environmental survey data could greatly improve the resolution and reliability of the information obtained from such surveys and increase the objectivity of the conclusions and predictions made from it. The multivariate methods commonly used to relate environmental data to biological data are indirect, e.g. graphical comparison of groups of sites with similar species composition with the distribution of environmental data at those sites. Grouping based on species composition is generally achieved using methods like clustering or non-metric multidimensional scaling (MDS), whereas principal component analysis (PCA) may be applied to group sites based on environmental variables. In general, the biologist deduces relationships by comparing grouping in the different data sets. The obvious disadvantage of such methods is that there is no measurement of the direct relationship between physical and biological gradients. Therefore it is not possible to define hypotheses to test the significance of co-occurring environmental and biological gradients, or to test changes in co-occurring gradients over years. In general, the methods are capable of delineating strong relationships but relatively poor at defining weak or mixed responses. More precise methods for the measurement of the strength of the relationship between environmental and biological gradients are available, but have rarely been applied to marine environmental data. Recently "correspondence analysis" (CA) and "canonical correspondence analysis" (CCA) which is used in gradient analysis, have been shown to be effective in identifying those environmental variables associated with the largest proportions of biological variance in a number of disturbed North Sea benthic communities (Feiler *et al.*, 1994; Greenacre & Feiler, in press). In addition, particular species which have a high negative or positive percent variance associated with the environmental changes have been identified. These analyses parsimoniously link trends in environmental and faunal variance in such a way as to allow significance tests of the observed changes to be made. Further analysis of the density fluctuations in these species from place to place and from year to year in relation to those of the environmental variables could be used to calculate dose/response curves for each type of disturbance. Such analyses could be used to develop predictive response models of the reaction of benthic organisms to particular environmental variables of groups of variables.

Improvements to data quality and standardisation

One of the major problem areas in long-term studies of biological change in benthic communities is in achieving comparability of data between workers from different areas or working subsequently in the same area. Technical standardisation of methodology and quality control of biological sampling in environmental surveys has only recently been given serious attention, stimulated by the growth of environmental assessment work and the need to establish rigorous biological environmental quality standards (EQSs). The collection of reliable data over extended time periods and comparison with similar information from other areas requires the adoption of rigorous protocols detailing standard methodology for the collection, preservation and archiving of samples, the sorting and identification of fauna and the methods of data analysis to be used in the final interpretations. Although protocols and guideline documents have been produced for, e.g. monitoring round oil platforms in the North Sea (SFT, 1990) and the HELCOM monitoring programme in the Baltic, such regional initiatives are not co-ordinated with other similar schemes elsewhere and, indeed, such schemes are not yet drawn sufficiently rigorously to preclude individual variations in a number of critical areas. The development of detailed protocols for application to all accumulative benthic survey data is essential if true comparability is to be achieved. Agreement on the form of such protocols across as wide a spectrum as possible of those organisations involved in the acquisition and use of long-term benthic survey data is an urgent need. Thus the creation, adoption and application of standardised techniques to control the quality and comparability of long-term data is perhaps the single most important improvement needed for the future development of long-term benthic studies.

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THE DETERMINATION OF GLYCOGEN IN PRESERVED MATERIAL AS A RETROSPECTIVE INDICATOR OF ENVIRONMENTAL STRESS

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A method is described for the measurement of glycogen in material preserved in formaldehyde solution or ethanol. Comparison of contemporaneous preserved and fresh-frozen material showed no significant differences. The effects of long-term storage on glycogen contents also appeared small in comparing specimens from the same site and different years. The analysis of long-term data sets by this method is also discussed.

INTRODUCTION

One of the subjects addressed by the steering committee on long-term data sets was the effective utilisation of historical data. The term 'historical data' maybe taken to include the physical entities that constitute museum and laboratory collections. Traditionally, this material has been primarily accumulated over many years for initial taxonomic study and subsequent reference; such material has been used more rarely as the basis of retrospective studies of population or community ecology. In the last few years however financial and other pressures have forced those responsible for such collections to assess their scientific value and, in some cases, to dispose of large amounts of material that is often unique in its temporal and or spatial coverage. Apart from the destruction of valuable information the loss of these collections also represents the loss of massive past investment of time and effort. This latter consideration is particulary true of collections of deep-sea material and so, as part of collaborative studies

sponsored by the MAST I and II programmes and the British Natural Environment Research Council 'Deepseas' project, the Department of Oceanography at Southampton University, working in conjunction with the Natural History Museum and the Institute of Oceanographic Sciences Deacon Laboratory has developed techniques to obtain new information from preserved material, thereby enhancing its value and reinforcing the justification for its retention.

The techniques and approaches described below produced results that not only addressed the specific topic of the treatment of historical data but also sought to answer the four main questions posed by the steering committee which were:

1. Can long-term studies be of scientific and decision making value?
2. What are the differences between long-term and short-term studies?
3. How can long-term studies be improved?
4. Can long-term studies show the difference between natural and anthropogenicchange, so as to determine the relative importance of the latter?

Techniques and approaches

The measurement of glycogen and other macromolecular storage products in shallow-water animals has been put forward as a simple means of monitoring their nutritional status particularly in response to seasonal or other major environmental change (Bayne *et al.*, 1980). The amount of glycogen per unit body weight represents the amount of assimilated energy stored after the metabolic requirements of an individual have been met i.e. as a first approximation glycogen concentrations are *usually* inversely proportional to the degree of environmental stress or disturbance. The potential of these measurements as indicators of ecological variation may be enhanced by coupling them with observations of reproductive state. In many cases however, but especially with respect to deep sea sampling, access is often confined to chemically preserved material.

Whilst it is relatively easy to make quantitative histological studies of the reproductive state of such samples the biochemical composition of material fixed in aqueous formaldehyde solution and preserved for long periods in buffered formaldehyde solution or ethanol is not normally examined because of the obvious problems of denaturation of proteins, loss of soluble components, and leaching of lipids in non-polar media. Pearse (1980) has reviewed the quality of

preservation of metabolites such as lipids and glycogen by buffered formaldehyde solution and 70-80% ethanol, however, and has described the standard histochemical methods that use amylase digestion as part of the procedure for the detection of glycogen in sections from chemically preserved material. Also, the precipitation of glycogen in fresh tissues by treatment with ethanol is incorporated in methods for the enzymic determination of glycogen given by Johnson and Fusaro (1966) and Passoneau *et al.* (1967). Given the accepted validity of the above methods it would seem feasible to make enzymic determinations of the glycogen contents of chemically preserved material that should be comparable with fresh or frozen samples. This hypothesis was tested as part of a study of the physiological ecology of deep-sea species.

Preliminary experiments on a variety of preserved specimens indicated that glycogen could be measured in samples fixed in formaldehyde solution and subsequently preserved in 4-10% neutral buffered formaldehyde solution or 70% ethanol. Material preserved in formaldehyde solution required washing in multiple changes of 70% ethanol over several weeks until the formaldehyde was removed. The presence of formaldehyde residues from initial preservation will inhibit the subsequent enzymic assay. The amount of washing was dependent on the size and nature of the tissues analyzed and, on the basis of the yields of glycogen from subsamples taken from a single animal, it was found that the best results were obtained from pieces of tissue no larger than 1 g wet weight. These tissue samples were placed in a volume of 96% ethanol equal to approximately 20 times the sample weight. The ethanol was changed at least 5 times over a period of 15-20 d; larger samples required a longer period and more changes of ethanol.

The presence of aldehydes, principally formaldehyde but also any free reducing sugars from glycogen breakdown during storage and washing, may be detected in the discarded ethanol washings using the Schiff reaction test described by Vogel (1948); Benedict's, Fehling's or Tollen's tests should not be used because there is a slow reaction between ethanol and these reagents. The continuation of washing after the first negative test is at the discretion of the experimenter but as an empirical safety factor the number of washes for the work performed at Southampton was set at a minimum of 5 or until there were 3 consecutive negative tests.

It should be noted that material preserved in acidic media such as unbuffered formaldehyde solution should be avoided as there is a potential error

caused by the acid hydrolysis of glycogen forming soluble oligo- and monosaccharides that are lost during the washing procedure, thereby producing an underestimate of glycogen content. Samples with a very high lipid content, such as fish livers, required pre-treatment before ethanol washing to remove all traces of lipid since they could not be completely removed by ethanol washing and were found to prevent complete enzymatic hydrolysis of glycogen storage granules. The lipids were removed by placing the samples in 2:1 chloroform-methanol mixture approximately equal in volume to 20 times the sample wet weight. The solvent was changed once over a period of 24 hours before proceeding to the ethanol washing.

After the final wash the ethanol was removed by freeze-drying so as to allow the enzymic determination of glycogen content using the method described by Keppler and Dekker (1984), who give the constraints and limits of accuracy of the method. Glycogen contents were calculated as mg glycogen (g dry wt)$^{-1}$ by comparison of samples with a standard of 1 mg cm^{-3} suspension of oyster glycogen (from Merck Ltd, Poole, U.K.) in distilled water. The latter procedure was adopted as a means of checking the accuracy of the enzymic assay of glucose liberated by amylase digestion of glycogen.

RESULTS

1. Validation

The validity of the above method was tested in two ways. Firstly, by comparison of contemporaneous samples collected from the Rockall Trough, January 1990. The livers of the deep-sea fish *Coryphaenoides rupestris* were divided at the time of sampling and either frozen or preserved in 4% buffered seawater formaldehyde solution. Comparisons of the fresh-frozen and

DEPTH(M)	FRESH-FROZEN	FORMALHYDE PRESERVED
	mg (g dry wt)-1	mg (g dry wt)-1
700	3.70 ± 2.53	3.18 ± 1.37
1,350	3.64 ± 1.27	3.09 ± 2.9

Table 1. Comparison of the liver glycogen contents of specimens of *Coryphaenoides rupestris* either frozen or preserved in buffered formaldehyde solution. Animals collected from the Rockall Trough, January 1990 (Stations 74/90/1 and 2). Mean values 1 SD, n = 18. All specimens were female.

formaldehyde solution-preserved samples (n = 18) from 700 and 1,300 m (Table 1) gave *t* statistics of 0.767 and 0.737 respectively so that the two-tailed probabilities were 0.45 and 0.47, indicating non significant differences between the two treatments at each depth. Secondly, the effects of long-term preservation were examined by measurement of the glycogen contents of the body walls of preserved specimens of the holothuroid *Oneirophanta mutabilis* collected between 1979 and 1983 during the IOSDL Porcupine Seabight programme (see Rice *et al.*, 1991). Fresh-frozen material of the same species, collected at similar depths in May 1991 during RRS `Challenger' cruise 79, was analyzed using the same method but was not pretreated with ethanol before drying. Measurements were obtained from 1-cm diameter discs of body wall cut from the anterior of the ventral surface of each animal (Table 2). A two-tailed *t* test was applied to the data and gave a *t* statistic of 0.166 giving a two tailed probability $P = 0.87$ and indicating that the difference between the two groups was non-significant.

PRESERVATION METHOD	MEAN GLYCOGEN CONTENT	SD
	mg (g dry wt)-1	
70% ethanol	1.414	0.589
Fresh frozen	1.482	1.220

Table 2. Comparison of the glycogen contents of preserved and frozen samples from *Oneirophanta mutabilis* collected from a depth of 4,800 m. N = 11

Application:

i) Investigation of the Bathymetric Zonation of Deep-sea Benthic Megafauna.

By assembling a suite of samples from the 'Discovery' collection it was possible to examine the relationship between glycogen accumulation and bathymetric zonation in two species of holothurian (see Figs 1 & 2). These samples were collected from the Porcupine Seabight and Porcupine Abyssal Plain by IOSDL, between 1979 and 1983. It would not have been possible for a single research cruise to be mounted so as to be able to assemble such a comprehensive set of samples with which to investigate the metabolic processes underlying these zonations. In both species it can be seen that there was a mean decline in glycogen content with increasing depth. In *Laetmogone violacea* the correlation

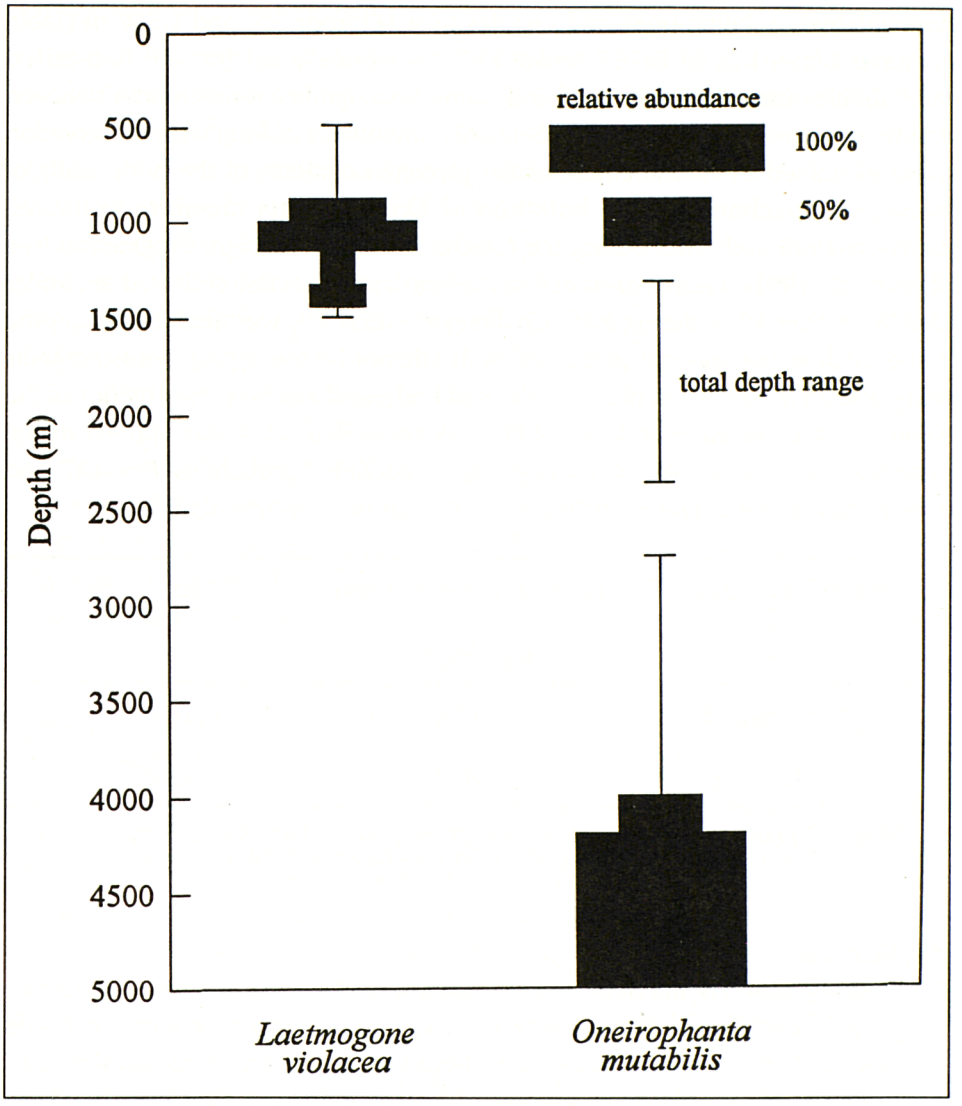

Figure 1. The bathymetric zonation of the holothurian species *Laetmogone violacea* and *Oneirophanta mutabilis* from the north-east Atlantic, shown as relative abundance versus depth. (modified from Billett, 1988).

was significant at the *P* 0.001 level and in *Oneirophanta mutabilis* the correlation was significant at the $P = 0.052$ level. The lowest glycogen levels found in *L. violacea* occurred at the maximum depth of occurrence. The sudden drop in glycogen in *O. mutabilis* between 4200 metres and 4400 metres coincided with a

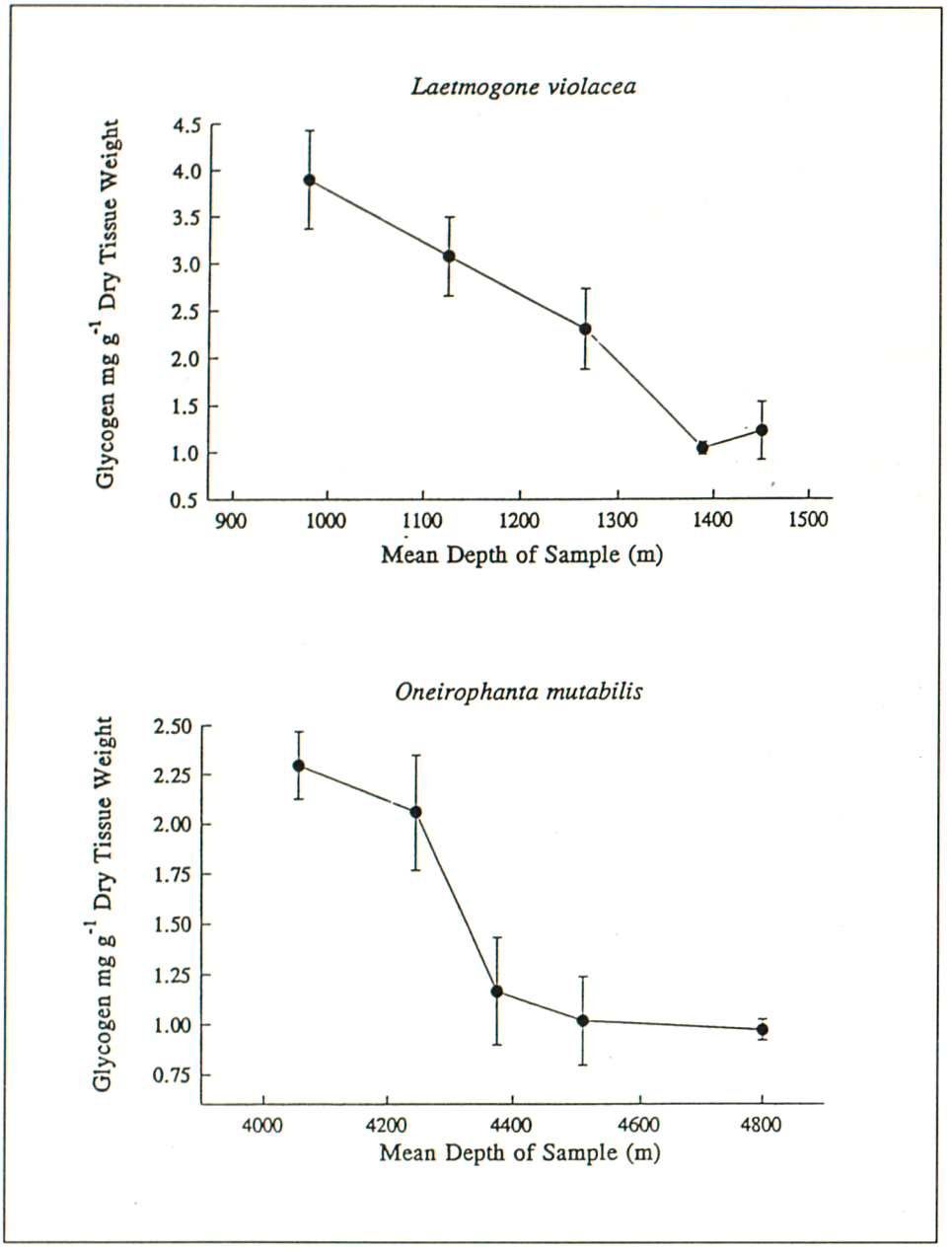

Figure 2. Body wall glycogen content versus sampling depth in holothurian species *Laetmogone violacea* and *Oneirophanta mutabilis* from the north-east Atlantic. Mean values SD.

change in the abundance of this species.

ii) Detection of biotic disturbance effects on the abundance of *Glycera mimica* Hartman.

Glycera mimica was one of the dominant polychaetes, often the dominant species, within the Rockall Trough samples, particularly those from the Scottish Association for Marine Science permanent station in the Rockall Trough, 54°N: 12°W, (Table 3; Paterson, 1993). Glycogen levels in *Glycera* showed an increase from 400m to 1000 m then significant drop before recovering and slightly reducing among the 2875 m replicate samples (Fig.3).

While individual variation in glycogen levels were large, the depth trends can be related to the abundance and dominance of *Glycera* within samples. When glycogen levels were low *Glycera* was observed to be a sub-dominant and often co-occurred with other predatory species (Table 3). In the 400m samples *Glycera* co-occured with *Typosyllis* and *Protodorvillea* both considered to be predators (Fauchald & Jumars, 1979). In both the 800 m and 1000 m samples the occurrence of other predator species was low whereas *Glycera* was abundant and the mean glycogen levels increased. At 1200 m the dominant species was another predator *Paraphinome pulchella* and the abundance of *Glycera* was particularly low with correspondingly reduced glycogen levels. Finally, glycogen levels rose and *Glycera* was found to be the dominant species at 1400m. While at 2875m on the floor of the Rockall Trough there was a slight decrease in glycogen, although *Glycera* was dominant in these samples, the predator species *Paramphinome* also occurred as one of the five most abundant species.

The data is suggestive of a link between glycogen levels, therefore `health', of Glycera and its dominance and co-occurrence with other polychaete predators. As a hypothesis we suggest that there is some form of interaction, possibly competion for similar resources, between *Glycera* and other polychaete predators such that when other species of polychaete predator are present *Glycera* is less successful and this shown by reduced levels of metabolic storage products, e.g. glycogen.To test this hypothesis will require refining the methodology to take account of the large individual variation and analysis of further samples at intermediate depths. Also it would be interesting to determine the glycogen levels of *Paramphinome pulchella* and relate the results to those of *Glycera*. If the patterns observed in this study are confirmed by further research then the implication is that deep-sea polychaete predators may not be specialised.

