Long-term Ecological Measurements
Report of a Conference

Woods Hole, Massachusetts
March 16-18, 1977

Prepared for:

National Science Foundation
Directorate for Biological, Behavioral, Social Sciences
Division of Environmental Biology

This material is based upon research supported by the National Science Foundation.

Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Copies may be obtained from the National Technical Information Service (NTIS), Document Sales, U.S. Department of Commerce, Springfield, Virginia 22161

- -

A group of scientists representing many areas of ecology met March 16-18, 1977 to discuss fundamental issues concerning long-term ecological measurements. The report of this conference is divided into two parts: (1) a summary statement from the entire co nference; and (2) specific recommendations regarding terrestrial freshwater and marine ecosystems, prepared by different sections of the conference.

The summary statement concerns the importance and feasibility of long-term ecological measurements and the major recommendations of the conference. In the section part of the report, these issues are reexamined for terrestrial, freshwater, and marine eco systems. In addition, the second section contains specific recommendations concerning what measurements are important for each of these kinds of ecosystems.

- -

SUMMARY STATEMENT

Introduction

Ecology requires long-term studies. They are indispensable and must be initiated. All ecosystems are in a process of long-term change. Some changes may be long-term cycles, others unidirectional. Some may be due to natural climatic, geological and biolog ical events and processes, some to subtle long-term anthropogenic influences. At present, few research strategies allow us to separate long-term cyclic from unidirectional changes; or anthropogenically-induced changes from natural ones. This and other cen tral ecological issues make clear the need for long-term quantitative data sets, which have irreplaceable theoretical and applied utility.

Important insights have come from years of regular study. This is elegantly exemplified by the classic papers of John Lund working at the British Freshwater Biological Association's Windermere Laboratory in the English Lake District. His long-term studie s led to important insights about the diatoms in lakes, short-lived organisms which to the unacquainted might seem to require only short-term studies.

Long-lived organisms, which provide the major biomass of many ecosystems and influence or control the rates of production and cycling of minerals in many habitats, must require even longer studies.

Yet our approach to research has emphasized the short-term. No one would suggest a study of Drosophila involving only 2 1/2 generations, yet the 2-year research support, typical in the United States, encourages just such an approach. American science see ms peculiarly lacking in long-term research. Of the 15 chapters on long-term studies in David Lack's Population Studies of Birds, none were by Americans. Too much of our research seems to appear out of a temporal and spatial vacuum, lacking the context wh ich can make results most meaningful. Clearly, for the benefit of American science as well as science in general, the situation needs correcting. This is all the more important now that man is bringing subtle, long-term pressures on natural populations, communities, ecosystems, and the earth's entire biogeochemistry.

In the few cases where sound, long-term studies have been initiated in North America, even a decade of measurements has made these study areas the focus of intense activity. These sites are sought out for research by many active scientists. This is well illustrated by the long-term measurement programs of the Canadian Freshwater Institute, Winnipeg, Manitoba, and the Hubbard Brook Ecosystem Study, New Hampshire. Such programs make clear that long-term measurements serve not only to test hypotheses, but have been the source of new and important questions.

Thus, long-term ecological measurements are essential, and case histories have shown that they can be done in productive and valuable ways. Their collection should be promoted by the scientific community.

It is no easy task to design a long-term program. A consideration of the past humbles us in our attempts. Looking back, we see examples of data collected for its own sake, of programs continued merely because they had been there for a long time, and of data almost worthwhile, but incomplete and lacking the crucial piece of information to make the whole set meaningful. A central issue or a hypothesis to test or to guide the collection of data seems to have been missing.

Yet we realize also that ideas have a lifetime, and that programs developed too specifically to test one idea may have little utility in the lone run. Some studies with vaguer initial rationales seem to have made possible the identification of important issues which can be missed in too highly structured projects. Moreover, studies started for one reason have proved to be most valuable for quite another reason.