400 m Replicates					
Dominants	**Trophic group**	**SBC210**	**Dominants**	**Trophic group**	**SBC211**
Aoinides sp A	SDT	156 (43.8)	Aoinides spA	SDT	68 (35.4)
Pereseilla spA	BMX	30 (7.5)	Glycera minima	Predator	31 (16.1)
Glycera minima	Predator	27 (7.5)	Typosyllis spA	Predator	12 (6.25)
Typosyllis sp A	Predator	20 (5.6)	*Ancistrosyllis* spB	Predator	7(3.6)
Notomastus spA	BMX	14 (3.9)	Notomastus spC	BMX	7 (3.6)
800m					
Glycera mimica	Predator	31 (21.4			
Peresiella sp A	BMX	16 (8.3			
Tharyx spA	SMT	9 (4.7)			
Polynoidae sp A	Predator	6 (3.1)			
Spionidae sp	SDT	6 (3.1)			
1000m					
Jasmineira sp A	SDT	67 (18.9)			
Glycera mimica	Predator	60 (16.9)			
Lumbriclymeninae	BSX	27 (7.6)			
Myriochele sp A	SDT	615 (4.2)			
1200m					
Paramphinome pulchella	Predator	39 (16.5)			
Poecilochaetus sp A	SDT	27 (11.5)			
Spiophanes cf. annoculata	SDT	16 (6.8)			
Maldaninae sp A	BSX	11 (4.7)			
Glycera mimica	Predator	10 (4.3)			
1400m		SBC64			
Glycera mimica	Predator	23 (11.9			
Myriochele sp A	SDT	11 (5.7)			
Aurospio dibranchiata	SDT	11 (5.7)			
Heterospio longissima	SDT	10 (5.2)			
Sclerobregma branchiatum	BMX	8 (4.1)			
Permanent Station 2875m		SBC46			SBC49
Glycera mimica	Predator	40 (15.7)	*Glycera mimica*	Predator	46 (19.2)
Aurospio dibranchiata	SDT	29 (11.4)	*Aurospio dibranchiata*	SDT	22 (9.2)
Paramphinome pulchella	Predator	16 (6.3)	*Allia quadrilobata*	SMX	18 (7.5)
Chaetozone sp A	SMT	14 (5.5)	*Tharyx* spA	SMT	17 (7.1)
Tharyx sp B	SMT	13 (5.1)	*Tharyx* spB13 (5.1)	SMT	17 (7.1)

Table 3. The five most abundant species in each of the Rockall Trough samples analysed. SBC refers to the quantitative spade box core sample number, trophic group follows the classification given by Fauchald and Jumars (1979), the numbers are the number of individuals in the sample and the number in brackets the percentage abundance.

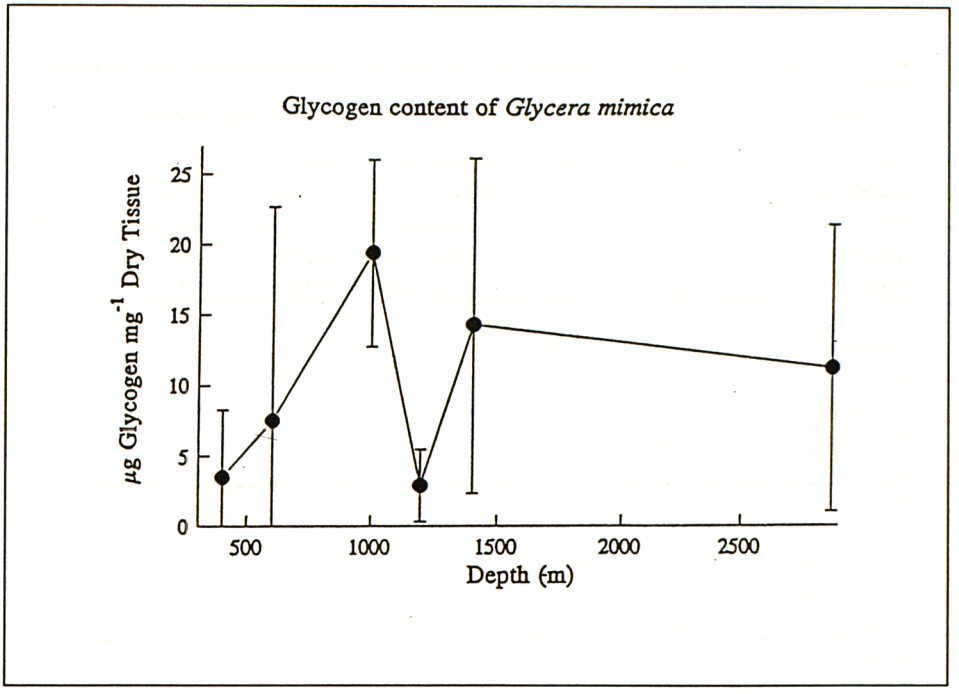

Figure 3. Glycogen content versus sampling depth in the polychaete species *Glycera mimica*, from the Rockall Trough, north east Atlantic. Mean values SD.

iii) The Somme Estuary Long-term Sampling data.

Access to the collection of benthic macrofauna collected from the lower Somme estuary by colleagues at the Group d'Etude de Milieu Esturiens et Littoraux (GEMEL) laboratory at St Valery-sur-Somme, France, made it possible to use the glycogen assay method to examine the temporal variability in the key macrofaunal species; in the example shown in figure 4 the long-term variability in the polychaete *Nereis diversicolor* was examined. This example illustrates the need to include periods of high resolution sampling when planning long-term studies. These data show the correlation between glycogen and faunistic changes and there are significant long-term cycles in the data of the order of 6-7 years (E. Gallagher, *pers.comm.*) However, there was insufficient temporal resolution to have shown the depletion of glycogen that is known to presage the decline of populations of another dominant estuarine macrofauna species *Cerastoderma edule* in Southampton Water (Savari *et al.*, 1991).

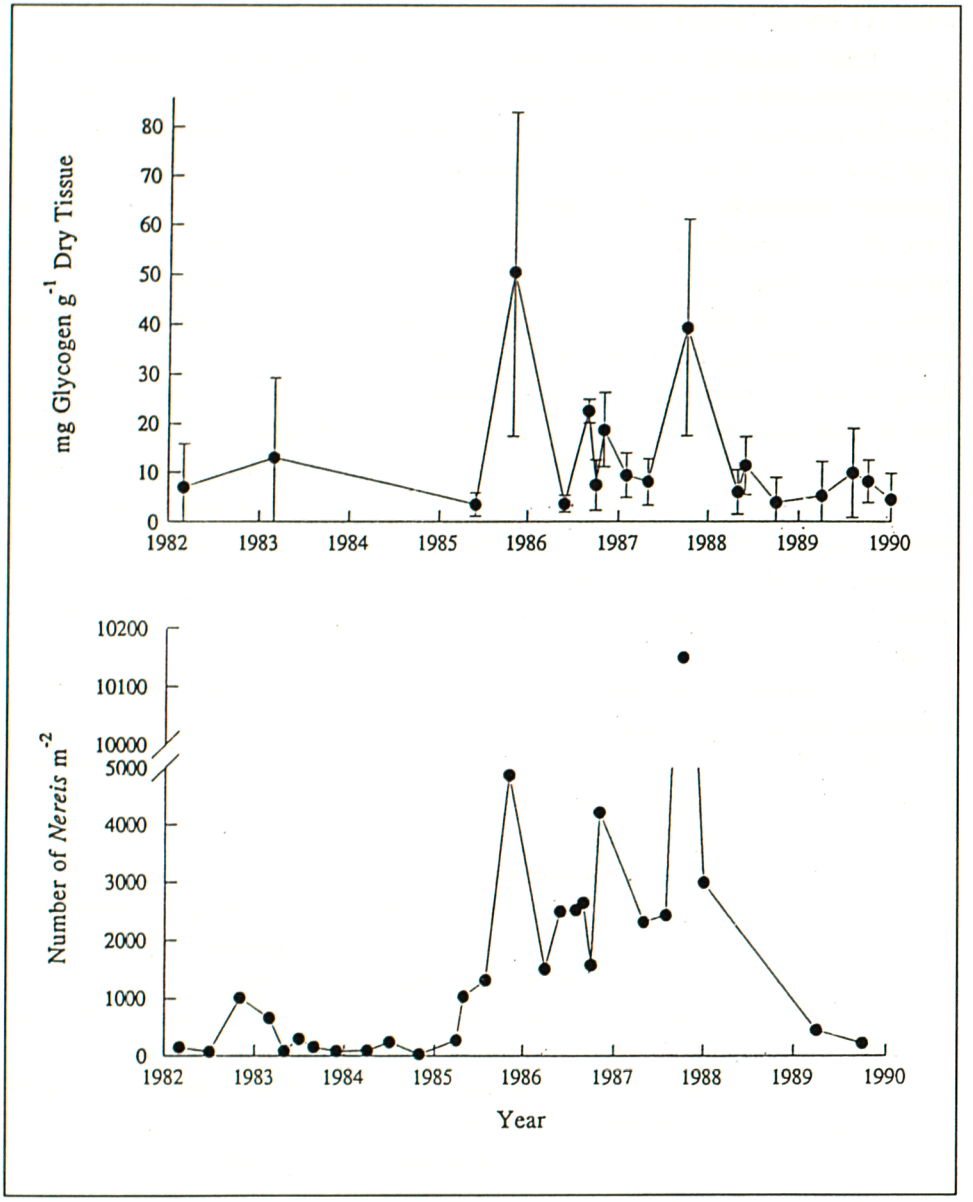

Figure 4. Glycogen content and areal abundance versus sampling depth in the polychaete species *Nereis diversicolor*, from the Baie de Somme, France. Mean values SD.

CAVEATS AND CONCLUSIONS

There are often apparently anomalous results produced by this type of investigation and it is a truism that no single indexation method can completely describe animals' responses to their environment. These difficulties can be overcome to a greater or lesser extent by adoption of what may termed a `pluralist' approach. In the examples given above the glycogen measurements were always considered in conjunction with histological examinations of the gonads and digestive organs, as well as all the available information on the physico-chemical conditions at the time of sampling. The benefit of such an approach is best illustrated by a brief example. Initial analysis of two species of decapod crustacean (*Nephrops norwegicus* and *Nephropsis atlantica*) showed that in both species their mean glycogen contents were minimal at their abundance maxima. Subsequent histological studies showed that they were accumulating lipids; lipid and glycogen storage cycles are generally antiphase in marine invertebrates, reflecting the effect of reproductive lipogenesis from complex carbohydrate substrates (Gabbott & Walker, 1971: Gabbott, 1975). Reproductive activity was most likely to be at a maximum at the abundance maximum.

To conclude, the retrospective analyses described above provide the following answers to the four questions posed in the introduction:

1. The methods described above enhance the scientific and decision making value of long-term data sets by extracting new information from them. This can be used to examine the processes underlying ecological patterns and can have a predicative capability.
2. The difference between long-term and short-term studies is generally one of the minimum sustainable sampling resolution required to answer the questions posed by the starting hypothesis and which will also be dictated by the analytical methods that are chosen. The use of new analytical methods such as that described here make it possible to fill in gaps in data and to retrospectively extend contemporary short-term studies. The analysis of the long-term Somme estuary data was intended to define the broad-scale variability in the ecosystem as the background for a more intensive 2 year study.
3. Apart from the need to re-evaluate the biochemical information contained in remaining long-term data sets the powerful new statistical analyses (described elsewhere in this volume) of such data greatly enhance the quality and quantity of information that can be obtained.

4. Given the great variability that can be found in ecosystems where anthropogenic effects are minimal then information defining a baseline of responses to the normal ranges of the major natural variables is a *sine qua non* of any attempt to accurately gauge anthropogenic effects. The definition of such baselines will require access to existing or new long-term sampling programmes with the appropriate levels of spatial and temporal resolution.

ACKNOWLEDGEMENTS

This work was a component of the Institute of Oceanographic Sciences, Deacon Laboratory (IOSDL) 'Deepseas' project and partly funded by the European Community's Marine Science and Technology (MAST) programme contracts MAST-0037-(EDB) and MAS2-CT92003. The contributions of Dr A.L. Rice, IOSDL; Dr J-P. Ducrotoy, University College, Scarborough and Drs M. Desprez, H. Rybrazyk and colleagues at the GEMEL laboratory, St Valery-sur Somme and Dr J D Gage, SAMS are gratefully acknowledged.

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ON SEASONAL AND INTERANNUAL ZOOPLANKTON AND BENTHOS DYNAMICS*

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ABSTRACT

Biweekly counts of zooplankton and benthic invertebrates at North Inlet, South Carolina (USA), 1981-1992, display seasonal patterns which are alternating periods of exponential growth and decay. These time series are well modeled statistically in the log scale by nonlinear least squares fits of simple splines (piecewise linear regression functions); coefficients of these splines have direct ecological interpretations as estimated annual taxon growth and decay rates, and as julian dates beginning growth and decay seasons. In this paper, a random effects analysis on the coefficients of these spline models, called mixed model spline time series, is offered as a means of quantifying the interannual dynamics of these taxa. Using this analysis with sufficiently long series, interannual variability in growth and decay rates, annual maxima/minima, net annual growth/decay, growth/decay season length, and growth/decay season start dates can be objectively measured and tested, as can (in principle) correlations in these and related quantities across years and between series. However, a series of ten years or longer is required for even minimally accurate assessment of interannual variability: conclusions on interannual benthic population dynamics based on only a few years' data are unreliable. As examples, six eleven-year series show considerable interannual variability in annual maximum and minimum abundance: the least variable taxa show about 30% variation from year to year in annual maximum and minimum abundances; two of the taxa, however, show 400-500% variation in annual extreme abundance from year to year. The statistical analysis used in this paper, though valid for these data, is only prototypical, and far from user-friendly in its current form. Support is needed for development of these and other statistical methods for ecological and environmental field studies.

INTRODUCTION

Variability in benthic abundance data is severe, as demonstrated here and in several other articles in this volume. This variability can be dissected conceptually into four sources: measurement error variability, spatial variability, seasonal variability, and interannual variability. The crux of the debate on the utility and necessity of long-term studies can be posed in statistical terms as a question concerning the relative magnitude of the interannual variance component: if interannual variability is in fact trivially small, there is little to be gained from extending a series beyond a few years' duration.

Though it is generally believed that each of the four sources of variability is nonnegligible in magnitude, this belief is largely based on cursory inspection of data descriptives such as time series plots of monthly means with standard error bars, and/or on the informal and often improper use of nested analysis of variance (ANOVA), using years and months-within-years as factors (e.g. Millard *et al* 1986; Michener *et al* , 1987). Informal, "eyeballing" assessments will usually overestimate the size of interannual variability, since any variance we see with our eyes is due to all four components and hence larger than any one component alone. Nested ANOVA can be a useful descriptive analysis, but assumptions underlying its formal inferences (e.g. hypothesis tests) are usually far from true, and at any rate these models are such crude approximations that they may blur important patterns in the data.

In this article we define a new approach to quantification of interannual variability for time series which display a pattern commonly found in benthic abundance data: alternating periods of exponential growth and decay. We apply this analysis, called mixed model spline time series analysis, to measure the interannual variability in annual maxima and minima in six eleven-year, biweekly time series of representative zooplanktonic, meiobenthic and macrobenthic taxon abundances. These have been collected at the North Inlet, South Carolina, USA estuary as part of the ongoing Long Term Ecological Research (LTER) project (Callahan, 1984; Franklin *et al*, 1990; Magnuson & Bowser 1990). From the results, it is apparent that (1) long series (ten years or more) are needed simply to get minimally accurate estimates of interannual variability; and (2) the interannual variance components in our abundance data are quite large in estimated magnitude, and are statistically significant. A final, tangential assertion is that the statistical tools currently available to obtain formal answers to many ecological questions are inadequate, and in need of active and financially supported development.

METHODS AND MATERIALS FOR EXAMPLE DATA

Study site.

North Inlet, South Carolina, USA (33° 20′ N, 79° 10′ W) is a hydrographically complex estuarine system (3200 ha) consisting of numerous tidal creeks (22% of area) and saltmarsh vegetation, chiefly *Spartina alterniflora* (70%). It is well-mixed and has a mean semidiurnal tide range of 1.6 m. Mean water depth of the major tidal creeks is 3 m (maximum 8 m), water velocities seldom exceed 2.3 m s^{-1}, and water exchange takes place via Town Creek with the Atlantic Ocean through the mouth of North Inlet about 2.5 km from the collection sites (Kjerfve *et al.*, 1991).

Field sampling.

For zooplankton, a site in Town Creek within 200 m of the of the mouth of Bread and Butter Creek was sampled every 2 wk from January 1981 to December 1985. Zooplankton were sampled with paired, sequential 153 µm closing nets with flow meters mounted in the center of the mouth opening. Both nets were deployed from a stationary boat during peak ebb tide velocity about 1 h before daytime slack low water. Closed nets were lowered to near the bottom (maximum depth 4 m) and opened by messenger. The nets were fished for 1 min at depth, raised half the distance to the surface and fished for another minute, and then raised to just beneath the surface for a final minute. A minimum of 1 m^3 of water was filtered in this manner. Upon retrieval, net contents were transferred from the cod end to storage jars, stained with Rose Bengal and fixed in a 10% formalin + seawater mixture.

Meiofauna were collected subtidally about 100 m inside the mouth of Bread and Butter Creek by taking 2 replicate 5.32 cm^2 cores to the depth of the redox layer (usually 1 to 2 cm) at the long-term muddy site described by Coull (1985). Each core was extruded and immediately fixed in 10% buffered formalin with Rose Bengal.

Macrobenthic fauna were collected subtidally within 50 m of the meiofaunal collection site by taking 2 replicate 141 cm^2 cores 15 cm deep (from 1981 to 1984) and 8 replicate cores (18.1 cm^2, 0 to 5 cm) from 1985 to 1992 (Service & Feller, 1992). Each sample was extruded and fixed in 10% buffered formalin with Rose Bengal. Data for only the 0 to 5 cm segment of the larger cores were used in this analysis.

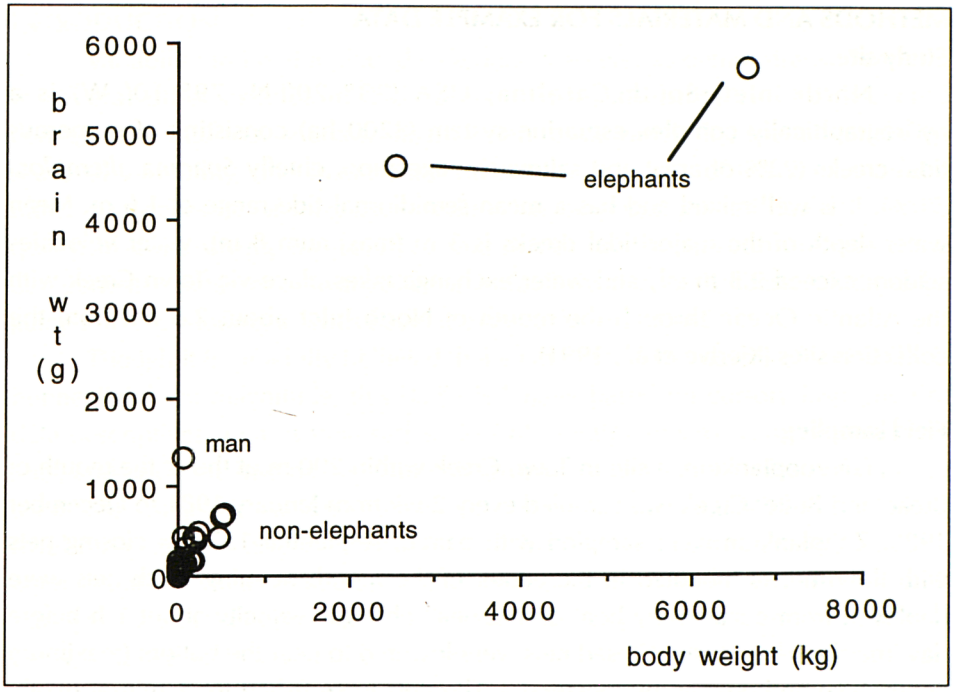

Figure1a. Brain weights versus body weights for 62 species of terrestrial mammals. Source: Allison and Ciccheti (1976).

Laboratory analysis.

After each zooplankton sample was brought up to 200 ml, 2 ml Stemple pipette subsamples were taken (2 replicates with replacement) and all organisms counted to major taxon. Counts were adjusted to number per m^3 according to volume filtered. Each meiofaunal core sample was extracted using Ludox centrifugation (de Jonge & Bouwman, 1977). All animals passing through a 0.500 mm mesh but retained on a 0.063 mm sieve were counted to major taxon. Macrofauna were extracted by gently washing preserved samples through a 0.500 mm sieve. All organisms retained were identified to major taxon.

Example series.

Six major taxon abundance time series have been selected as examples for analysis: two each from zooplankton (barnacle nauplii, total copepodids), meiofauna (total nematodes, meiobenthic bivalves), and macrofauna (*Capitella capitata* , macrobenthic polychaetes). Five of these six are for mixed-species

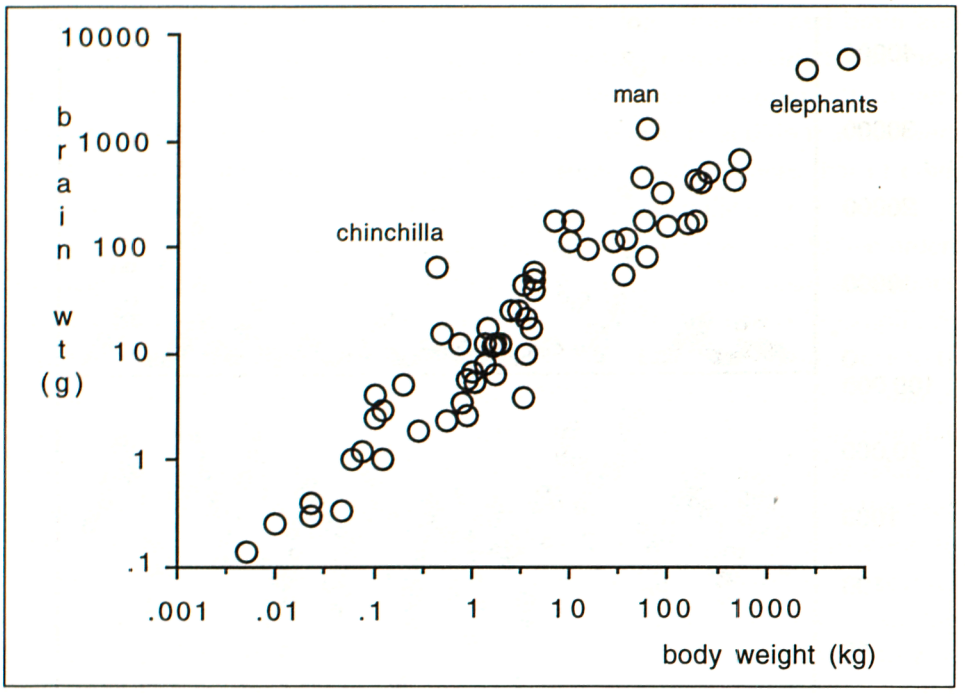

Figure 1b. Data from Figure 1a, plotted on logarithmic scale.

assemblages. These series were not chosen because of any hypothesized interrelationships or ecological interactions, but simply because they are abundant groups whose time series display the range of patterns we have observed in most of the other more abundant zooplankton and benthos taxa. Less abundant taxa are not used as examples here, since the analyses discussed do not, in their present prototypical form, perform well for taxa which disappear (abundance = zero) for substantial lengths of time each year. Adaptations of the methodology for these sorts of interrupted series are (in principle) possible, through the use of generalized linear models (McCullagh & Nelder, 1989).

DATA ANALYSIS

Choosing a metric.

Data in nature often vary across orders of magnitude; when they do it is usually more meaningful to inspect and analyze them in a logarithmic scale. As support for this claim, consider the data shown in Figure 1a, a plot of typical brain weights versus body weights for 62 species of terrestrial mammals. The

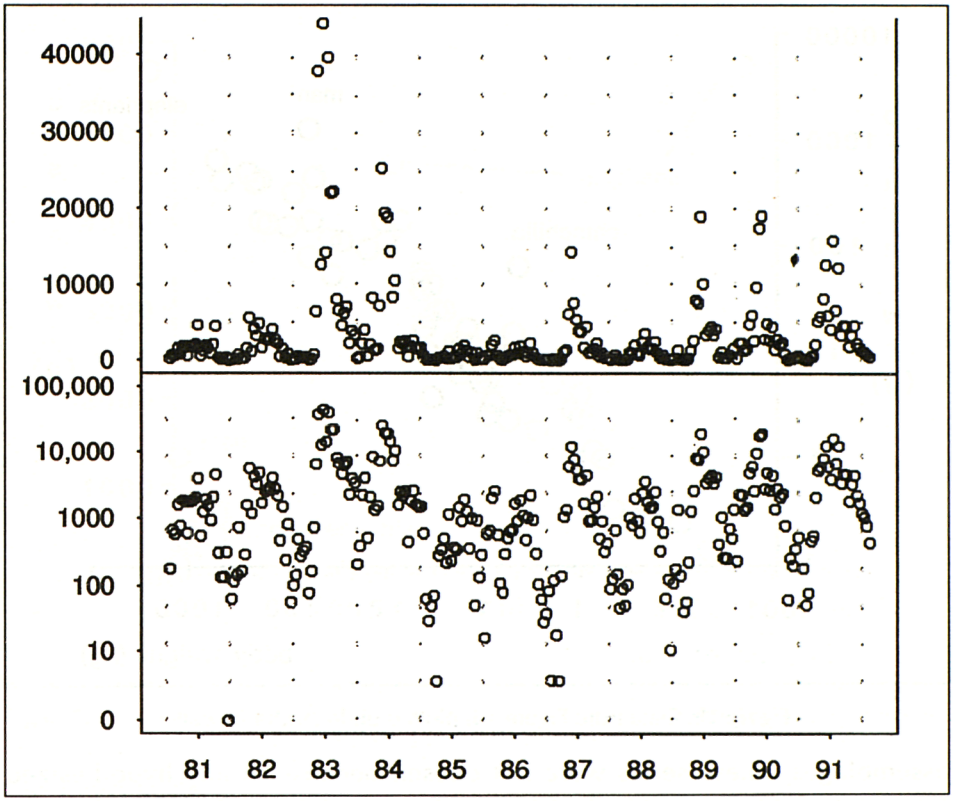

Figure 2. Barnacle nauplii abundance (no·m^{-3}) versus year, plotted on arithmetic and logarithmic scales.

underlying goal of this particular analysis, from Allison and Cichetti (1976), was to compare the species' brain weights after making some correction for body weight. The plot shows the two species of elephants, and man, but the other 59 species, which include animals as small as mice and as large as the giraffe, have been squeezed into the origin. Using the raw data, the elephants' points will be so influential in any regression or similar analysis that such an approach would be, in effect, an "elephants versus non-elephants" analysis. Incidentally, removing the elephants is little help: that plot shows the giraffe, horse, and cow, with the other points still squeezed into the origin. Indeed, if ocean-going mammals were included, the elephants would be squeezed into the origin by whales.

Data that vary across several orders of magnitude should be analyzed on an order-of-magnitude scale: by logarithms. Figure 1b shows the same 62 species'

data plotted on a log scale (or equivalently, the $\log_{10}$-transformed brain and body weights plotted on an arithmetic scale). The plot shows a fairly clean linear relationship; simple linear regression in the log scale is apparently a very appropriate way to correct brain weight for body weight. In addition, a discovery has been made: the chinchilla has a brain weight about 10 times that of other mammals its size. This fact is completely hidden in the raw data.

Our own benthic abundance data typically varies across two to five orders of magnitude. As one example, Figure 2 shows plots of (top) mean abundance and (bottom) mean $\log_{10}$-abundance per sampling date for barnacle nauplii. At top, the peak abundances of 1983-84 squeeze most of the other points close to 0. In particular, notice that the low-abundance 1981-82 years appear very similar to the 1985-86 years in the raw data, whereas in the log scale it is apparent that barnacle nauplii were more abundant in 1981-82 than in 1985-86 by nearly a factor of ten. The plot of the raw data also gives the false impression that the peak abundances appear and disappear suddenly in time, perhaps as a reaction to some natural event, when in fact the growth and decay seasons are several months in duration, as the log-scale plot shows with close inspection. Also, the changes in the log scale appear in most years to be surprisingly linear, corresponding to alternating exponential growth and exponential decay in the untransformed abundances.

Data inspection.

All further analyses discussed herein were conducted on the means, by date, of $\log_{10}$((count+1)/area or volume) data. Common (base 10) logarithms were used because their values retain more immediate meaning to human beings than "natural" logarithms. Averages by sampling date were used primarily to defuse issues of pseudoreplication, particularly in the zooplankton data; weighted regression was used in cases of unequal replication, e.g. the macrobethos data. In plots (Figure 3a,b), a nonparametric regression curve has been added to help the observer follow changes. These curves are LOWESS (LOcally WEighted Scatterplot Smoother) "smooths" (Cleveland, 1979), as implemented by the software Splus®, which was used for all graphics and as a programming language for data analyses. These LOWESS smooths are helpful to a point, but have the unfortunate and well-documented drawback that they tend to round off sharp changes in the curve: the reader is urged to conceptually sharpen the points on many of the peaks and valleys seen in the data! A better smoothing algorithm for

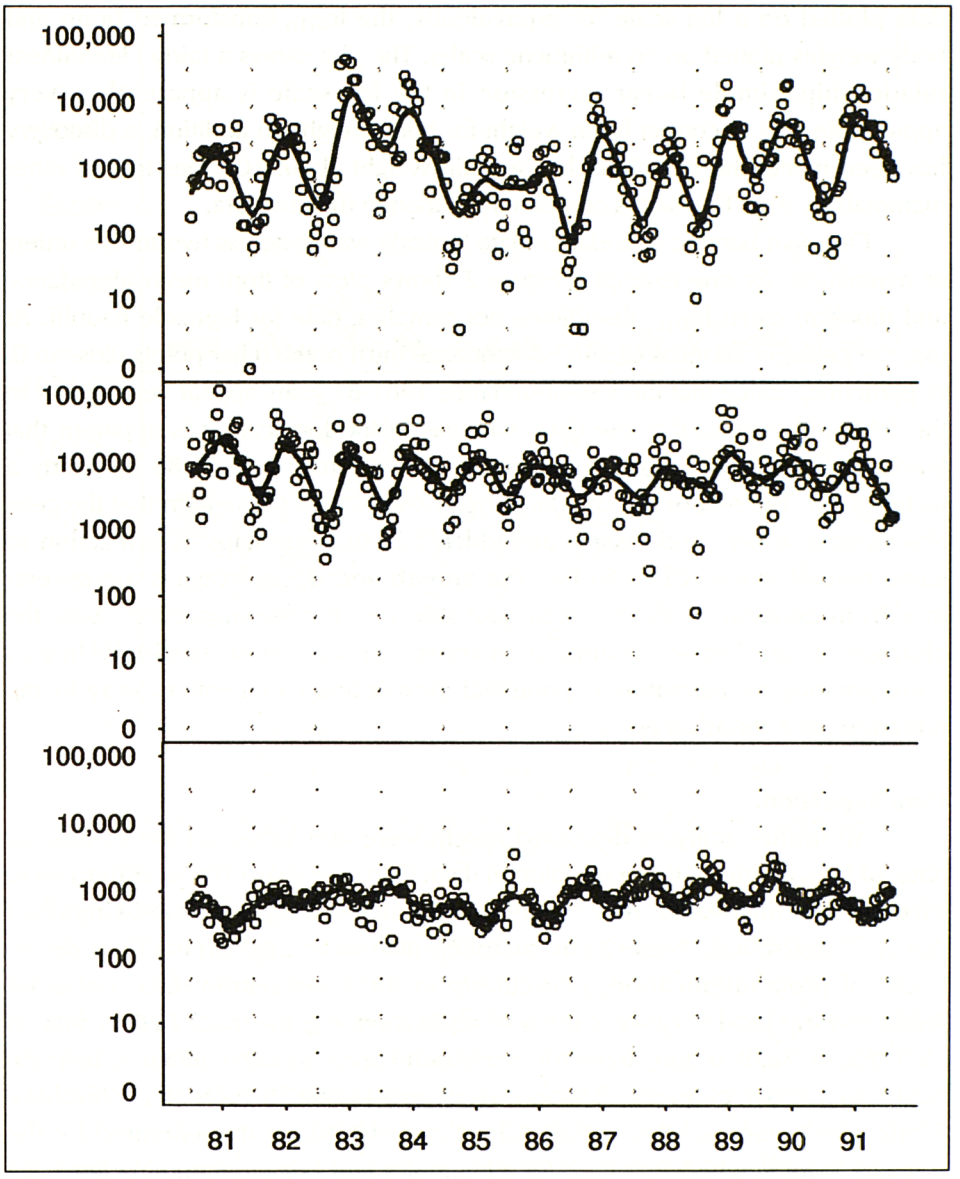

Figure 3a. Abundance versus year for example taxa, with fitted LOWESS smooths. From top: barnacle nauplii (no·m^{-3}), total copepodids (no m^{-3}), total nematodes (no·10cm^{-2}).

data with sharp changes in direction and/or discontinuities is the McDonald & Owen (1986) algorithm, which was still being coded at the time of this writing.

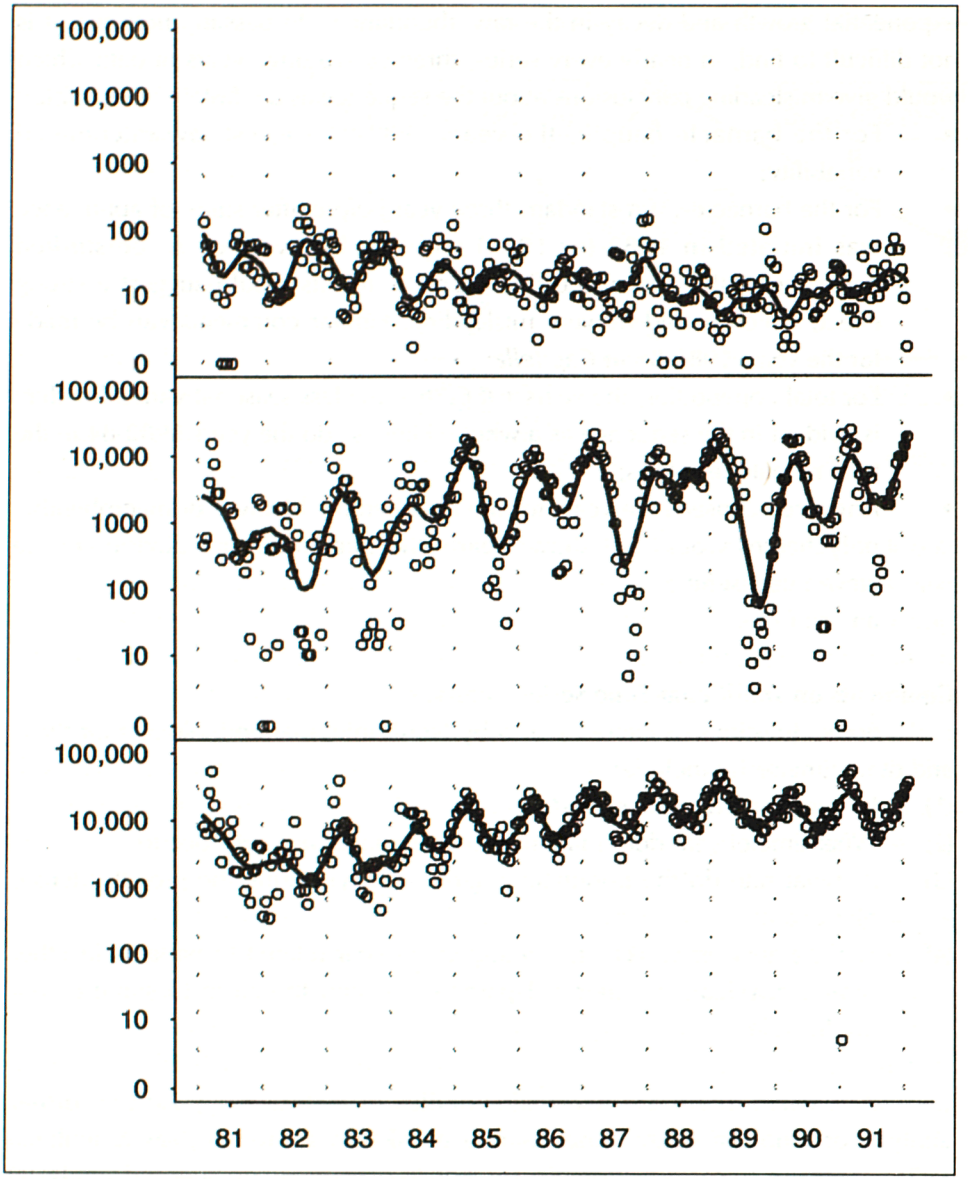

Figure 3b. From top: meiobenthic bivalves (no·10cm^{-2}), *Capitella capitata* (no·m^{-2}), macrobenthic polychaetes (no·m^{-2}).

Figure 3 shows the six time series used as examples here. Each of these logarithmic plots shows, to a greater or lesser degree, alternating near-linear increases and decreases, corresponding to alternating periods of approximately

exponential growth and decay in the raw abundances. In passing, note that it is not difficult to find, in nearly every series, three consecutive years of data which would give misleading conclusions about the sequence as a whole! For example,

- For the barnacle nauplii, the years 1989-91 suggest low interannual variability;
- For the barnacles, if a standard three year before-after study of abundance was initiated in 1982 (or 1984) with the intervention to be studied occurring at the end of the first year, the results would suggest a strong effect, which would be very misleading. Similar comments can be made for the years 1984-86 in *Capitella*;
- For total copepodids, the years 1986-88 show less seasonal variability than is evident in the sequence as a whole; likewise do the years 1982-84 in the total nematodes series;
- Any three consecutive years for the meiobenthic bivalves or macrobenthic polychaetes would not show clearly the trends that are obvious in the eleven year series;

  and so forth.

Comments on Traditional Time Series Analyses.

Some questions of interest posed by North Inlet marine biologists for these and other time series include:

(1) Is there a trend in the series?

(2) What time of year does maximum (minimum) abundance occur?

(3) At what rate do the populations grow (decay) during the growth (decay) phase; and

(4) Are the answers to (1) - (3) in any given year related to patterns in other biotic, physical, or chemical parameters, and therefore to some extent predictable?

At present, there are two major bodies of methodology for the formal analysis of time series: the time domain or ARIMA approach (Box & Jenkins, 1976), and the frequency domain (or Fourier analysis, or Spectral analysis) approach (Platt & Denman 1975; Fry *et al.*, 1981) Neither type of analysis is well suited to answer the above questions, especially (2) - (4), as will now be discussed.

In the time domain approach, the observation at a given time is modeled

as a random shock specific to the time plus a weighted sum of a few most recent observations, plus a weighted sum of a few most recent random shocks. These models can also be adapted to reflect seasonal patterns by an extension of this scheme. They were born out of econometrics, for the purpose of black-box forecasting of observations a few time periods into the future, e.g. profits next quarter. Model fitting involves some expert (subjective) decisions, requiring equally spaced data. The fitted models can mimic the patterns of change in an ecological series, but the model parameters do not have straightforward, meaningful ecological interpretations. This, together with the fact that black-box short-term forecasting is not the goal of most scientific studies, may explain why time domain analyses are not widely used in ecological time series analysis; they do very little to enhance scientists' understanding of the system generating the data.

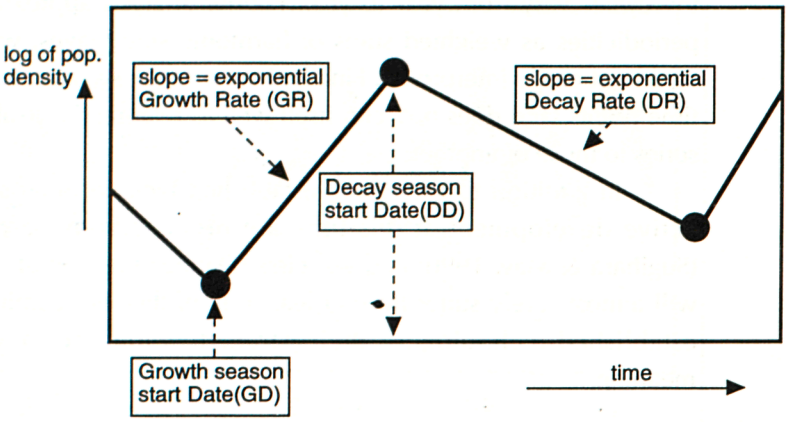

Figure 4. Anatomy of a (piecewise linear) spline for a single cycle.

The frequency domain approach can be regarded as modeling the series as a weighted sum of sine waves of various periods, amplitudes, and phase shifts, plus random error in each observation. Since most (all) environmental time series are to some extent periodic, this approach is a step closer to what is required to understand the dynamics of the underlying system. Fourier analysis is certainly useful for finding the dominant periodicities in an ecological series. However, there are usually few additional discoveries of note: analysis of dozens of North Inlet time series has shown periodicities related to the seasonal cycle, the tidal cycle, and the diurnal cycle, but nothing else of interest (Coull, 1986; Gardner *et al.*, 1989). Moreover, though ecological series usually have strong periodic components, these periodicities are not typically sinusoidal. The cycles in our Figures are much more sharply-pointed than a sine wave, and the amplitudes of

the cycles vary from year to year. Fourier analysis approximates non-sinusoidal periodicities as weighted sums of harmonic sine waves, whose coefficients are again not easily interpreted. Finally, Fourier analysis also requires equally spaced time points, and does not lend itself well to relating the peaks and valleys of one series to those of another.

In addition to these well-established types of time series analysis, under active development at this time are new methods based on Chaos theory (Sugihara & May, 1990) and wavelets (Daubechies, 1988). These methodologies will almost surely suffer from at least one of the shortcomings of the more well-established technologies: their parameters may not have direct ecological meaning.

Spline regression.

As a building-block for a time series analysis based on ecologically meaningful parameters, consider a regression model for a series consisting of alternating linear increases and decreases. A spline is a piecewise function; the values joining the functions are commonly referred to as knots. Between the knots, a spline can be defined in any of a number of ways, usually as a quadratic or cubic polynomial. For logarithmically transformed benthic abundance data, straight line segments are a simple, adequately accurate, and interpretable choice for the inter-knot function. In any given year, the spline function is then defined by four parameters: growth season start date (GD), growth season growth rate (GR), decay season start date (DD), and decay season decay rate (DR). For any given choice of knotdates, the growth and decay rates can be estimated by a multiple linear regression analysis; see Eubank (1988, Ch. 5). The least squares estimated knotdates can then be determined iteratively by a nonlinear minimization routine such as those discussed in Gallant (1987, Ch.1). This is a tricky process, though, and the nonlinear search for the least squares knotdate values may not converge if the alternating pattern is not well defined. Approximate confidence intervals and hypothesis tests are available via the general theory of nonlinear regression (Gallant, 1987).

Feller *et al.* (1992) conduct a spline regression on several 5-year series of North Inlet benthic data. As a single example of spline regression for our 11-year series, an intermediate step in mixed model spline time series analysis, Figure 5 shows the least squares fitted spline for the barnacle nauplii data. The corresponding numerical results are shown in Table 1. The typical estimated

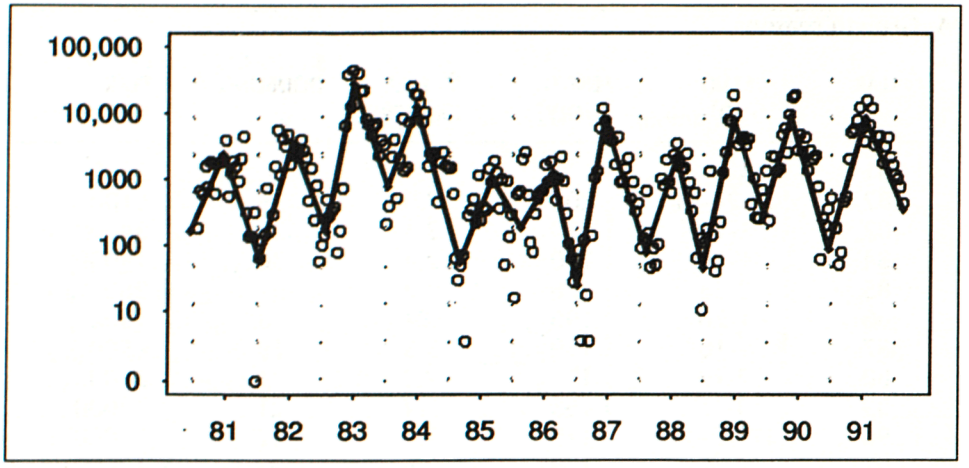

Figure 5. Barnacle nauplii abundances with fitted least squares spline.

growth season start date (Table 1, part A) is in mid-January, with growth season length about 170 d; the decay seasons (part B) seem to be slightly longer, about 200 d. The exponential growth and decay rates, as estimated from slopes of the fitted interknot line segments, can be expressed in several meaningful ways. Table 1 expresses them both as percent increase (decrease) per day, and as the doubling time (halflife), i.e. the number of days required for the population to double (halve) during the growth (decay) season. Apparently the typical growth rate is such that the barnacle nauplii mixed species population doubles (approximately) each 30 d during growth season. The final value in each table is the estimated peak (minimum) abundance achieved in that year; note that these estimates can vary by more than a factor of ten from year to year. Though standard errors are not shown for the estimates in Table 1, they are available, as are tests for nearly any conceivable hypothesis of interest.

Mixed model spline time series.