Thus, it is clear that the right long-term study is invaluable, but it is all too easy to design a wrong one or an uninteresting, only vaguely useful one.

The participants at the Conference on Long-Term Ecological Measurements have attempted to grapple with these problems. We have considered the if, why, and what of such programs, their feasibility, their justification, and their content. We have set down some guidelines which seem to us helpful in increasing the probability that we have guessed right about what our heirs might wish we had measured. These guidelines seem crucial, but all too elusive!

Because it seemed possible that long-term studies would be more appropriate for some sets of ecosystems than for others, we have examined the possibilities of long-term studies separately in terrestrial, fresh water, and marine and wetland ecosystems. This report consists of an initial summary statement and separate, more specific, statements concerning each of three of the four areas (excluding wetlands).

Guidelines for the establishing of long-term ecological measurements

There are two basic approaches to long-term studies, one through individuals and one through institutions. A scientist who has done good work and wants to do it for a long time seems a safe bet to maintain accuracy and precision in his measurements and to be motivated to seek insights from his observations. Our society's methods for funding research have tended to obstruct, rather than promote, the continued, long-term studies of good scientists and good projects.

We recommend that mechanisms be developed that make possible and promote longer studies by competent scientists. These mechanisms include: specifically funding projects that are agreed to be good for longer periods than is now typical in ecological programs and funding programs for young scientists that provide small sums to do inexpensive, long-term studies needing comparatively infrequent measurements which could be done easily as part of their other research.

While we are comfortable with the first approach, increasing the potential for individuals to carry out long-term studies is clearly not enough. We need only reflect on how few active ecologists are working now on the same project or the same topic as they did 5 years ago, or that they did for their doctoral thesis, to realize that some long-term records that are needed will not be obtained through individuals alone. Records must be longer than one person's career.

Many kinds of institutions can participate in long-term measurements of use to central scientific issues in ecology. Some Federal agencies are already involved in such projects in regard to applied environmental problems. We recommend that, wherever possible, these agencies seek the cooperation and advice of ecologists involved in fundamental research. Better communication should be established so that the data developed in such Federal programs, which are in the public domain, are in fact made readily available to the scientific community. Existing data sets seem sometimes elusive, and the design of such data sets could profit from the input of scientists not directly in the Federal service, but in need of the long-term data.

The kind of cooperative research illustrated between the Forest Service and the academic community at Andrews Forest, Oregon, and Hubbard

Brook, New Hampshire, should be promoted elsewhere in this agency and should serve as examples to other agencies.

There is a definite need for new programs for long-term ecological measurements. There are many kinds of institutions and many possible mechanisms for the establishment of such programs. We recommend the establishment of such programs, although we agree that they must be established with great care. The selection of sites is extremely important. Wherever possible, the site should be one where there has already been established productive and useful short-term research.

We know so little about the natural temporal behavior of completely undisturbed ecosystems that a second guideline is to identify a few pristine ecosystems where crucial parameters could be monitored. We urge that a pilot program be established for some such sites. The sites selected would be those that were thought to be least likely to suffer catastrophes and to be influenced to the smallest degree by the slow anthropomorphic insults to the environment. Interest in such pristine sites does not imply a disinterest in sites subject to known perturbations.

The selection of other sites depends on their representativeness for major ecosystems and populations; the interest shown in them by active scientists; their importance to major ecological issues; their apparent lack of undesirable impacts; and their availability for long-term monitoring. The specific selection of such sites requires study beyond the scope of this report, study which we urge should take place in the near future.

The NSF-sponsored study of Experimental Ecological Reserves (EERs) is a useful guide for important long-term measurements. That report recommends sites clearly suitable for important experimental, manipulative research. At a few selected EER sites, the kinds of programs described in the later sections of this report should be initiated as pilot projects. If these appear successful, then the program should be expanded. (Clearly the selection of long-term measurements sites need not be restricted to the EER list.)