Spline regression as described above is essentially a descriptive analysis: the years of data in hand are assumed to be of interest in and of themselves, with no desire to generalize to the long run. With more than a few years of accumulated data, however, it is natural to generalize the spline regression estimates and make statements about the underlying process that generated them (this has in fact been done, informally, in the paragraph above). A formal approach to this would be to adopt a random effects analysis on the annual spline

A. Growth seasons

YEAR	START (D)	LENGTH (DAILY)	% INCR TIME (D)	DOUBLING	PEAK NO M^{-3}
81	-	-	-	-	3300
82	12-26-81	203	2.0	36	6100
83	1-19	177	3.3	21	34000
84	1-30	140	2.4	30	19000
85	2-28	178	1.2	57	980
86	1-26	196	.84	83	1500
87	1-18	159	3.8	19	9500
88	2-10	172	2.2	31	3400
89	1-7	165	3.4	21	12000
90	11-15-89	172	2.2	32	12000
91	1-4	179	2.6	27	12000

B. Decay seasons

YEAR	START (D)	LENGTH (DAILY)	% INCR TIME (D)	DOUBLING	PEAK NO M^{-3}
81	6-11	197	1.7	41	120
82	7-18	185	2.2	31	100
83	7-16	198	2.0	36	720
84	6-18	255	2.0	34	110
85	8-26	153	.81	85	280
86	8-11	159	2.5	27	27
87	6-26	230	2.1	33	77
88	8-01	160	2.7	26	47
89	6-22	147	2.5	27	280
90	5-07	242	1.8	37	140
91	7-01	-	-	-	-

Table 1. Spline regression analysis, barnacle nauplii

4-tuples (GD,GR,DD,DR), regarding each year as though it were randomly sampled from a pool of years generated by the underlying ecological process. A fully general methodology of this type is still under development, but a simplified version of it can be performed immediately as follows: focus on any one aspect of interest of the annual cycle, e.g. peak abundance. It can be estimated in each year, with known standard deviation, by the spline regression. With m such estimates in hand, the following simple random effects model for year i may be used:

A. Peak Annual Abundance

Taxon	Long run Median	Interannual std.dev. multiplier	P-value[1]
barnacle nauplii (no·m^{-3})	6300	2.9	<.0001
total copepodids (no·m^{-3})	19,000	1.4	.0124
meio. bivalves (no·10cm^{-2})	36	1.8	.0207
meio.nematodes (no·10cm^{-2})	1300	1.3	<.0001
Capitella capitata (no·m^{-2})	14,000	2.3	.0028
macro. polychaetes (no·m^{-2})	20,000	1.9	<.0001

B. Minimum Annual Abundance

Taxon	Long run median	Interannual std.dev. multiplier	P-value[1]
barnacle nauplii (no·m^{-3})	190	4.9	<.0001
total copepodids (no·m^{-3})	2500	2.0	<.0001
meio. bivalves (no·10cm^{-2})	7	1.4	.0531
meio.nematodes (no·10cm^{-2})	490	1.4	<.0001
Capitella capitata (no·m^{-2})	164	4.0	<.0001
macro. polychaetes (no·m^{-2})	2900	2.1	<.0001

[1] For the hypothesis of no interannual variability.

Table 2. Interannual dynamics of annual extremes for example taxa

(est. peak, year i) = (long run mean peak) + (year i effect) + (est. error)$_i$,

i = 1,...,m.

Here, the year effects are taken to be random. The year effects' variance is the interannual variance component for (in this case) peak abundance. Since the standard deviation of the error is known from the spline regression, the interannual variance component and the long-run mean can be estimated by the method of maximum likelihood. Approximate standard errors and hypothesis tests are available using the general theory of maximum likelihood (e.g. Serfling, 1980, Ch. 4).

Table 2 shows the results of the above described interannual analysis as applied to the annual peak and minimum abundances of the six example taxa.

The results have been expressed in the units of the original data to facilitate direct interpretation. The "interannual standard deviation multiplier" is a measure of the interannual variance component's size. A given taxon's results can be interpreted as follows, using peak abundance as an example: we may expect, in the long run, about 2/3 of the annual peak abundances to lie in the interval

(long run median) x/÷ (interannual standard deviation multiplier).

The interannual standard deviation multiplier is a reasonable measure of typical year-to-year variability, since the actual peak abundance will fall outside the interval quite often, in about 1 of 3 years. Another possible expression might be in terms of a 95% range, i.e. about 95% of the annual peak abundances would lie in the interval

(long run median) x/÷ (interannual standard deviation multiplier)^2,

so that in only one year out of 20 would the peak abundance fall outside this range. To illustrate these interpretations with concrete values, for barnacle nauplii, about 2/3 of annual peak abundances will lie in the interval 6300 x/÷ 2.9 = (2100, 18000), so typical year-to-year variability in peak barnacle nauplii abundance is about 300%. In only about one year out of 20, the peak abundance will fall outside the range 6300 x/÷ $(2.9)^2$ = (750, 53,000).

The table results show that the extreme abundances for barnacle nauplii and *Capitella capitata* are most variable among these taxa, which agrees with intuition formed by inspection of the timeplots. For these two, peak abundances vary at 200-300% year to year, slightly less than minimum abundances, which vary by 400-500% from year to year. Even the least variable taxa show multipliers of about 1.3, meaning that their annual extremes will typically vary by 30% from year to year, which is still very substantial.

The final column in Table 2 is a P-value for the hypothesis of no interannual variability. These P-values, to some extent, will be small when the sizes of the estimated standard deviation multipliers are large, but they are also affected by the spline regression's standard errors. In each case, there is strong or very strong evidence of nonzero interannual variability in taxon peak and minimum annual abundance.

A number of variations on the model specified by the equation above are immediately possible; others would require more effort. A trend in time can be tested easily by modification of the first term to a linear function; other fixed-effects modifications to the model come to mind for other settings, hence the term "mixed model spline" time series. Another, more time-consuming development that should be pursued is the inclusion of a term to allow correlation over time of

the year effects. Any such correlation is probably small, but is ignored by the approach used here.

CONCLUSION

A prototype analysis for quantification of interannual variability in benthic and zooplanktonic time series has been defined and applied to six 11-year series. The results show strong evidence that annual peak and minimum abundances in the example taxa vary substantially from year to year, by 30% in the least extreme cases, in others by as much as 500%. Clearly, for series such as these, any conclusions based on a few years' data are unreliable.

In addition, the accuracy of the estimates of interannual mean and variance is dependent on the number of years of data being analyzed. One cannot accurately estimate year-to-year variability with two or three years any more than one can accurately estimate experimental variability with just two or

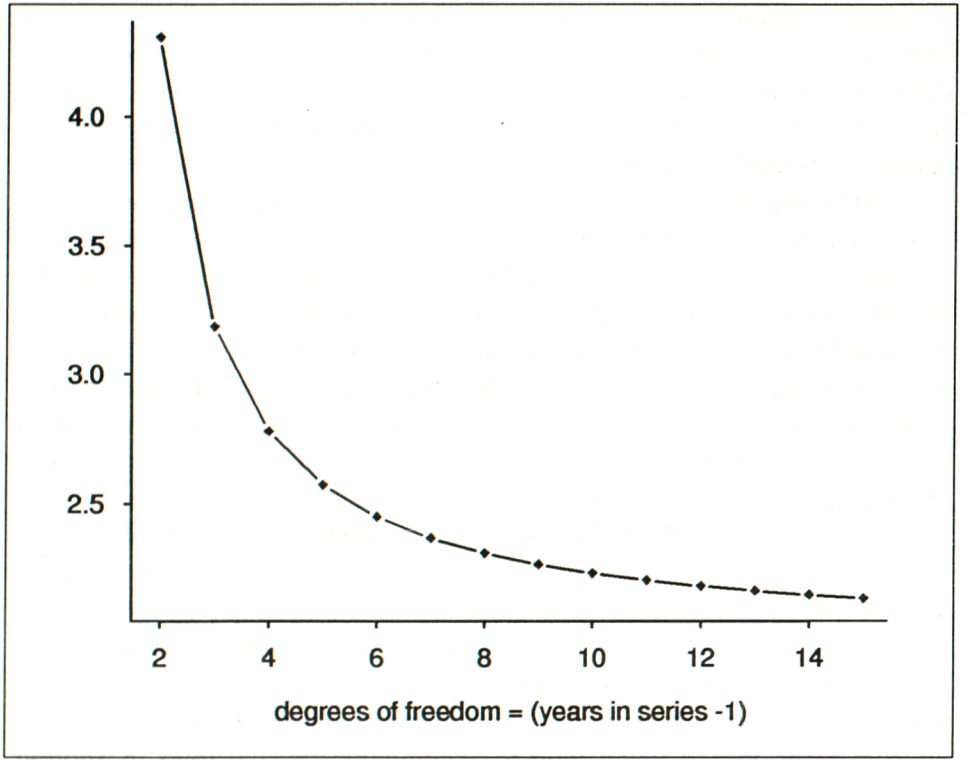

Figure 6. 95% critical constants for Student's t-distribution.

three replicates. Figure 6 graphically displays this fact, showing the critical points for use in a "Student's t" 95% confidence interval plotted against the degrees of freedom of the estimate of standard deviation used in the interval. As the degrees of freedom increase, the critical points converge to 1.96, which when rounded gives the familiar "estimate ± 2(std. error)" rule of thumb used for "quick-and-dirty" approximate confidence intervals. Note, however, that for very low degrees of freedom the critical constants are substantially larger than 2; the critical point for 1 degree of freedom is 12.71, so large that it would distort the graph to include it. Low degrees of freedom lead to very wide confidence intervals and insensitive (low power) hypothesis tests. This forced, mathematically derived conservatism is nature's way of telling us that variances computed from a few observations are unreliable; they are even more unreliable when the data are not normally distributed! The Figure 6 phenomenon also occurs in the critical F-constants used to perform most hypothesis tests, but we chose to plot the t-distribution constants in honor of our Irish hosts: Student's t-distribution was derived by W.S.Gosset just after the turn of this century. Gosset was working for the Guinness brewery in Dublin at the time. He was forbidden to publish company secrets, but he felt the discovery too important to keep secret, so he published his results using the pseudonym "Student".

Mixed model spline time series analysis depends heavily on the existence of a pattern of alternating near-linear increases and decreases in the logarithms of the abundance data, and should not be applied to series which do not display this pattern fairly clearly. The analysis has been successful for our biweekly series, and might work on monthly data, but probably would not be successful using a temporal resolution more coarse than monthly. Temporal spacing is an extremely important experimental design decision: a coarse temporal spacing may be appropriate for mere long-term monitoring, but to gain information to enhance understanding of ecosystem dynamics requires much more detail.

The analysis displayed here is merely a prototype for a potentially much more useful methodology, one that could help ecologists understand the mechanisms driving population dynamics, rather than simply monitoring and measuring them. Specifically, it should be refined to include several aspects of the same series, to see if (e.g.) long growth seasons tend to accompany long decay seasons. A bivariate version would allow answers to questions such as whether unusual highs in one taxon tend to accompany unusual lows in another. Generalization to patterns other than alternating linear increases and decreases

might allow for correlation of benthic abundance data with physical and chemical measurements, whose seasonal patterns tend to be more complex. Support is needed for development of these and other statistical methods for ecological and environmental field studies.

ACKNOWLEDGEMENTS

We thank the Baruch technical staff, especially L. Barker, R. McCutchen, G. Ogburn-Matthews, and S. Service, and the Data Management Group, especially J. Jefferson, for their assistance in collecting these data. Meiofauna samples were sorted by B. Dudley. This research was supported by the National Science Foundation grants DEB 8012165, BSR 85143326, and BSR 9011664 (F.J.Vernberg, principal investigator (PI), all authors co-PIs), and OCE 8007968, 8308114, and 8916255 (B.C.Coull, PI).

*Contribution No. 1099 from the Belle W. Baruch Institute for Marine Biology and Coastal Research.

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SPATIAL DATA FOR LONG-TERM ECOLOGICAL MONITORING

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INTRODUCTION

Long-term monitoring is a scientific and a managerial imperative, with obvious benefits in terms of establishing baseline, trend and the impact of both natural and anthropomorphic forcing factors. It is tempting to assume that the primary challenges involved lie mainly in data acquisition, but in reality subsequent data management and the visualisations or analyses that derive from the managed data are often more demanding. The problems are heightened in the case of ecology by the complex nature of the discipline, and by the ever-changing conventions and conceptual models through which it can be conceived and expressed. For example, a long-term record of temperature or CO_2 may be bedevilled by changes in instrumentation or sampling protocols, but the underlying definition of the variable remains quasi-constant on the timescale of an individual monitoring programme. The same stability cannot be claimed with confidence for ecology, and even the constituent elements such as biology, pedology or geomorphology are subject to some conceptual drift on timescales which impinge upon long-term monitoring programmes.

The challenge to be faced by the information scientist in the context of long-term ecological monitoring is thus one of establishing a robust and documented approach which is sufficiently flexible to ensure that both technical and conceptual migration can be assimilated without threatening the integrity of the project. The key lies in ensuring a clearly articulated lineage for all data, coupled with a data-handling framework which maintains the purity of raw constituent data sets while integrating them at operational level into syntheses which are internally consistent and externally intuitively interpretable and satisfying. And all of this needs to be achieved with multiple very large data sets of enormously varying format, provenance and measurement system! Mercifully, this demanding expectation is met (in principle, and increasingly in practice) by a recent technology that appears in many guises but usually under the name of Geographic Information System (GIS). It is appropriate to consider the

relationship between GIS and ecology, before looking at the practical applications of this joint technology and their underlying problems. Out of this background it is possible to discern some significant policy implications, though as yet there is considerable room for improvement in the rate at which such policy opportunities are translated into operational strategies.

The characteristics of long-term ecological monitoring datasets

The emerging science of geoinformatics embodies many elements of function and procedure which are generic, and such elements can often be applied with minor tuning to almost any dataset in any discipline. There remain, however, a number of characteristics which are specific to a particular discipline or type of entity, and in this respect it is helpful to commence by attempting to establish the diagnostic criteria which distinguish the datasets yielded by long-term ecological monitoring projects from those associated with other studies. The literature yields suggestions such as:

- the data sources are varied and the formats diverse.
- the data model and data acquisition techniques may well have evolved through time, so that data standards are difficult to define.
- the entities concerned include many which are ill-defined or intangible (assemblage, succession, rarity, diversity).
- the resulting data sets are large.

Further elaboration is disappointingly sparse, and few authors apart from Swanson and Franklin's (1988) treatment of the US NSF Long Term Ecological Research (LTER) Program even mention the specifically *long-term* characteristics of ecological monitoring. Powers *et al.* (1994) strengthen the characterisation somewhat in the context of GIS implemented to monitor the impact of the Glen Canyon Dam on the Colorado River by defining "long-term" monitoring as "determining change in resources over time, preferably every three to five years", and by recognising trend prediction and the documentation of particularly significant events as being important aspects of such programmes. GIS capabilities are well able to handle such requirements, and to go far beyond them. To take the specification further, and thereby permit the recognition of the policy implications of the spatial data yield of long-term ecological monitoring, it is necessary to seek those aspects which relate to the definition of what makes ecology itself distinctive in GIS terms.

Ecology and geographic information systems

A GIS is fundamentally a large and integrated database coupled to a powerful set of data management, analysis, modelling and presentation functions which can be used to create information that is not implicitly contained within the source data. As such, GIS shares with databases the four distinct roles of organising, facilitating, associating and bisociating (Branson *et al.*, 1994). *Data organisation* may well dominate the role of a database, with the aim being efficient and secure storage. This capability lies at the heart of archiving. The *facilitating* function of a database derives from its ability to provide effective but managed access to the data, concentrating on circulating the raw data without imposing any manipulation.

The other two primary functions of the database move beyond this level by using the data as inputs to manipulative processes. Sciences such as biology and ecology have conventionally used the concept of *association* between variables, which often forms the core of GIS analysis. Simple data visualisation techniques (graphs, maps) have an inherent tendency to accentuate pattern or relationship. Associations may be identified through selective database queries, and other associations may emerge from spatial or temporal co-incidence, drawing on the combination of data from many sources. Finally, imaginative use of GIS can move beyond the essentially linear, logical and deductive processes of associative database query, and moves into the realm of *bisociation* (Branson *et al.*, 1994), whereby innovative links/patterns are perceived when hitherto disparate data sets are brought together by chance rather than by imposed logic.

Clark and Gurnell (1991) note that the technical requirements for a large integrative spatial database of the type that would be generated by long-term ecological monitoring include data standards, data structure standards, data transfer standards and an integrating technology such as that offered by GIS. In this context, the end user will seek from the GIS three distinct functions, each with its own demands on data (Clark, 1991a):

- *Aggregation of data sets.* (Requiring standardized units and measurement techniques).
- *Comparison, classification and assessment of variability in time or space.* (Requiring either data standardization or very careful data documentation to distinguish real from artificial differences between data sets).
- *Explanation of patterns within the combined data sets.* (It is shown below that hypothesis building is possible provided that data are documented, but

model building and analysis require standardized data.)

It is clear that the focus of GIS on data integration renders it in principle highly suited to the task of portraying and exploring a complex concept such as ecology (Clark, 1991b; Edwards *et al.*, 1992). Somewhat surprisingly, however, there has been relatively little emphasis on "ecological GIS" in either the ecological or GIS literature. Unusually, Stow (1993) endeavours to identify aspects of GIS which have specific ecological ramifications. The list is useful, though hardly surprising:

- Provide a database structure for efficiently storing and managing ecosystems data over large regions.
- Enable aggregation and disaggregation of data between regional, landscape and plot scales.
- Assist in the location of study plots and/or ecologically sensitive areas.
- Support spatial statistical analysis of ecological distributions.
- Improve remote-sensing information extraction capabilities.
- Provide input data/parameters for ecosystem modelling.

Such lists concentrate on GIS functionality, and relate it to potential ecological needs. However, it seems more likely that the real essence of ecological GIS lies not just in its multi-variate and multi-scale nature, but in more fundamental properties such as its integrative characteristics; its emphasis on links; its focus not just on time slices, but on dynamic change/succession; and its frequent reliance on surrogate data. At the same time we can see potential GIS contribution to the handling of ecological/habitat notions such as connectivity, proximity, shape/crenellation and minimum viable size (mosaics of patches linked by corridors or edges - Bridgewater, 1993; Lavers and Haines-Young, 1993). At a still simpler level, the ability to query information associated with the mapped variables, and to produce event-specific combinations of variables to respond to particular enquiries, may be sufficient to justify the use of GIS rather than static maps in contexts such as managing real-time response to oil spill impact on wildlife (Jensen *et al.*, 1990).

A notable example of sophisticated system design for an ecological GIS is provided by Davis *et al.* (1990) in their consideration of the challenge of providing a robust, operational and multipurpose system to support the preservation of biological diversity. The topic is typical in the complexity of the concepts involved, the diversity of the data, and the difficulty of managing

effective data flows under operational conditions. GIS is the preferred approach not only because of its integrative capabilities, but also because it encourages multiple and innovative uses of the data once acquired. The questions raised by Davis *et al.* (1990) are significant as an indication of their high expectation of the capability of GIS as a creative tool within the ecologist's portfolio:

- What is the range of a given species or community type?
- Which species are at greatest risk?
- Which sites have greatest species richness?
- Which biologically important sites are at greatest risk?
- Which ecosystems are adequately protected?
- What environmental factors are related to sites of greatest biodiversity?
- Can diversity be predicted on the basis of these factors?
- Where can ecologically sustainable development occur with acceptable impacts on biodiversity?
- What are the trends over time in species and ecosystem diversity?

It is significant that almost all of these questions involve an element of subjectivity in either definition or application, so that an appropriate GIS would require to be far more than just a database with associated mapping functions.

Davis *et al.* (1990) are unusual in the extent to which they embed complex ecological concepts within their GIS specification, and Karra *et al.* (1994) are more typical in discussing straightforward approaches to handling a range of broadly "ecological" attributes, but focusing on the environmental and biological components rather than on the integrated whole. It seems that ecology *sensu stricto* has suffered some neglect in the GIS context, but the associated spatially-oriented science of Landscape Ecology has received considerably more attention (Haines-Young *et al.*, 1993; Huber, 1994). Landscape ecology shares a common heritage with Land Systems analysis, and thus a common link through to Land Information systems (LIS) - all of which have been closely involved in the development and elaboration of the broad spectrum of approaches that share the name GIS. Of particular significance in this respect is the scale hierarchy of integrated landscape units: ecotope, facet, system, and landscape. These (or some variant of them) lie at the heart of landscape ecology, and lend themselves effectively to handling by GIS.

It is clear that GIS potentially brings to ecology in all its forms the power and freedom of a new set of techniques through which to integrate and process

data, and thus offers a real prospect of both methodological and substantive advance. On the other hand, GIS represents for many ecologists a new philosophy and a new language, more akin to computer science than to biological science. Once we get beyond description, then GIS can be a tool in handling any chosen paradigm such as community equilibrium and competition, and their role in shaping spatial ecological patterns. GIS should be seen as the servant of the paradigm in such cases, rather than as its master. At the more sophisticated level, GIS offers opportunities for handling uncertain, fuzzy or probabilistic patterns Wood and Foody, 1993. In all such contexts, GIS far transcends the basic role of data storage and mapping with which it is often labelled, but requires creative and professional application if it is to achieve its potential in long-term ecological monitoring.

Adding value to ecological datasets through gis

Classification as a GIS role in ecology

It is apparent that classification is a process which is inherent to GIS operations in ecology as in most other fields. The process of classification has long offered a basis for integrating complex data sets so as to provide effective support to analysts and decision makers. The purposes of classification are fundamental to the scientific process and are highly effective in many professional contexts, but at risk of over simplification it is possible to identify the following broad aims as being of particular significance to the practising ecologist or conservation planner seeking to use GIS:

- Generalisation of complex descriptions in an informative and consistent manner is of the highest significance in any operational field. Restriction of the variables to be measured, and definition of the temporal/spatial sampling framework, both impose *de facto* generalisations on the data, but it is often necessary to provide still greater compression of the information if it is to serve a practical purpose. Combination of variables, and simplification of detail, both represent approaches to this core process of generalisation - and are particularly important in small scale/large area operations.
- Combination of multiple types of information under a single heading is an important purpose of classification, and a core function of GIS. For example, if decisions on river habitat management require appreciation of the extent to which a river channel is stable or unstable, then it is

convenient to include measures of both planform and cross section into a single index of dynamism, and to incorporate some indication of whether the channel locational/dimensional change is progressive or self-cancelling. Classification can be an effective approach to such combinatorial requirements, though it is both conceptually and technically challenging, since the variables concerned are rarely additive in any meaningful sense - thus yielding a significant potential source of error and uncertainty.

- Simplification of detailed data sets or observations is an intuitively important precursor to the search for meaningful underlying patterns. The simple act of subdividing a continuum into a small number of discrete classes renders the resultant characterisation more amenable to perception of trends or associations with other variables. Quantitative systems will generally prefer the resolution enhancement that comes with continuous data, but human interpretation and decision-making in fields such as conservation, planning and environmental management will often opt for classification. This very basic conflict of requirement underlies a major data management imperative which has particular significance in long-term monitoring programmes - raw data at maximum resolution should always be held within the system, regardless of the degree of integration and simplification that is adopted for decision support purposes. It is a particular strength of GIS approaches that they operate effectively with spatially continuous data, whereas conventional mapping approaches have often adopted a classificatory framework. It is entirely feasible for the GIS output to be classified, while the raw data and interim models remain spatially continuous.
- Communication to non-specialist as well as expert users is one of the core aims of the "labels" which we attribute to classes in a classified data set. The more complex and multivariate the data, the greater is the need to summarise attributes effectively in order to ensure that a common definition and understanding is shared by all those involved in integrated processes such as river management or water resources exploitation. A comprehensive multivariate database may be invaluable for analytical or monitoring purposes, but in practice it is often necessary to encapsulate its essence in class labels such as "lowland mixed woodland", "high diversity and quality" or "low habitat value". Such terms have great utility, but only

if based on standard definitions and rigorous classificatory processes. Similarly, the distribution of classes in time and space can provide invaluable support to data visualisation, and to the greatly increased perception of pattern which this brings. Here again, there are significant policy implications in the designation of the classes and labels used in GIS support for long-term ecological monitoring programmes.

Handling time in ecological GIS

GIS technologies and procedures developed essentially as a spatial framework for data management, analysis and modelling, and have long been uncomfortable in handling time as anything other than an associated attribute of the spatial data. With long-term monitoring, however, time is of the essence since ecology and its constituent components (habitat; distribution of taxa) are highly dynamic. The most common approach to moving beyond time as an associate attribute relies simply on designating and mapping the status of entities at specific times (or time ranges). Following from this, it is possible to calculate and display the spatial pattern of change between two such time slices. For example, Bird (1991) takes a time-slice approach by comparing landcover for UK National Parks for the mid-1970s (1:24000 scale air photography) with the mid-1980's (1:20000 air photography), covering in total just under 10% of the land area of England and Wales. Although hardcopy map output was supplied as standard, the change analysis handled by GIS. Similarly, Miller *et al.* (1991) focus on time slices, but in this case each "slice" incorporates an asynchronous range reflecting air photograph availability (ie 1946-1950: 1964: 1988-9). The categories used in this study of the Scottish Cairngorm Mountains are also very broad by ecological standards (eg coniferous plantation; semi-natural coniferous woods; undifferentiated broadleaved; undifferentiated mixed woodland). Nevertheless, the relatively simple study framework is supported by an error assessment based upon a nominal spatial buffer, which does provide a useful initial guide to the robustness of change estimates.

Despite its conceptual limitations, this type of study has genuine policy potential, since it is usually simple enough (and often capable of retrospective generation) to be regarded as cost-effective at national or regional level. For example, the Countryside Information System has been developed by the Institute of Terrestrial Ecology for the UK Department of Environment, to provide information on the countryside for policy-makers (Haines-Young *et al.*, 1993).

This prototype project is based on the 1990 Countryside Survey (IFE and ITE), which builds partly on changes identifiable through previous surveys of ITE from 1978 and 1984, using the ITE Land Class System on 1km x 1km grid squares. The data model represents key elements of the rural environment relevant to national policy concerns, and the system has been geared to the needs of the IT non-specialist. In due course the land cover component of the data model will progressively be replaced with the image-based (Landsat) land cover map produced more recently by ITE, so that the system will be able to fulfil a long-term ecological role. The Land Class System is seen by ITE as representing a simple national ecological model, but the use of the term GIS is hardly justified for this approach, since it utilises little more than basic mapping functions.

Implicitly, the EC CORINE database is relevant to ecological monitoring in the same sort of way because it embodies a commitment to the notification of environmental change: "If our environment and natural heritage are to be properly managed, decision-makers need to be provided with information which is complete and up-to-date on changes in aspects of the biosphere." (CORINE, 1992). For example, land cover work commenced in Ireland early in 1992 using georectified Landsat Thematic Mapper images. The project was led by the Ordnance Surveys of the Republic of Ireland and Northern Ireland (Brand and Mitchell, 1993). The CORINE classification is not strictly ecology, but embodies ecological principles (eg integrative; interconnected) and converges on some land units which embody ecological information (eg pasture, peatbog, heath).

Many of these approaches provide a surrogate for time in the form of date-stamped data, "snapshots" of particular time slices, or depictions of the amount or rate of change between time slices. However, the handling of *change* as such in GIS remains elusive despite a significant and growing research literature. Much of the essence of an ecosystem lies in its stability or lack of stability, the rate and direction of change that it is undergoing, and the spatial distribution of these characteristics, and it follows that operational ecological GIS will need to advance somewhat beyond its present state if it is to contribute creatively to the dynamic of temporal data handling and exploration. This challenge largely lies on the shoulders of the technical GIS specialists, since the most likely solutions lie in the realm of the GIS data structure and associated manipulative functions. Other aspects of the time domain point towards data animation, a branch of data visualisation which is receiving substantial attention at the present time. Finally, there remain challenges for the ecologist, since ultimately the effective handling

of time in any discipline lies in resolving the dilemma of whether it is best treated as an attribute of the chosen entity, or a dimension within which the whole system operates. The two viewpoints point towards different solution realms.

Problems of implementing gis-based ecological monitoring

Problems of spatial data quality and error

> *"We can now produce rubbish faster and with more elegance than ever before"* Goodchild and Gopal (1989)

The concept of "data quality" encompasses a variety of attributes which contribute to the overall efficiency and value of a GIS application (Clark, 1992), including accuracy (which specifies the extent to which the recorded attributes faithfully represent the variable of interest), precision (which indicates the resolution of the measurement process) and reliability (which subsumes associated properties such as objectivity). Such properties can be recorded at the time of observation, or can in some cases be resurrected retrospectively from historical evidence.

Error (regarded here as being a difference between real-world properties and their recorded depiction in the information system) can be viewed as the converse of quality. It is an inevitable, acceptable and in some senses welcome property of data, but it becomes dangerous and damaging when it is unknown or overlooked. Over the last five years in particular, there has developed a clear appreciation of the nature of the problem that GIS error presents (eg. Goodchild and Gopal, 1989: Brunsdon *et al.*, 1990: Lemmens, 1991: Chrisman, 1992: Goodchild, 1993), and from this it is possible to derive some general approaches to (or at least towards) solutions to the problem. Error is a complex concept, involving precision (in measurement, recording and processing) and accuracy (in sampling, the data model, the data structure and processing). Error can also be conceived as uncertainty. Geertman and Ruddijs (1994), for example, identify from the literature (Bedard, 1987: CNIG, 1992: Gong and Chen, 1992: NCDCDS, 1988) a series of uncertainty elements which can be combined into something approaching a comprehensive model of GIS error -

Completeness uncertainty.

- Spatial (locational/topological) error.
- Temporal (relative and absolute time) error.
- Attribute error (sampling, measurement accuracy and precision, discretization, generalisation, classification, *a priori* attributes).

- Logical consistency and conceptual error (semantics, data model, data structure).
- Data lineage uncertainty (recording, transfer, archiving, processing, presentation).
- Meta-uncertainty (uncertainty about the extent to which other uncertainties and errors are known to the user).

This basic typology of error in spatial data can be focused significantly if attention is restricted to uncertainties in the categorical maps which are often used to carry the information inherent in spatial monitoring datasets. Aspinall and Pearson (1994) identify three major components:

- Class identity (are the classes correctly interpreted/identified).
- Class heterogeneity (extent of the internal class variability and inclusion of other taxonomic classes within the mapping unit).
- Class boundary location (are the boundaries between classes correctly located?).

Building on this position, it becomes clear that classic taxonomy leads the biological sciences towards a traditional Boolean logic within which each individual belongs uniquely and unambiguously to one class (though our individual or professional ability to allocate it to the correct class may be flawed). With complex holistic concepts such as ecology, incorporating notions such as vulnerability or value, this simple idea may at times suffice without being strictly sustainable in practice or in principle (Stoms *et al.*, 1992). In such circumstances, recourse to fuzzy set theory, whereby the individual can be attributed with varying certainty to several classes, is likely to be considerably more appropriate (Banai, 1993: Geertman and Ruddjis, 1994). GIS procedures can be developed to handle such an approach, but they have the problem that their significance is unlikely to be appreciated by non-expert GIS users. At the same time, it is the integrative and combinatorial aspect of GIS that most obviously buys power only at the expense of an increasing risk of unforeseen error propagation (Carver, 1991).

It is suggested by Burrough (1991) that "*Unfortunately, results are often judged in terms of the quality of graphics used rather than on their intrinsic value*", and he concludes that an intelligent GIS needs to be able to inform the user about the quality of the generated information and about alternative strategies through which to improve this information (one of which involves the use of meta-information: see Section 5.2 below). The task of responding to the

problem of GIS error and uncertainty is divided by Coward and Heywood (1991) into three steps - establishing a measure of uncertainty for the data product; determining how to use the accuracy statements thus produced; and reporting the uncertainty for the final output. For continuous quantitative data, a number of statistical approaches have been evaluated, but for practical purposes Geertman and Ruddjis (1994) propose the alternative of using sensitivity analysis (which operates by assessing the affect of deliberately imposed variations in data and processing properties) rather than uncertainty analysis (which is more rigorous, but requires prior knowledge of data sources and propagation). A demonstration of such an approach is provided by Clark (1994) in the context of assessing the vulnerability of coastal ecosystems to marine oil spills.

In practice, error can best be defined and managed specifically in the context of user requirements, since it is a relative rather than absolute property. Maffini *et al.* (1989), state that error in digital geographic data is inevitable, and cannot be removed simply by improving instruments and operators, though it can be controlled through such efforts. Instead of concentrating on error and uncertainty elimination, they suggest that we should improve the operational ability to cope with error, in part through better awareness of its significance and in part through the development of GIS tools to allow error specification to become a part of any working GIS application. Metadata represent a step in this direction.

Metadata as a response to data quality problems

Metadata (information about the properties of a data set which may be appended to or made available with that data set) represent an effective first-order response to handling the implications of error and uncertainty propagation in spatial data, particularly long-term data. Of special significance in this latter case is the tracking of data lineage (the "life history" of the data set), which is particularly significant in the context of complex multi-stage GIS operations, and this can become a focus in its own right (Lanter and Veregin, 1992). To be effective, the lineage should incorporate data model, data acquisition, data structure, all stages of processing, and presentation/visualisation.

While metadata clearly serve as an effective cautionary or warning device to enable users to apply a measure of caution to their interpretation or utilisation of GIS results, the task of moving from qualitative to quantitative error propagation evaluation is challenging. Wesseling and Heuvelink (1992) suggest

that effective error propagation techniques for a given GIS function require the following metadata:

- What are the properties of the function?
- Which of the parameters of the function are stochastic, and which deterministic?
- What is the probability distribution of the stochastic parameters?
- What are the spatial means and standard deviations of the stochastic parameters?
- What is the correlation between different parameters at the same location?
- What is the correlation between spatial parameters at different locations?
- Is every set of correlated parameters permissable?

While this list appears intuitively reasonable in principle, it implies a set of data standards which is very rarely met in conventional ecological monitoring reports. Monckton (1993) examines the meaning and significance of metadata, noting interestingly that the term "meta" often carries meaning about change (as in metamorphism) not just information about present state. Operationally, the term not only covers the technical definitions carried in the file header, but also a plethora of user information including the physical characteristics of the data, its uses, availability and price. The purpose is thus to identify and locate data, as well as to expedite its transfer and appreciate its quality (lineage). Metadata facilitating the search for appropriate data may be most useful at the macro-scale, though an individual user may have more localised interests. At the meso-scale, the "data dictionary" concept from database science is appropriate, providing an indication of the structure of the database, the entries in each field and their links to other fields, and possibly the physical system attributes involved. It is at the micro-scale (the individual dataset) that metadata play a role focused on spatial data quality and lineage throughout its life cycle, thus providing the inputs for error tracking.

Once beyond the research community, data quality assessment is used by both operational and decision-making staff to indicate how much reliance can be placed in-house on the results of any analysis using the data, and also to provide a foundation for public accountability (Clark, 1993). These two uses have rather different requirements. For in-house purposes, a technical data attributes can be tagged to the data set provided that the staff concerned are trained in the use of such evaluative metadata. For public accountability, the data quality record is open to public review, and for this review to be informed it must be undertaken

under circumstances in which the meaning and significance of the quality information can be properly explained and handled. In this context it must be stressed that quality indices for public use should ideally be purpose-specific. Thus, ecological data that may be of acceptable quality for assessing river maintenance engineering may be wholly inadequate for conservation review purposes.

Problems and opportunities of data commodification

Clark (1993) notes that data represent the fuel which drives GIS, and that as with most other energy-related debates, it is economics rather than physics which dominates both the provision of alternative strategies and the selection of a preferred option. Thus, as long-term monitoring begins to feed into operational rather than research systems of management or decision-making, it will emerge that the data have value and that this value creates a potential market. Here, as in every aspect of geoinformatics, the ecological data themselves, or the base data necessary for their full analysis and modelling, will be commodified. This represents both a problem and an opportunity. The problem arises because the research funding for the initial monitoring programme may well not include an element for the purchase of ancillary data. The opportunity arises because if the data yielded by the monitoring project can be sold (at full or marginal cost), then the revenue generated can support future data acquisition and management. The contention between these two viewpoints is active and often bitter, and the dilemma is clearly presented by Rhind (1992). Many data sets (and almost all topographic map data) are created by public funding, but while data users and value-added service providers often argue that subsequent data supply should be on a cost-of-dissemination basis, governments with few exceptions regard public data sets as a commodity through which to recoup at least part of the acquisition cost that has been funded through public expenditure. The issue is difficult to resolve, but it is clear that there is a strong case in favour of debating the implications and identifying a consensus on preferred strategy early in the project planning cycle, rather than risking the emergence of uncertainty or conflict once the data have begun to accumulate.

Policy implications

Branson *et al.* (1994) draw the distinction between a data *bank* and a data *investment*, and the financial analogy suggests options for long-term monitoring

databases and GIS. A data bank puts its resources to work and thus adds value to them, but at the same time honours the integrity of the initial deposit so that the restoration of the original input data is always guaranteed. A data investment, on the other hand, is more speculative, more entrepreneurial, and ultimately more profitable. It takes the deposited knowledge and actively puts it to work wherever the "return on investment" seems likely to be highest. The data owner may no longer be the active agent driving the use of the data, but stands to profit greatly through the productivity that is achieved by combining many related deposits of information in the hands of a skilled investment manager. Data banking leads to security: data investment leads to "wealth" (intellectual and managerial). The primary aim of GIS in relation to long-term ecological monitoring should therefore be to add value to the data in such a way as to render a significant and continuing return on the investment of funding and effort.

The policy implications of GIS in long-term ecological monitoring emerge in two contexts: "internal" implications reflecting upon the effectiveness of the GIS component of the monitoring project itself, and "external" implications affecting the public decisions that are made on the basis of the project's results. These two dimensions are significantly different in their nature, their outcome and their associated strategies.

Internal project policy implications

Clark (1991) has proposed a series of components that would need to be incorporated in any strategy for managing the data yielded by any major international initiative. Most of these elements have been addressed above, but their compilation points the way towards the kind of agenda that would be needed to ensure that data handling is treated as a creative and inherent part of the scientific process rather than as a mechanical adjunct to science (Clark, 1994):

- Agreed indices of the environment (data model), including surrogate indices.
- Agreed standards for operator and instrumental variance, including both accuracy and precision.
- Agreed format for archiving and indexing existing and newly acquired data (data structure; raw and derived data).
- Minimum data documentation standards for archiving and publication (metadata; data quality assessment).

- Improved documentation of, and access to, major existing data sets (including data search and rescue).
- Hardware independent archiving and infrastructure.
- Cross-referenced and interactive data directories, linked to global networks.
- Location-independent access to data, and agreed strategy for data marketing.
- Debate on broader horizons of information archiving (including a foundation for data exchange/sharing).

Few of these issues are founded on technical constraints or considerations, and most lie centrally within the realm of scientific professionalism. As such, they are sensitive as well as significant, and require both consensus and the weight of professional expectation if they are to become accepted as necessary components of working practice. Once the required degree of consensus had been achieved, it would be possible to build components such as those listed above into the activity sequence of the monitoring project. The obligation for promulgating a responsible attitude towards data handling in such projects rests usually with the professional bodies of the discipline concerned, or with the major global data repositories, including the World Data Centers, the UNEP GRID program and the World Conservation Monitoring Centre (formerly the IUCN Conservation Monitoring Centre).

External project policy implications

It is apparent that the care taken to collect and manage data within long-term ecological monitoring projects provides a potential foundation for policy construction and review, strategy design and decision making. However, the extent to which this potential translates into action, and the degree to which this action is beneficial to society, to science or to the environment depends very much upon external factors at the implementation stage. Scientists rarely hold the responsibility for making policy decisions on the basis of their data, and often find themselves effectively excluded from any involvement in this process. Minor policy matters lie within the bureaucratic realm, while major policies are reserved to politicians and their economic advisers - groups not noted for the depth of their scientific mastery. The ramifications are far-reaching and beyond the remit of an introductory survey, but three associated issues arise and invite comment:

- Rationality (ostensibly the hallmark of science) has become an inherently

appealing but intrinsically imperfect exclusive framework for decisions. Unless strong safeguards are incorporated, there is a real tendency for data to fuel existing assumptions rather than being used to test, sharpen or reject those assumptions. Since scientists lose control of the use to which their results are put once they have been deposited or published, it is imperative that raw data always carry sufficient metadata to enforce consideration of context and qualification, and that derived data should be designed and presented in the language of the politician, and against the "metagoals" of society (Lonergan, 1985). GIS, with its intuitive and convincing link to place, has a major role to play in this context, but can be effective only if its design takes account of the major policy implications as well as the many internal technical requirements and constraints.

- Uncertainty characterises all policy and management decisions involving long-term environmental management, and thus is inherent to the policy debate that emerges from long-term ecological studies. Clark and Gardiner (1994) note that when planning takes place within a context of suppositions about the system attributes which can justifiably be assumed, it follows that effective approaches to planning must respond to major shifts in these assumptions. Uncertainty in science has usually been viewed as a product of model simplicity or measurement deficiency. Recent developments in awareness of global environmental change, an increased appreciation of the complex interlinkage within and between systems, and a widespread acceptance that some key elements or externalities of system behaviour are non-linear all suggest that these traditional approaches now need significant supplementation. If uncertainty is regarded as an operational component within the policy review or planning procedure rather than as a technical flaw, then it can be tackled through technical, managerial and attitudinal adjustments. Since the results of long-term ecological monitoring projects fuel this system, they should be geared to making a positive and significant contribution. GIS developments now in hand begin to offer real prospect in this respect, with the potential of fuzzy systems and of varying degrees of "expert" guidance within the system being closely bound up with the attempt to render interpretation and decision-making flexible, sensitive and realistic.
- Communication lies at the heart of the chain which links the scientist, the long-term monitoring programme, the information system and the policy

maker. Communication technologies have developed apace over the last decade, and now offer an unprecedented range of opportunities to transfer message and understanding. The limitations that remain - and they are legion - lie in the message that is placed at the core of such communications. Science has traditionally maintained a clear separation between observation and interpretation - which now translates into a separation between data and information; between information and action; and indeed between science and society. The increasingly technocratic basis of policy-making (or, at least, the increasing extent to which technocratic arguments are presented to justify policies), suggests that scientists including ecologists may increasingly need to bridge these chasms.

Such issues may appear to move well beyond the data design criteria of most ecological monitoring projects, but the investment required for a major long-term project, and the socially-significant implications of the results of such projects, demand that we should take the broader view.

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HISTORICAL

OPTIMAL USE OF DATA AND SAMPLES COLLECTED BY THE CONTINUOUS PLANKTON RECORDER

[illegible]

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ABSTRACT

Continuous Plankton Recorders of Northern Seas have served in a large Mono ships of opportunity in the North Sea and the North Atlantic since 1926 to the present day, with approximately 150000 samples being analysed and archived during this period. Over 300 different taxa are routinely identified and counted on the samples. The resulting data have traditionally been used to examine spatial, seasonal as well as long-term patterns in plankton occurrence. However, there are problems with the quality of the CPR data. Of primary importance is the fact that the flow rate through the sampler has never been monitored and so the volume of water filtered per sample and hence the absolute abundance of plankton is unknown. Furthermore, the plankton counts that are made may not even give a good measure of relative abundance since clogging of the filtering mesh, which influences the flow rate, may vary both seasonally and spatially. A method is therefore proposed to recalculate the historically collected CPR data in terms of absolute abundance.

Due to these shortcomings it is suggested that, at present, the CPR data is used in ways that make few assumptions concerning absolute plankton abundance. In particular the value of the CPR data for investigating the diel vertical migration of zooplankton is discussed.

A second major problem with the CPR data is that many taxa are not identified to species level. The problems this creates are illustrated by examining records of coccolithophores in the data base. Although other studies have shown that the species *Emiliania huxleyi* is numerically the most abundant coccolithophore in the North Atlantic and North Sea, it is too small to be recorded in the CPR analysis. Instead the CPR records for 'coccolithophores' are weighted towards larger species. Consequently, the only way of examining the distribution and long-term changes in the occurrence of *E. huxleyi* is to re-

examine samples. This example illustrates the importance of preserving and archiving the CPR samples.

Background to the CPR survey

Continuous Plankton Recorders were conceived and designed by Alister Hardy in the 1920's (Hardy, 1926). Although there was some deployment of CPRs before the Second World War, it is since 1948 that recorders have been towed routinely from ships of opportunity in the North Atlantic and the North Sea. The result is a unique data set describing the occurrence of various planktonic groups that has formed the basis of for several hundred scientific publications examining principally seasonal, spatial and decadal time-series changes in plankton occurrence (cf. Robinson, 1970; Oceanographic Laboratory, Edinburgh, 1973; Aebischer *et al.*, 1990). CPRs continue to be deployed, with the survey currently being run by the Sir Alister Hardy Foundation For Ocean Science, Plymouth.

The design of the recorder is shown in Fig. 1. Water enters via a square aperture of cross-sectional area 1.61 cm^2, passes along a tunnel within the sampler, through a band of silk mesh (the 'filtering silk', nominal aperture 270 m, dimensions of the filtering area 10.2 cm x 5 cm) and then exits at the back of the

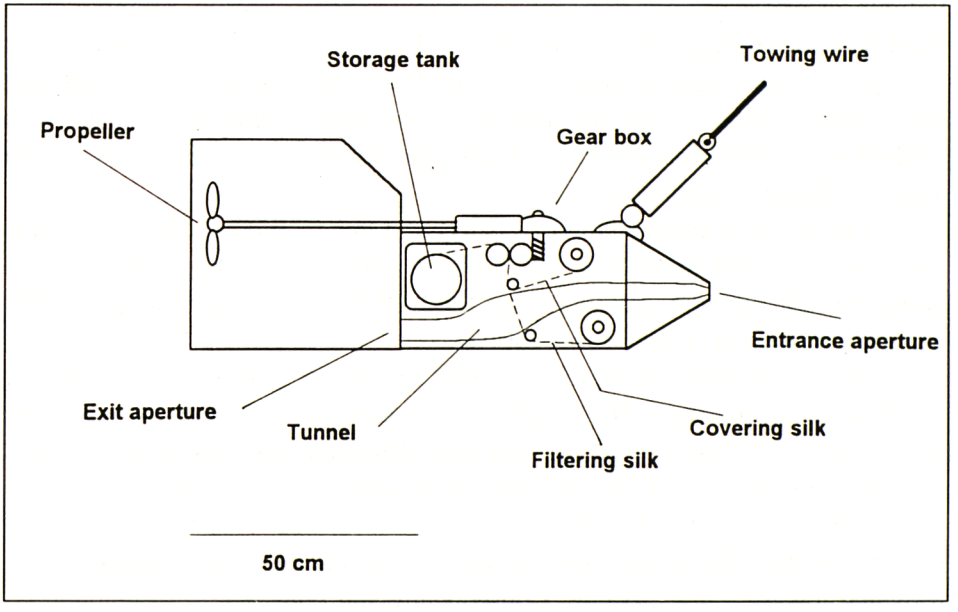


Figure 1: A schematic diagram showing the construction of the Continuous Plankton Recorder (from Hays, 1994).

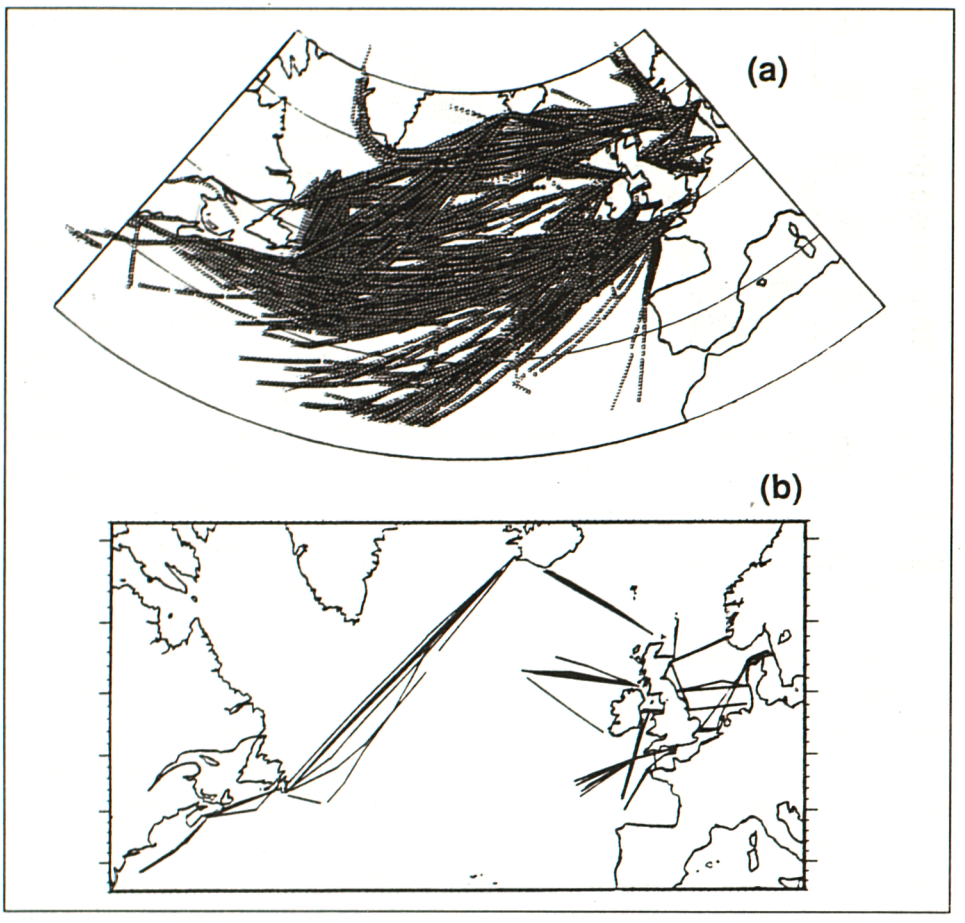


Figure 2a: A map showing the positions of all the samples taken with CPRs between 1962-1974. The map serves to illustrate how when the sampling from different years is pooled, there is almost complete CPR coverage of the North Sea and North Atlantic. In any one year, however, sampling will be more restricted, as shown in **Figure 2b.** which shows the tow routes that were conducted in a single year,

recorder. The filtering silk is constantly wound into a storage tank containing formalin, being driven by an external impeller via a gear box. Before entering the storage tank, the plankton on the filtering silk is sandwiched by a second moving band of silk (the 'covering' silk). On return of the recorder to the laboratory, the silk is removed from the storage tank, unwound and then cut into sections representing 10 nautical miles (approximately 18.5 km) of tow. The amount of phytoplankton and zooplankton on these samples is then assessed in a routine analysis procedure in which over 300 different taxonomic entities are identified

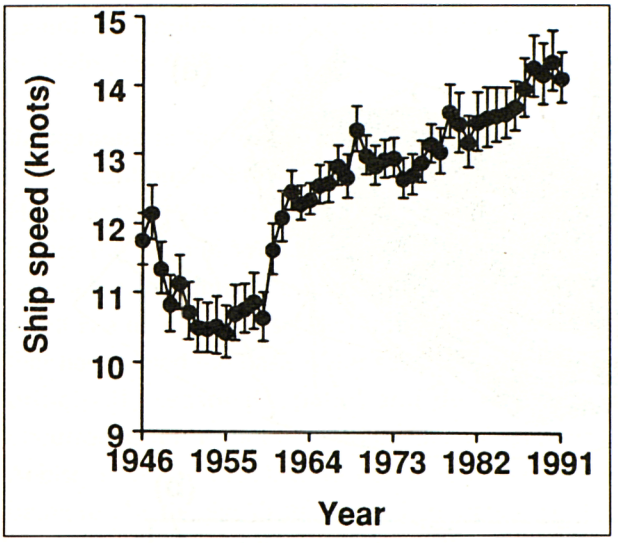


Figure 3: The mean annual towing speed (± 2 *SE*) of CPRs between 1946-1992 (from Hays & Warner, 1993)

(Colebrook, 1960; Warner and Hays, in press).

The use of ships of opportunity allows extensive spatial coverage to be achieved (Fig. 2a). Tows are made along a number of specific routes at approximately one month intervals (Fig. 2b) and hence complete seasonal coverage is obtained. However, tow routes periodically change as a consequence of the changing financial resources of the survey and due to changing merchant shipping routes. In total, since 1948 over 150000 CPR samples have been analysed, representing over 5 million km of towing. After they have been analysed, the samples are stored in buffered formalin and archived.

As a consequence of using ships of opportunity there has been an unavoidable change in the towing speed of CPRs during the time series (Fig. 3). For example, the mean towing speed increased progressively from 10.5 knots in 1952 up to 14.2 knots in 1991. Furthermore, the use of ships of opportunity means that there is no active control of towing depth. Instead, the amount of wire that is let out on each CPR deployment is varied depending on the ship speed. By constantly monitoring the depth of CPRs during tows, it has been shown that this system ensures that the towing depth is independent of the towing speed with CPRs operating at a mean depth of 6.5 m (Hays and Warner, 1993). In addition, during experimental tows a finer mesh has been positioned behind the normal 270 µm CPR silk mesh to quantify the loss of plankton through the recorder. These experiments have similarly shown that the retention of plankton on the filtering mesh is not effected by the towing speed (Hays, 1994).

The results from the CPR survey are stored on a readily accessible relational data base system. Use of this data by the scientific community is encouraged and enquires regarding access to the data should be directed to Dr

J.C. Gamble, The Sir Alister Hardy Foundation For Ocean Science, The Laboratory, Citadel Hill, Plymouth PL1 2 PB, UK.

Calculating absolute plankton abundance from CPR samples

In simple terms there are two parameters that need to be measured in order to quantify the absolute abundance of plankton from net hauls: (1) the number of animals that are caught and (2) the volume of water that was filtered to catch those animals. As has been repeatedly demonstrated it is not sufficient to assume that the volume of water filtered equals the inlet aperture area multiplied by the distance of a tow, since other factors such as the shape of the sampler and the amount of plankton clogging up the filtering meshes will influence the flow rate (UNESCO, 1968; McQueen and Yan, 1993). However while the number of animals in each CPR sample is routinely assessed, the volume of water filtered to collect each sample has not historically been measured. Consequently it is not possible to accurately estimate the absolute abundance of plankton from the present CPR records (Hays, 1994).

It might be argued that since the CPR methods of data collection and analysis are constant, that the results from the survey can still be used to give an indication of the relative abundance of species in different areas, seasons and years. This is, however, unlikely to be the case since clogging of the CPR meshes may vary in both time and space. For example, from a purely visual inspection it is clear that the CPR silks are considerably more clogged in summer samples than winter samples.

The fact that the water flow rate through the CPR was not been measured historically largely reflected a lack of appropriate instrumentation and technology. However, flow meters are now commercially available that can constantly monitor the flow rate through a CPR with this data then being stored on an in-situ data logger. Current initiatives are therefore directed at equipping CPRs with such instrumentation with the first operational measurements of flow through a CPR planned to be made in the late summer of 1994.

As well as allowing the direct determination of the absolute abundance of plankton from the CPR samples taken in the future, measuring the flow rate may also, indirectly, allow us to calculate the absolute plankton abundance from the historically collected samples. Variations in the flow rate are due to clogging of the filtering mesh with plankton. By measuring the flow rate it should therefore be possible to derive a relationship between the volume of water filtered per 10-

nautical mile CPR sample and the amount of plankton on that sample. Once this relationship has been established, the amount of plankton on each of the historically collected CPR samples (this 'amount' having being quantified in the routine CPR analysis) may then be used to predict (with a known error) the volume of water filtered for that particular sample, thus allowing the absolute abundance of plankton to be estimated with known confidence.

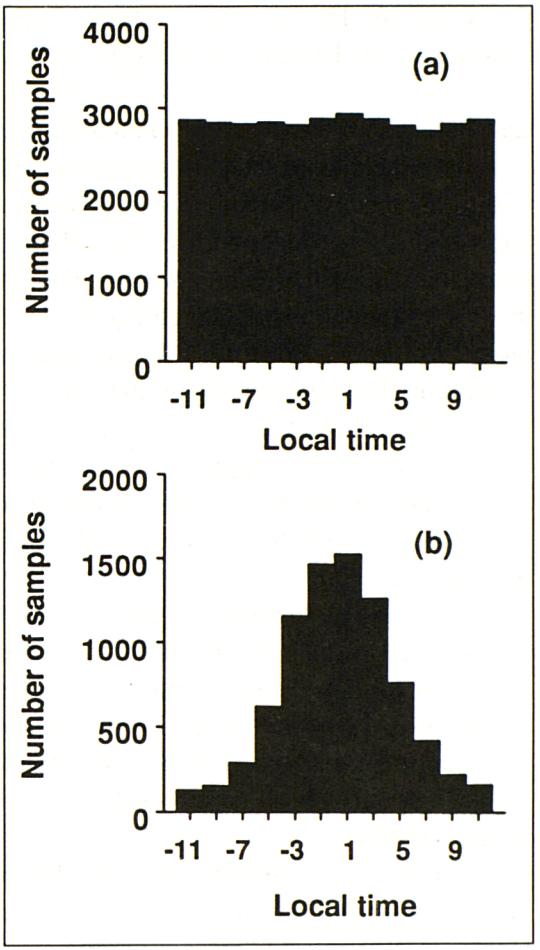


Figure 4(a): The local time of day in hours since midnight (i.e. -1 represents the number of samples collected 0 to 2 hours before local midnight, +1 represents the number of samples collected 0 to 2 hours after midnight, etc) that CPR samples were taken in the north-east Atlantic and (b) the local time of day that *M. lucens* occurred on these samples (from Hays *et al.*, submitted a). The probability of *M .lucens* occurring on samples increased towards midnight, as a result of night-time vertical migration into the near surface waters.

Conversion of the extensive CPR data set to absolute units is thus a realisable goal. Clearly it will greatly enhance the value of the data set, allowing more scientifically robust analysis of the spatio-temporal patterns of plankton abundance in the North Sea and North Atlantic.

Quantification of vertical migration: a robust use of the CPR data

Since the absolute abundance of plankton cannot be derived, at present, from the CPR data set, it is important to use the data in a ways that make few assumptions concerning absolute units. One appropriate use of the data that has been recently explored, is to examine diel vertical migration (DVM) by

zooplankton.

DVM is a widespread trait in both marine and freshwater plankton communities. The generally observed pattern is for a population to occur at a greater depth during the day and a shallower depth during the night ('normal' DVM)(cf. Lampert, 1989). Typically this movement is investigated by net hauls being made at a number of discrete depths to quantify the day and night vertical distributions of a population. DVM is then inferred when there is a significant difference in the mean day and night depths with the magnitude of this difference being described as the 'amplitude' of vertical migration (cf. Bollens *et al.*, 1993). Clearly the CPR data cannot be used in this manner since the samples are all collected at a fixed near-surface depth (Hays and Warner, 1993). However, given this sampling regime it would be predicted that species undertaking DVM should show a diel variation in their occurrence in CPR samples, being caught predominantly in samples taken at night, while for species not exhibiting DVM their occurrence in CPR samples should be similar in both the day and night.

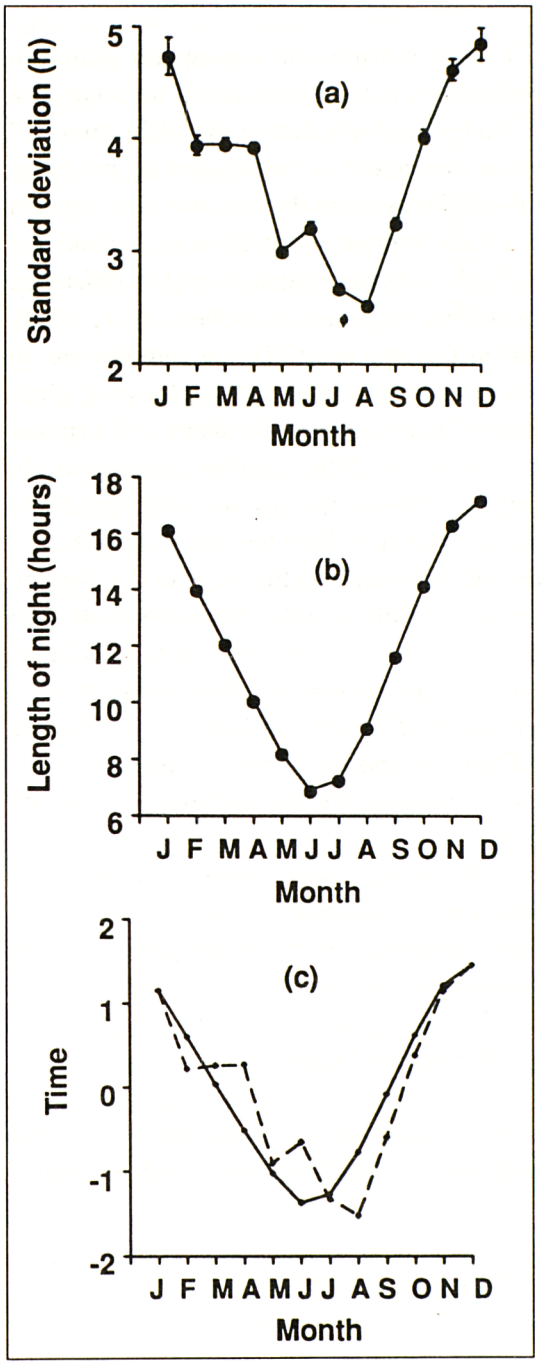
To explore these predictions further, we examined the times of day that the copepod *Metridia lucens* was occurred in CPR samples from the north-east Atlantic. *M. lucens* was selected for this initial examination since it occurs frequently in the CPR samples and it has been shown by other studies to be a species that may vertically migrate (Dagg *et al.*, 1989; Bollens *et al.*, 1993). As expected, given this known DVM behaviour, the maximum occurrence of *M. lucens* was in CPR samples taken close to midnight and the minimum occurrence in samples taken around midday (Fig. 4).

Since the times of day that *M. lucens* was caught followed an approximately normal distribution when time was plotted as hours since midnight (Fig. 4), the standard deviation () of this distribution can be used to given an index of the length of time that the population was present near the surface where:

$$d^2 - \F(1[\sum(fx)^2,\sum f) - \F((\sum fx)^2],\sum f) \quad \text{eqn. 1 (Bailey 1981)}$$

with f = the numerical abundance of *M. lucens* in each sample, and x = the time in hours since midnight that the sample was collected, with the standard error of this standard deviation given by:

$$\text{Standard error} = d/\sqrt{2n} \quad \text{eqn. 2. (Sokal and Rohlf 1969)}$$



where n = the total number of *M. lucens* in each respective season and area.

To examine the seasonal variation in the surface occupation by *M. lucens*, was calculated for different months of the year . There was a marked seasonal variation in the length of time that *M. lucens* spent near the surface (Fig. 5a). Of this variation, 80% was explained by the mean length of the night in different months (Fig. 5b). Thus during mid-summer when the nights were approximately half as long as they were during mid-winter, *M.lucens* similarly spent about half as long near the surface compared to mid-winter. It has been suggested that DVM serves to reduce the risk of mortality from visual predators (Zaret and Suffern, 1976). According to this hypothesis, zooplankton that are susceptible to visual predation,

Figure 5(a): The mean length of time (± 2 SE) that *M.lucens* was present near the surface in each month in the north-east Atlantic. (b) The mean length of the night in different months in this area. (c) The graphs in (a) and (b) reduced to zero mean and unit variance to facilitate visual comparison. There was a significant linear relationship between the length of time that *M.lucens* was present at the surface in each month (- -) and the mean night length in each month (æ). ($F_{1,10} = 42$, $r = 0.80$, $P < 0.001$) (from Hays *et al.*, submitted a).

such as large and/or highly coloured species, only forage near the surface when it is dark thereby reducing their probability of being perceived by predators. In accord with this hypothesis, *M. lucens* varies the amount of time it spends near the surface, so that throughout the year it tends to restrict its near surface foraging to the nightime and hence to periods when its probability of being consumed by visual predators is low.

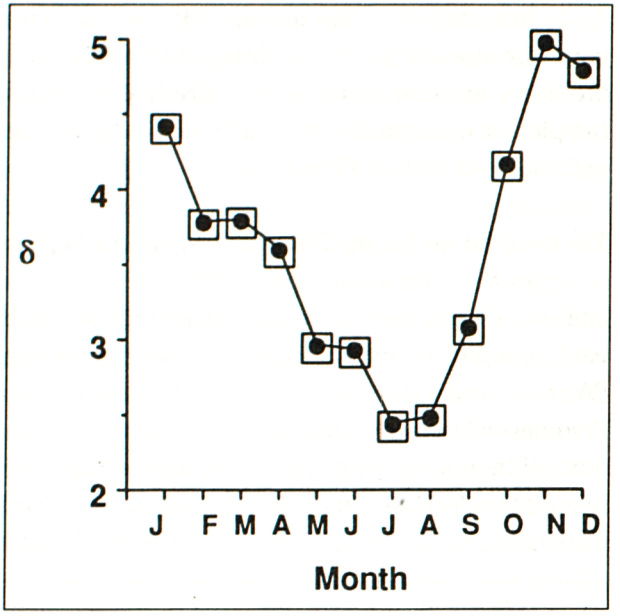


Figure 6: The mean length of time () that *M.lucens* was present near the surface in each month in the north-east Atlantic. æ = the results using the raw CPR data (from Fig 5a), = the results assuming that the absolute abundance of *M. lucens* was 100 times that recorded in the CPR analysis, and ® = the results assuming that seasonal mesh clogging chan.ged the mean monthly volume of water filtered per sample by an order of magnitude through the course of a the year (see text for details). It is clear that neither the relative or absolute abundance has a major influence the value calculated for .

The strength in this calculation is that it is very robust in terms of the assumptions that are made concerning either the absolute or relative abundance of a species. To illustrate this point, the calculation of for *M. lucens* was repeated, but instead the abundance on each sample was multiplied by 100. This gross change to the absolute units had little effect on the calculated monthly values for (Fig. 6). Secondly to change the relative abundance of *M. lucens* in different months, it was assumed that there was seasonal clogging of the filtering mesh so that the mean volume of water filtered per sample varied seasonally by an order of magnitude. The assumed relative mean flow rates were: January = 1.0, February = 0.7. March = 0.5, April = 0.3, May = 0.1, June = 0.1, July = 0.1, August = 0.3, September = 0.5, October =0.7, November = 1.0, December = 1.0. This simulated seasonal clogging of the filtering mesh also had little impact on the calculated values of sigma (Fig. 6).

In conclusion, the use of CPR data to examine diel vertical migration is very appropriate as the technique is influenced very little by the inherent problems in determining either absolute or relative abundance from the CPR samples. It is suggested that such robust techniques continue to be explored to make full use of the CPR data set.

The need for archiving CPR samples: coccolithophores as a case study

In the CPR survey over 300 different taxa are identified in the routine analysis. Due to constraints on the amount of time that can be given to analysing each sample, inevitably some organisms are not identified to species level. (Warner and Hays, in press). For example, any coccolithophores (class Prymnesiophyceae) observed in the routine CPR analysis are simply recorded as 'coccolithophores' and not to any further taxonomic level. Recently there has been considerable attention focused on one particular species of this group, *Emiliania huxleyi*, due to the potential importance of this species in biogeochemical cycling (*cf.* Holligan *et al.*, 1993). *E. huxleyi* has been shown to be the most numerically abundant species of coccolithophore in the North Atlantic and North Sea (Braarud *et al.*, 1953; Okada & McIntyre, 1979) and can form extensive blooms covering many 1000's of kilometres that are readily perceived by satellite observations (Holligan *et al.*, 1983) . It might be

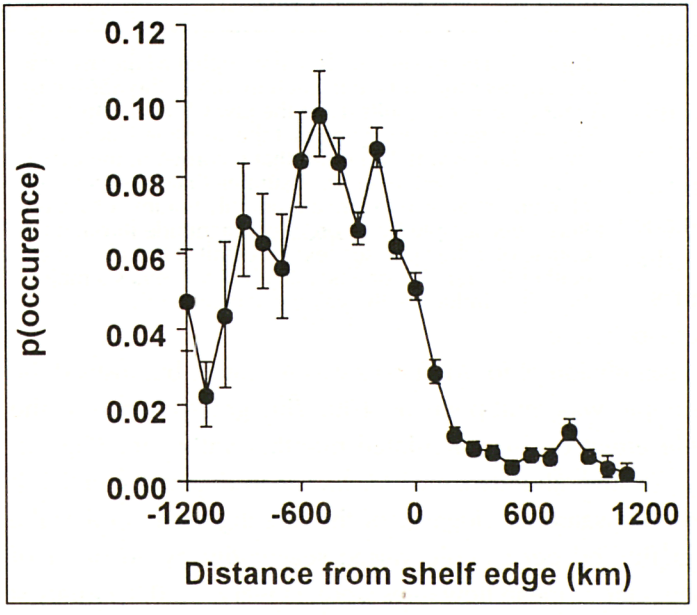


Figure 7: The probability (± 1 SD) of coccolithophores being recorded in 20 years of CPR sampling (1973-1992) in relation to the distance of samples from the 200 m depth contour (from Hays *et al.*, submitted b). Negative distances represent samples in the north-east Atlantic and positive values samples from the North Sea.

assumed that since *E. huxleyi* is the most abundant coccolithophore in the North Atlantic and North Sea, that it should also be the species that is identified most often in CPR samples. However, the spatial distribution of coccolithophores in the CPR records shows low occurrence in the North Sea compared to much higher occurrence in the oceanic Atlantic (Fig .7). This pattern is inconsistent with the known widespread distribution of *E. huxleyi* and suggests that it may be other coccolithophore species that are identified in the routine CPR analysis.

To investigate this further, an expert in coccolithophore identification (Derek Harbour of Plymouth Marine Laboratory) identified coccolithophores that were being recorded in the routine CPR analysis. The species observed by CPR analysts was *Coccolithus pelagicus*, a large oceanic species (up to 32 m in diameter, Heimdal, 1993), and while *E. huxleyi* was present on the CPR samples, it was simply overlooked in the routine analysis due it small size (typically 5-8 m in diameter, Jahnke, 1992). Since the CPR samples are stored in buffered formalin, *E. huxleyi* is well preserved and can be readily identified in the archived samples. Consequently, while little can be learnt about *E. huxleyi* from the records of coccolithophores in the CPR data base, it is possible to re-analyse the archived samples for this species.

CONCLUSIONS

The extensive spatial (North Atlantic and North Sea) and temporal (all seasons, 45 years) coverage achieved by the CPR survey is unique in marine science. There is, however, a need to improve the quality of this data set by monitoring the water flow rate through the recorder, thus allowing quantification of absolute plankton abundance. While this goal is being realised the data set still has great potential for examining questions where absolute plankton abundance is not needed. CPR samples have historically been archived and this should continue as it allows the re-examination of samples by novel methods not used in the original analysis.

ACKNOWLEDGEMENTS

The CPR survey is funded by the Ministry of Agriculture Fisheries and Food (U.K.), Department of the Environment (U.K.), Department of Fisheries and Oceans (Canada), NOAA/NSF (USA), the European Commission and the Consortium (Netherlands).

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THE ROLE OF COLLECTIONS AND ASSOCIATED DATA IN LONG-TERM STUDIES

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ABSTRACT

Collections of natural history specimens from all over the world have been deposited for hundreds of years in museums, ranging from the large institutes in Paris, London and Washington to the small specialised museums attached to marine labs and universities. These collections have grown to astonishing size, 76 million objects in Paris alone. Collections, and the metadata associated with them, potentially represent an astonishingly comprehensive source of long-term data. Collections are a vital resource for validating historical records. This can be important, for example, in tracking changing species' biogeographic ranges with time as a way of monitoring global climate change or degradation in habitats or biodiversity. However, there are problems. The cost of curating collections continues to rise in a situation where funds are shrinking. Ironically, collections are endangered just when new roles are being found for them in modern research. New techniques need to be developed to allow analysis of preserved rather than fresh material. The metadata associated with collections needs to be reordered and stored in a form that allows modern questions to be answered. In this paper we describe both traditional and modern roles of museums and consider the weaknesses and opportunities that museum collections and data present for long-term biological research. In particular, we consider how new technologies, especially information technologies, can transform the practical value of museum-held information for long-term studies.

INTRODUCTION

The oldest long-term, biological data sets are the collections, and associated metadata, held in marine laboratories, university departments and museums. These collections have been made over a considerable number of years and were primarily intended as taxonomic references. However, they

represent a long-term data base and in this paper we will describe some features of these collections and consider how useful they are for more general long-term studies. For example, the National Museum of Natural History in Paris was created in 1626 as the Royal Garden of Medicinal Plants. A century later, Buffon, who was the *Intendant* (Director of the King's Garden), embellished the garden, doubled its surface and expanded the collections over a 50 year period. Under the *Convention Nationale*, the "Jardin des Plantes" was further expanded and a zoo was added. In 1793, it became the Museum of Natural History, the largest scientific research centre in the world at that time, with 12 chairs in research and education. The next 100 years were perhaps the great age of collection-based biological research leading to the publication of Charles Darwin's *The Origin of Species*, arguably the most significant work in the field of biology. Collection-based research has perhaps been rather overshadowed in the twentieth century by newer disciplines, such as molecular biology and mathematical modeling, but we contend that much of value remains to be unlocked from natural history collections in addition to their primary taxonomic function. Even today, with more than 1,850 scientists (about 500 scientific staff and students), technicians, librarians, gardeners and animal caretakers, the National Museum of Natural History continues to be a large biological research institute and The Natural History Museum (London - the NHM) and the National Museum of Natural History, The Smithsonian Institution (Washington) are of comparable sizes. However, no less significant collections of specimens and data are stored in smaller museums around the world, many of which are attached to marine stations or university departments. In this paper, all organisations with collections will be included in the generic term - museum.

A natural history museum has three fundamental responsibilities: (1) research, (2) heritage conservation and (3) diffusion of knowledge. The main research objectives are the study of biodiversity and evolution. Four levels of biodiversity studies have been undertaken (Chauvet & Olivier, 1993; Maurin, in press): (1) intra-specific diversity, measurements of genetic diversity for the distinction between variants of the same species or the genetic differentiation within the same population; (2) specific and inter-specific diversity between species within a given geographical area based on inventories of living species; (3) ecological or ecosystem diversity and (4) the evolution of diversity over geological time scales. Diversity can be measured at various levels, such as continents or regions, or in small biogeographical areas, or habitats.

For some years, collections in all fields of natural history have grown due to the development of oceanographic cruises and international expeditions which has strained the storage capacity and budget of museums (Hureau, 1993). In the same way, the development of new techniques have affected the care of collections, usually with undesirable financial consequences. It is ironic that, just as there is a new interest in the data locked up in collections, and new methodologies for unlocking (see Hawkins *et al.*, this volume) and disseminating that data, many organisations, for which curation is not one of their primary duties, are having to dispose of valuable material that they have held for many decades. Even the specialist museums are now having to consider the financial implications in accepting new material.

The range of museum collections

Museums possess collections of great richness. More than 76 million various objects are conserved in the Paris Museum, with a further 67 million reference specimens stored in London (Bodmer *et al.*, 1993). The French National Collection can be broken down into 60 million units of insects and arthropods, including about 200 million mounted specimens, 9.5 million flora specimens, 2 million marine invertebrates, 2 million palaeontological items, 1 million mounted vertebrates, 800,000 ethnological and anthropological items, 200,000 minerals, 60,000 living plants and 5,000 living animals belonging to more than 650 species. The collections occupy about 100,000 square metres distributed in 20 buildings and gardens in Paris and in Provence. The annual increase in the number of objects is between 2 and 5 percent. The Museum has a great number of types, many described by illustrious zoologists like Buffon, Lamark, Cuvier, de Blainville and d'Orbigny. The collections were initially registered in different forms, but generally on a card-index and/or register in each laboratory or service involved in storing collections. To date, no general protocols for registering exist so each laboratory manages its collections independently. A similar situation exists in the NHM, the curation programme employing nearly 100 staff whose specific responsibilities include curatorial activities, handling visitors and loan of specimens, and the long-term enhancement of the collections (Bodmer *et al.*, 1993). With no agreed national protocols, it is hardly surprising that no international protocols for specimen registration exist. This lack of protocols is one of the factors inhibiting the wider availability of information on where specimens are to be found.

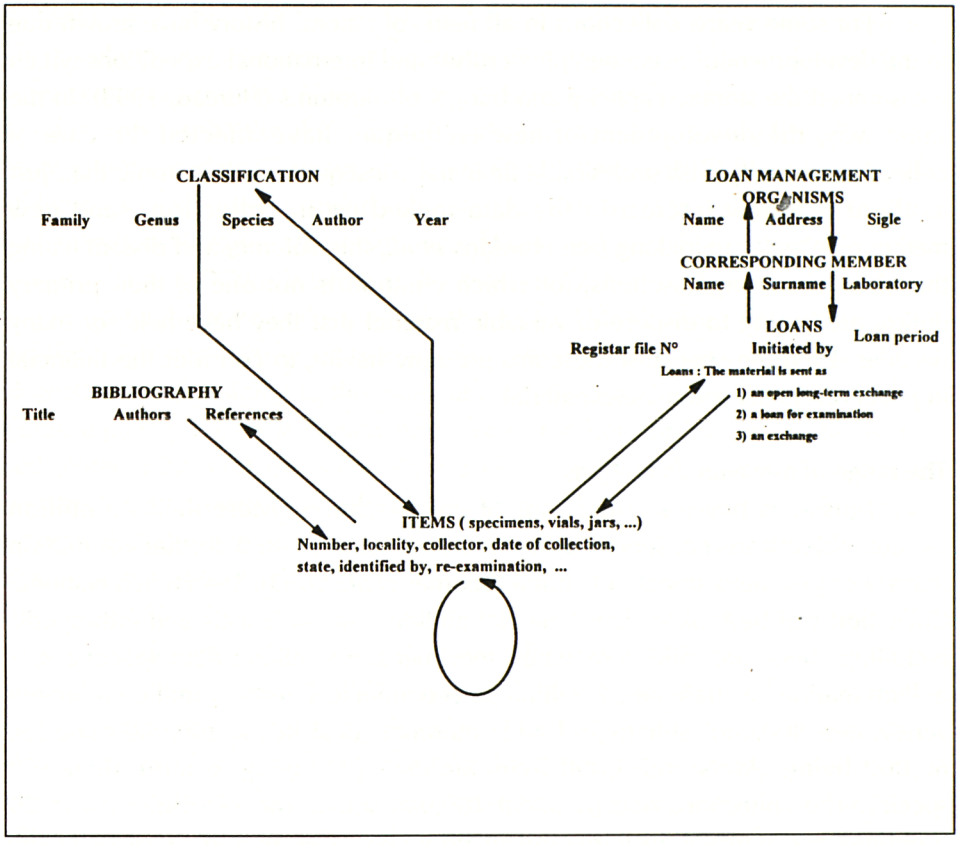

Figure 1. Conceptual scheme of the GICIM (Gestion Informatisée par le Centre Informatique du Muséum) data base. From Hureau *et al.*, in press.

Description of a collection

Collections are not just an inventory and a load of stored specimens, but form a reference pool useable by scientists throughout the world. The conceptual model of a collection is summed up in Fig. 1. At the centre of the collection there are the items. These are stored in various forms such as stuffed specimens or preserved in formalin or alcohol. The method of storage is important as it inevitably limits the type of analysis that can be made using a collection specimen. For example, many types of chemical analysis are prejudiced by the preservative employed, e.g. formalin can play havoc with DNA or immuno-assay tests.

Card-indices and registers record the name and number of specimens. In the majority of cases, the items are classified, but samples brought back from

expeditions may remain unclassified due to the high number of specimens (like insects from the canopy of Guyana) or to the lack of specialist expertise - even the largest museums now find it difficult to cover all groups. Unclassified specimens are not without value as they can form a historical record. The bibliography gives the authors and references of works on the objects. An important role of museums involves loans to all parts of the world. For instance, a total of about 300 loans per year were sent out by the 'Laboratoire de Biologie des Invertébrés Marins et Malacologie' corresponding to about 10,000 specimens; a total of 1,871 loans (61,300 specimens) were sent out in 1992/93 by the NHM (Bodmer *et al.*, 1993).

The incorporation of new methods of data acquisition and management of collections will be particularly important, because it will make it possible to find, rapidly, the metadata for an object: initial registration; name of collector; locality and date of collection; name of the specialist who had made the initial identification; status; holotype; paratype; information on the stored state; state of the specimen (special preparations); scientists who have studied the specimens; loans and re-examinations; figures and bibliography of the specimens - and so on. The objectives of the NHM in curation are to develop a pilot digital imaging system for the capture, storage and transmissions of images and to standardise and computerise procedures for handling loans (Bodmer *et al.*, 1993). In the long term, new technology will increase the practical value of museum collections for purposes other than straightforward taxonomy but, in the short term, it adds to the financial burden of curating collections.

Descriptions in natural science

The description of objects which compose our world is a fundamental component of knowledge transmission. It could be a mental representation for oneself or a written representation for others (Le Renard & Conruyt, in press). A scientific description must, theoretically, be objective because it should not depend on interpretation. Ideally, the description is made in textual form with illustrating pictures. Audio-visual techniques can help the representation of an object. A perfect description will allow researchers to recreate the original object; in practice, a description is satisfactory when it gives a "good representation" of the object, especially concerning its unique properties (Le Renard & Conruyt, in press). The notion of homology is very important as it ensures that only truly comparable characters are compared. It derives from the fact that every biological

object has an organisation plan which is identical to all other objects of the same kind. Recognising and taking into account this plan gives a natural structure to descriptions, following what is called a *descriptive model* by Le Renard & Conruyt (in press).

Nevertheless, many old descriptions, and some recent ones, are not satisfactory because an inadequate number of characters were employed, e.g. some species of amphipod had been described only by their pereiopod 7, without any indication of the other morphological characters which are considered to be characteristic of the genus. This is why collections remain so important in biological science. Nowadays, an inadequate description is unacceptable, and homologous characters must be defined for each type of organism as a *descriptive model*. Metadata based on primitive or simply poor quality original descriptions will incorporate an unacceptable level of error and invalidate long term studies such as changes in species ranges with climate change which depend on correct identifications in historical data. Historical collections have an important role to play in validating such data.

The advantages of good comparable descriptions are numerous. Firstly, specimens are, in general, disseminated in different collections, in various places, and that makes inter-comparison of specimens long and difficult when we want to examine material. Secondly, some specimens are delicate and deteriorate with use. Others are perishable, or some of their characters deteriorate with time. So, collections of descriptions reducing consultation of specimens prolongs their availability for future basic research. It is clear that the role of present scientists, especially museum taxonomists, is to develop such descriptive models in a form that is usable to other scientists and conservationists.

Making this information available in a form that is easy and cheap to use is of fundamental importance. Audio-visual information technology offers easier diffusion of these descriptions, especially in countries with limited financial support where the price of books could be an important handicap. An innovatory step here has been the Expert centre for Taxonomic Identifications (ETI) based in Amsterdam. ETIs are essentially multi-entry computerised keys on CD ROMs connected to large comprehensive data bases. They exploit modern computer, video and graphic capabilities to allow fast and efficient identifications for both professionals and laypersons. Taxa covered presently include European birds, sea cucumbers, European fishes and marine planarians. The advantages of this seminal Dutch system is that they are cheap, portable, comprehensive, pictorial,

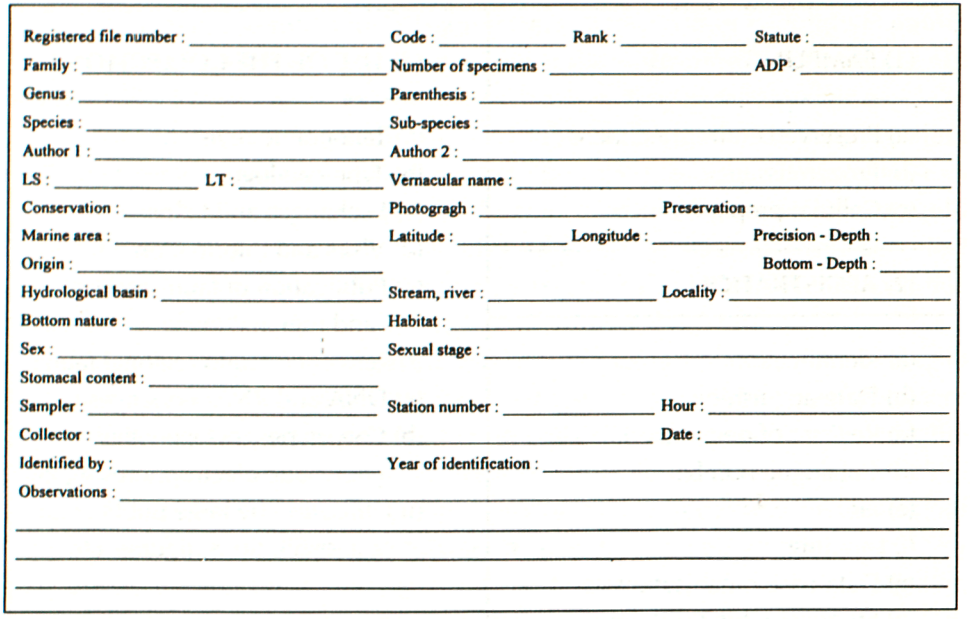

Figure 2. Model of the registered data for the GICIM data base (Hureau, pers. comm.).

user-friendly and, most of all, likely to lead to correct identifications. The databases consist of four segments: keys, general information, specialised information and teaching programmes. As well as descriptions, literature and nomenclature, the CD ROMs carry information on biogeography, ecology, parasitology, behaviour and even lists of specialists.

Computerisation of collections

Since the beginning of the 1980's, the collections and associated metadata have been computerised in museums. For example, the first collection in Paris to be computerised was the fish collection which includes about one million specimens of freshwater and marine species (Hureau, 1993). Currently, 95% of this collection is computerised in the GICIM data base (Gestion Informatisée du Centre Informatique du Muséum). The data are registered in a single model (Fig. 2), and are typed in clear to ensure a low number of errors. The organisation of Ichthyological collection service is presented in Table 1.

The computerisation of collections in the Paris Museum has become possible by the establishment of a computer centre called C.I.M. (Centre Informatique du Muséum) at the beginning of the 1980's. This centre is now

(1) SAMPLING	(3) USE OF THE COLLECTIONS
(a) Preserved entire specimens (b) Frozen tissues (c) Cellular preparation	(a) Taxonomic revision (b) Type catalogue (c) Exchanges and loans (d) Visits and information (e) Publication of faunistic lists and regional fauna (f) Reference and regional fauna (g) DNA and RNA sequences (h) Caryotypes, cytogenetics, enzymatic electrophoresis (i) Utilisation by large public, e.g. exhibitions, figures, etc.
(2) REGISTRATION	
(a) Identification (b) Data acquisition (c) Register of new material (d) Catalogue number (e) Jar (f) Labeling (g) Data base organisation (h) Storage in the Zoothéque (i) Control and correction of data (j) Informatised data (k)Informatised files (l) Management of files	

Table 1. Organisation of the ichthyological collection service from the National Museum of Natural History, Paris. (Hureau & Duhamel, pers. comm.).

linked by a network with all the buildings and laboratories scattered around the Botanical Garden. Several generations of computer have been installed in the Centre: first a mini-computer 6/43 of the CII Honeywell Bull, IBM 9377 and now an IBM RISC/6000 with the UNIX language. A Data Base Management System (DBMS:ORACLE version 7) linked to a Geographical Information System (GIS: ARC-INFO)is used for the management of the data (Hureau *et al.*, in press). The data bases are available world-wide through NCSA Mosaic for MS Windows.

In the Data Base Management System, the processing operations use data in a number of different data bases which are independent and opened simultaneously (Mulitbase), such as chronological sampling. One of the objectives of the Museum will be to make a common base of geographical names and a common taxonomic list for all computerised data. Nevertheless, some

problems exist: geographical names, e.g. French name, English name, correspondence between old and new name (absence in numerous old collections of precise geographical stations); and with synonymy of species.

At present, 24 data bases from 13 laboratories, corresponding to about 270,000 items of raw data, have been set up in the computer centre (Hureau *et al.*, in press). The data acquisition is time demanding, especially for old collections with a large number of objects, like entomological and botanical collections. So, for these collections only type material can be computerised due to financial limitations.

For the collections, the greatest interest of these data bases is the ability to locate a specimen in collections storage and also to extract and select specimens according to a given parameter, such as the origin, the place of its collection, the geographical co-ordinates, and the name of the collector. The greatest problem facing the world's museums in computerisation of their records is the cost, not of equipment, but of the staff-time to enter data and, most importantly, check it for accuracy. Putting the information into a database with a cross-referencing capability is critical as traditional written records are designed to locate a particular specimen within the collection by name and supply any accompanying data for that specimen only. Such records cannot readily answer questions such as 'what fauna have been reported/collected from the Isle of Avalon?' or 'how far north have unicorns been collected each summer since 1850'. But answering such questions is likely to be an increasingly important function of museum collections as environmental science recognises the importance of long-term studies in understanding natural processes and changes.

Storage

Storage of collections becomes increasingly problematical as society invokes new rules on, for example, health and safety which, although designed for industry, have a major impact on museums' funding. For example, the Zoology spirit collection of The Natural History Museum represents a significant fire and explosion risk; the 'spirit' in question is 80% alcohol. The building that has housed this collection for many years cannot pass the latest regulations. It will, therefore, be necessary to build a new structure with safety standards adequate for current and future regulations and move all the spirit collection into it. This will not be cheap.

Around 1976, it was decided to re-open the Zoological gallery of the Paris

Museum, a large building built in 1889, holding all the zoological collections, which had been closed to the public since 1965 due to a lack of maintenance funds (Hureau, 1993). It was necessary to remove all the collections and a large three-storied underground building named "Zoothéque" was built under the Botanical Garden, just in front of the Zoological Gallery. The building cost 43MF (7 million US$) and was completed in 1984. From March 1984 to February 1985, all the staff of the zoological laboratories participated in transferring the collections from the old Zoological Gallery to the Zoothéque (Hureau, 1993). The length of the Zoothéque is 73 m and the width 30 m, giving a volume of 50,000 m^3. The Zoothéque is safely isolated; the temperature is kept at about 15°C and the humidity between 55 and 60%. It is also protected against fire (more than 600,000 litres of alcohol are stored) and water infiltration, as well as unauthorised entry (Hureau, 1993) - unfortunately in the modern world security against hostile human action is necessary. Nevertheless, after ten years, the Zoothéque is already too small, and new considerations of storing specimens, especially dry specimens, are urgently needed for the future.

Funding allocations

The sums of money required to fund a major museum are significant. For example, in 1991, the annual budget of the Paris Museum was 138 MF (23 million US$) not including the salaries of the 1,850 employees of the museum (a further 122 MF). Only one third of this budget (46 MF) came from the government through various ministries (mostly the Ministry of University Education and Research) and this was allocated almost exclusively to research and maintenance of the collections (Hureau, 1993). Management received only 24.5 MF (about 18% of the total budget): libraries (3.5 MF), and zoological gardens and maintenance of the building housing the collections (16 MF). A result of the decreasing financial independence of the Paris Museum was the significant decrease in the budget allocated to publications (especially, Mémoir du Muséum and Bulletin du Muséum) from 3 MF to 1 MF, and the maintenance of the natural history collections (Hureau, 1993). The move towards applied or directed science is unlikely to reverse in the immediate future and it will be important for the scientific users of museum facilities, i.e. the scientific research community, to ensure that the right priorities are set for utilisation of increasingly limited resources.

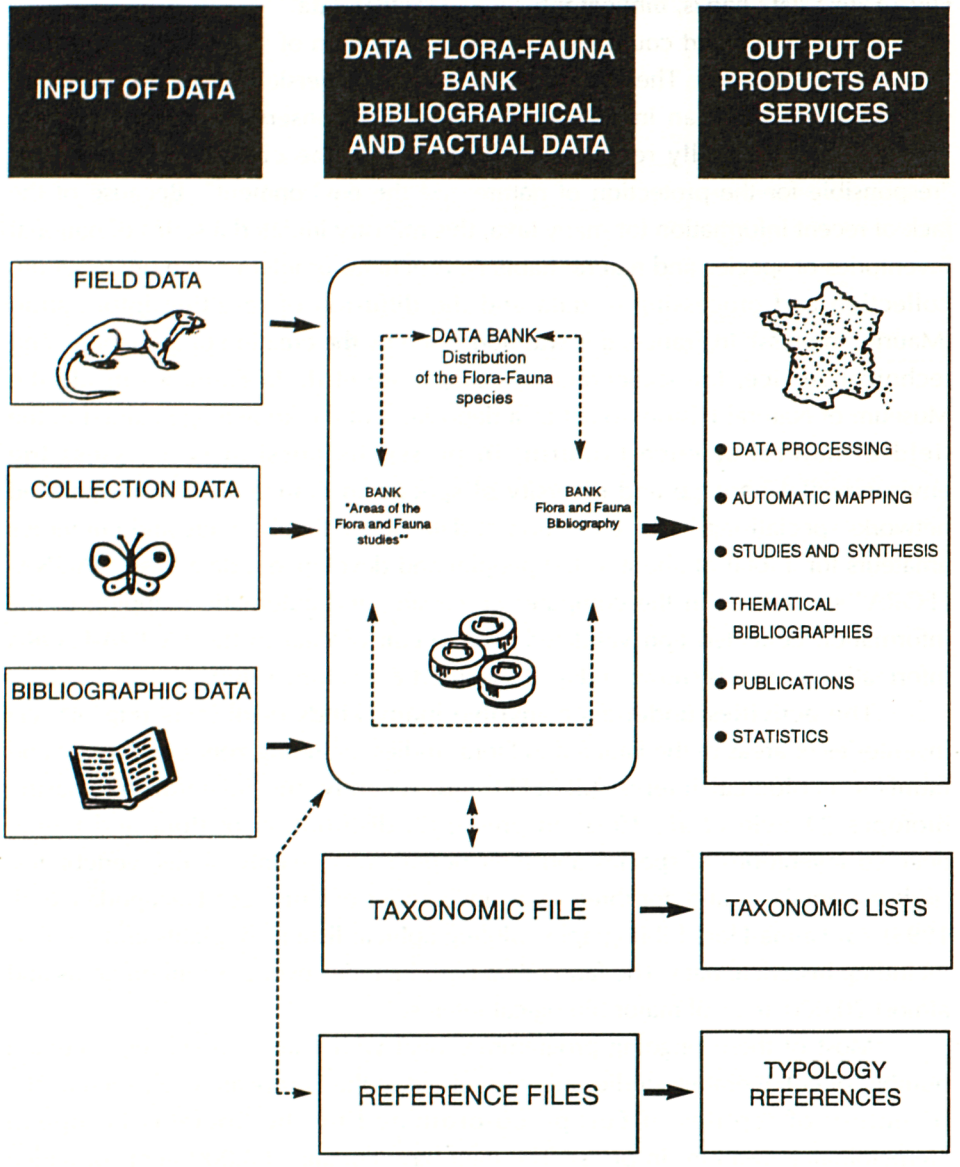

Figure 3. Data flow in the FAUNA-FLORA information system (from Beaufort de & Maurin,

Flora-Fauna data banks, bibliographical and factual data

Many developed countries now have some form of 'Action Plan' to assess their own biodiversity. The Rio Convention on biodiversity makes each country responsible for such an inventory. In France, the conservation of the Natural Heritage was officially recognised in 1971 with the creation of a ministry "responsible for the protection of nature and the environment". Because of the lack of recent information for many taxa, this ministry initiated a series of national inventories of species and natural habitats. A general problem is the organisation, collection and processing of data and the diffusion of resulting information (Maurin, in press). In France, this was addressed by the creation of a scientific and technical service, the <<Secrétariat de la Flore et de la Faune>> inside the Museum of Natural History to act as a depository of the knowledge gained in the field of natural science (Maurin, in press). Its mission is to assess the environmental heritage and diversity of species in France. The SFF organised networks specialising in the collection of data (scientific observers and numerous amateurs for a total of about 4,000 people) and developed a data base "FAUNA-FLORA" specialised in the computer processing and automatic mapping of the information collected and validated. The circuit of data in the FAUNA-FLORA information system is shown in Fig. 3 (Beaufort & Maurin, 1988).

The activities undertaken involve many kinds of objects (Fig. 4): (1) inventories of areas of the Fauna and Flora studies including zones of floristic and faunistic ecological interest (ZNIEFF) and, recently, the inventory of marine biotopes (Dauvin *et al.*, 1993, in press); (2) distribution of flora and fauna, detailed inventories of species and their populations, mainly plants, vertebrates, birds mammals, ... and, for three years, inventories of Crustacea Decapoda (Noël, 1993); (3) Fauna-Flora bibliography, bibliographical listings of plants and animals including historical data. The fauna data base includes over 2.5 million items and almost 20,000 areas of major biological interest.

Most of these ongoing programmes deal with France; however, a certain number of collaborative studies are carried out at the European level, such as the inventory of reptiles of Europe co-ordinated by the Societas European Herpetologica (Maurin, in press). The data base contains 60,000 items provided by a European network of specialists. Similar projects are underway for both breeding birds and mammals (Maurin, in press).

Our knowledge comes principally from historic and current distribution data for the various species. However, the actual information varies greatly

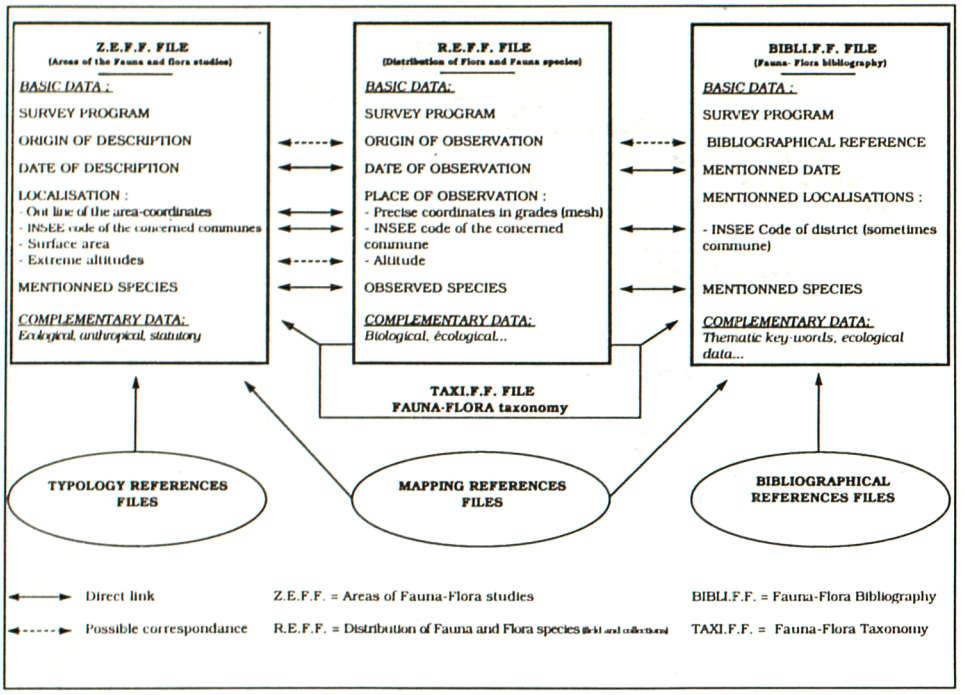

Figure 4. Main links between the sub-units of Fauna-Flora of the Secretariat of the Fauna and Flora (from Maurin, in press).

depending on the group. The charts and maps produced by the Secretariat of the Flora and Fauna in France are based on the collection of presence/absence distribution data by Département (a French administrative division); this allowed a simplification of the data collection and processing. Historical data from 1940 to 1990 illustrates the temporal changes of fauna and flora in France. For instance, the otter (*Lutra lutra*), which, despite being a protected species, has been in decline since the beginning of the century. The main causes for this are intensive trapping, the destruction of suitable habitats and water pollution (Maurin, in press). Conversely, the musk rat (*Ondatra zibethica*), a North American species introduced into France for its fur, was originally confined in fur-farms but escaped into the wild. This species has spread to such an extent that, since the beginning of the century, it has colonised almost the entire country (Maurin, in press).

During the period 1975-1991, all the groups of vertebrates were covered by reference maps published in the form of an atlas. The data bases, which contain between 30,000 and 80,000 items of raw data depending on the group

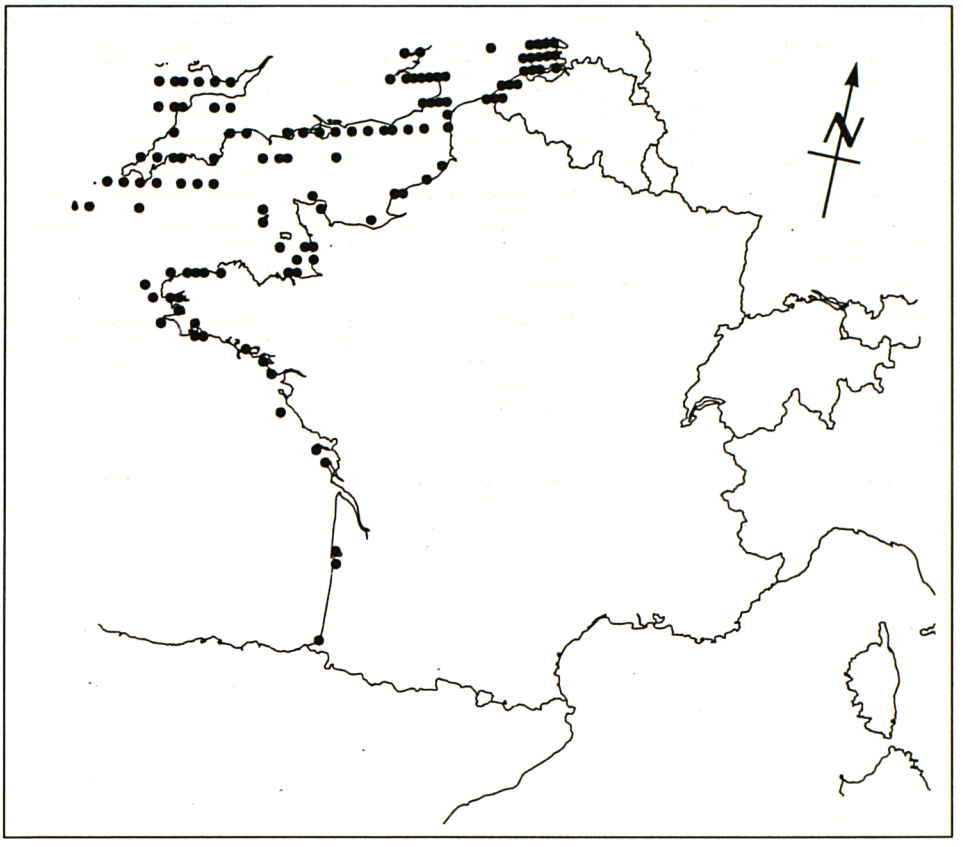

Figure 5. Distribution map of *Cancer pagurus* L., 1758 (Crustacea:Decapoda) in French waters (from Nöel,1993).

concerned (Maurin, in press), show a net increase in the number of species of vertebrates in France between 1900-1930 (586 species) and 1980-1990 (603 species). The increase is, for the most part, due to the number of species introduced by man (19 species).

The first inventory of marine invertebrates on Crustacea-Decapoda was initiated in 1991. More than 400 contributors participated in this work which will continue for a decade (Noël, 1993). A preliminary atlas had been published with 13,277 raw data entries from 3,305 stations from European seas. 317 species had been registered giving a potential of about 330-340 species. Fig. 5 illustrates the repartition of a species of crab, *Cancer pagarus* L. (1758), in the waters around French coasts and southern parts of the British Isles.

A fauna-flora data base is created by a political decision, but involves the

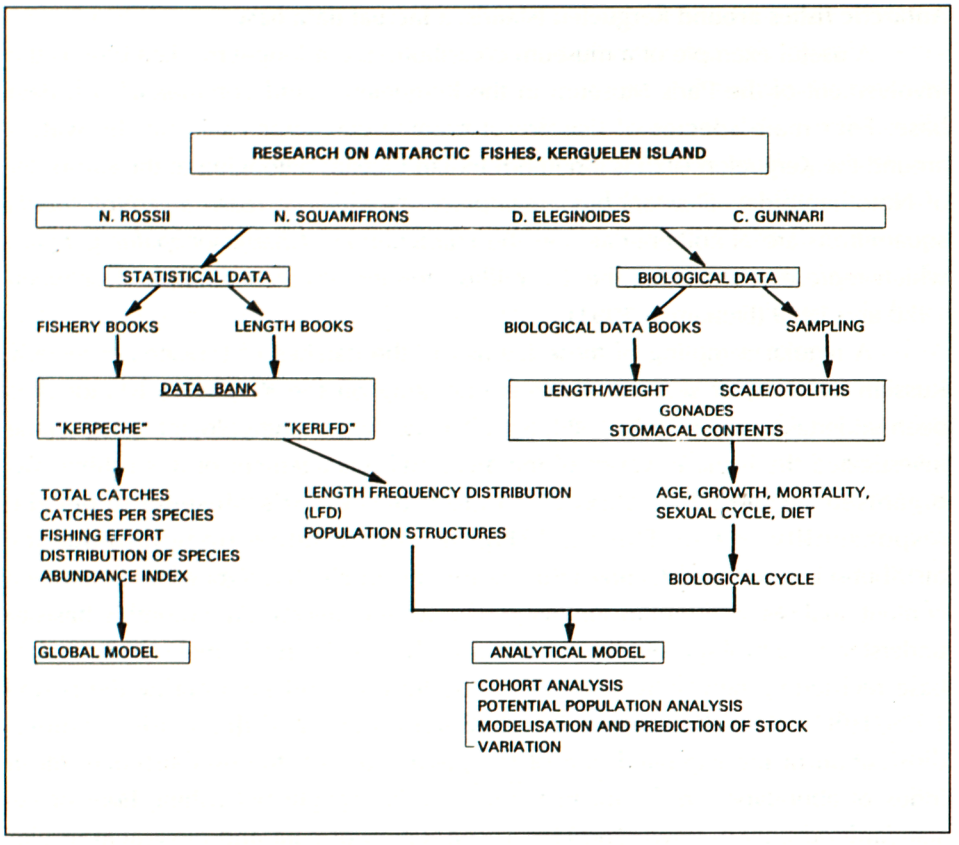

Figure 6. Scheme of the Antarctic fish data base (from Duhamel, pers.comm.).

collaboration of several participants, such as administrative institutions, public bodies and non-governmental or private organisations. An important feature for the archiving of natural heritage data is the complementary role of amateur naturalists, the most important workers in this area, to professionals in the collection of data. Like astronomy, natural history is one of the few branches of modern science where amateurs can make an important contribution. A key role for museums now involves the training of amateur parataxonomists, particularly in tropical countries. The role of the Secretariat of Fauna and Flora has been pivotal in the French Programme to produce a national approach and to co-ordinate all these national and (certainly in the coming years) European networks of naturalists.

Antarctic fishes around Kerguelen Islands: a factual data base

A useful example of a museum contribution to a long-term data base is the involvement of the Paris Museum in the Kerguelen Island commercial fish data base. Four main species of fish are of commercial importance in the waters around the Kerguelen Islands (Southern Indian Ocean) belonging to the sub-order of Notothenioidei; *Dissostichus eleginoides, Notothenia rossii* and *Notothenia squamifrons* are Nototheniidae and the Harpgiferidae *Champsocepalus gunnari,* which represented 42% of the 2.7 million tonnes of catches reported between 1970 and 1989 (Duhamel, 1991).

A regular sampling of these ice-fish in the catches of trawlers, especially Russian trawlers, or scientific vessels operating off the Kerguelen Islands, has been undertaken since 1979/1980. Simultaneously, an ichthyological programme investigated the inshore waters of the area. The management of this fishery was organised by the Ichthyology Laboratory of the Paris Museum under the responsibility of Guy Duhamel (Fig. 6). Quantitative (length/frequency distribution, catch and fishing effort ratio) and qualitative (gonad and stomach content analysis, and otolith sampling) data were collected on a monthly basis to understand the biology and the dynamics of the species (Duhamel, 1993). A data base registering the results of some 35,000 trawls, conducted during the period 1979/1980 - 1989/1990 permits; (1) determination of the spatio-temporal distribution of the exploited part of the population; (2) the establishment of an index of abundance in the mean number of fish caught per fishing hour of the standardised bottom trawl, and (3) the correlation of data and biological results. Two types of data, statistical and biological, allows determination of a global model of the fishery and an analytical model of the populations. For example, the length/frequency distribution of the dominant species, *C. gunneri,* shows the presence of one cohort per year and a limited maximal size of never more than 40 cm. The age groups (cohorts) were followed easily during a 4-5 year period because the mean growth was quick and regular from one year to another (Duhamel, 1993). The variation in abundance observed for a series of cohorts is related to the combined effects of natural mortality (predators) and fishing morality particularly affecting age 2 and 3 cohorts. A 3-year cycle of abundant cohorts should be related to a high mortality rate, natural or amplified by exploitation (Duhamel, 1993).

CONCLUSIONS

Collection-based research is one of the oldest forms of biological science and the museum collections stored and curated around the world have the potential to be an invaluable source of long-term historical data. Traditionally, these collections, and associated data, were designed for taxonomic research and the challenge is now to make them equally useful and accessible to answer ecological, biogeographical and other biodiversity questions that need an historical perspective. The cost of maintaining collections continues to mount and both specialised and non-specialised 'museums' are finding it difficult to balance budgets. Ironically, the new technologies, in analysis of both specimens and data, that are giving collections a wider importance than systematics are, themselves, a major burden on Museum finances. The new technologies for examining biological specimens include DNA amplification by the polymerase chain reaction (PCR). This allows the recovery of molecular data from stored specimens and it has greatly confirmed the value of traditional museum collections (Hureau, 1993). New chemical analytical techniques that work with preserved specimens (see Hawkins *et al.*, this volume) will make collections a treasure trove of historical data.

The computerisation of museum collection records is critical. Such data bases have two objectives (Hureau, 1993): (1) saving staff-time (at least in the long term); and (2) free and easy access to all the data for the world's scientific community; computerised catalogues and a server making data rapidly available to workers all over the world. Technical developments, in computers and programmes, allow the management of important data bases. So, data volume is not a great handicap for data base management due to the high performance of modern computers.

The role of museums was also evident in the computerisation of catalogues of species and bibliographies. Recently, Fauchald and Ward (1994) compiled on compact disc all the 30 year-old references on Annelida-Polychaeta. This kind of work should be extended in the future.

Incorporation of new data acquisition and analysis are also particularly important to define homologous description. This should permit comparison and computerisation of descriptions useable in ETI-type expert systems, image analysis and video systems (Hureau, 1993). But problems associated with the costs of these requests are also important: (1) the cost of compiling data into computers is high and must be balanced against other scientific priorities, e.g. the

necessary time to input the data of the Paris fish data base, 75, 000 data, was about 8 years; (2) the validation of data can take a great deal of time but is absolutely essential; (3) the budget to care for the natural history collections remains insufficient; (4) the dramatic reduction of specialists for many taxonomic groups is an important handicap for natural science and it is important to incorporate their knowledge into expert systems before it is lost.

Another objective of museums will be to sample regularly and widely within a given area. For instance, in a recent study programme of the Seine, the Paris Ichthyology Laboratory was required to store all the specimens of the 30 species of fish collected during this study. Nevertheless, several problems still remain: (1) cost of sorting animals, in the case of benthic samples or insect collections; (2) cost of identifying specimens; (3) cost of storing material - which will multiply if each species or specimen is stored separately. It will be more realistic to stock voucher material for ecological studies. As taxonomic knowledge and techniques improve, voucher material allows verification of identifications and the correction of mistakes.

Archiving collections and historical data in museums is a major challenge for the future. Museums have undergone much-needed transformations to make their data relevant to the needs of modern science, nevertheless, some people believe that museums have simply lost their way. As Erzinçlioglu (1993), some scientists think that museums must rediscover the unique role they used to play: as institutions of taxonomic research. A balance will have to be found between the contribution of museums in "Modern Big Science" in international programmes and their traditional contribution of taxonomy and collections to natural science which will continue to be an important museum role.

ACKNOWLEDGMENTS

We thank our colleagues Raymond Baudouin, Guy Duhamel, Jean-Claude Hureau, Jacques Le Renard, Hervé Maurin and Gordon Paterson who have contributed to the discussion and have furnished the sources of the documentation for the preparation of this communication.

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Formatted and typeset in Optima 10/14 (mostly) by Tony Moreau, June 1996.



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Luxembourg: Office for Official Publications of the European Communities

1997 — XVI, 200 pp. – 16.6 x 22.1 cm

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