It is essential that such programs be subject to periodic review of the kind characteristic of all National Science Foundation funded projects. Such careful reviews, combined with great care in the selection of sites and determination of what to measure, are our best guarantee for the success, utility, and importance of these programs.

Long-term measurement programs should not compete for funds with proposals for short-term research projects. Such long-term programs should not be interpreted as mechanisms for new sets of huge, encompassing analyses of whole ecosystems. The purposes of the programs suggested here are quite different: to select crucial factors which are essential to major ecological issues. While the time scale is large, and while in the long run such programs should exist in many locations, there is a need to determine the minimal level of monitoring necessary.

The problem of what to measure suggests the importance of certain kinds of ecological collections, not now obtained or stored, which would be extremely valuable. These include: some inexpensive-to-collect, and small-sized samples of insects; representative tissues of major vegetation and vertebrates; samples of the air, water, and soil.

Museums and other repositories should be encouraged to hold such collections; this should not be the function of EERs or biological field stations. These collections would help deal with the dilemma of hindsight: it is difficult for us to project what we will need in the future, but we are frustrated today because we lack some crucial past measurements of tissues, air, water, and soil (e.g., the concentration of CO_2 100 years ago; mercury in fish 100 years ago).

A sparse collection of a few samples collected at infrequent intervals could be invaluable if the time and site of collection were recorded.

The next steps toward implementation

This report leads to a specific recommendation to promote long-term ecological measurements.

In regard to the development of such measurement schemes through institutions, we recommend the following steps:

1. Pilot projects should be established to conduct long-term ecological measurements under the Biological Research Resources Program of the National Science Foundation.

2. An Ad Hoc committee of ecologists should be established by the NSF Biological Research Resources Program to develop the initial pilot projects. This committee would deal with specific details which are a consequence of this report, and which include:

a. Selection of sites;
b. Storage and retrieval of the data;
c. Integration of activities among pilot sites;
d. Standardization and calibration (i.e., quality control) of measurements;
e. Manpower requirements and availability;
f. Coordination with Federal agencies involved in data acquisition. (For example, who should do aerial mapping, weather data collection, baseline geological surveys; what data are already being collected and are available for the site through other agencies.)

3. The establishment by the Ecological Society of America of a Standing Committee on Long-Term Ecological Measurements. This committee would serve as a liaison between the ecological community and the National Science Foundation in developing programs. It would also serve as a liaison between the ecological community and government agencies involved in data acquisition.

4. The establishment, at periodic intervals, of ad-hoc review committees to make site visits, to review a program, to determine what measurements should be added or omitted, what measurement frequencies should be increased or decreased, and whether the program should continue.

In regard to mechanisms to promote the collection of long-term ecological data by individuals as a part of short-term intensive research activities, we recommend that a program of small supplemental grants be established which would enable scientists to add a monitoring portion to an already existing research project, when that monitoring could not be justified or funded directly in regard to the short-term purposes of the research. The criteria for making such grants would include evidence that the monitoring would be useful to major issues in ecology and useful to other investigators as well as the grantee. Preference would be given to young investigators who demonstrate a long-term commitment to such studies.

The participants at the conference considered the more specific issues concerning long-term measurements in terrestrial, fresh water, and marine ecosystems. Summaries of their discussions follow.

Because the groups worked separately, their reports are unavoidably different in approach and content. It was felt that the particular insights of each group were valuable, and therefore no attempt was made to alter the section reports to make them parallel in form or content.

TERRESTRIAL SECTION

Approach of Terrestrial Section:

The terrestrial section considered whether it would be desirable to collect long-term ecological measurements at various sites across the country.

There are two strategies which can be employed to answer the question:

A. To identify the most useful data, based on our collective experience;

B. To identify the most useful data by proposing a series of central hypotheses or questions and then examining the required data set.

The disadvantages of the first strategy are that (1) it may not be possible to predict, now, the information that is useful and required in the future, and (2) the answers might not be clear without identifying, evaluating, organizing, modifying, and providing a conceptual basis for existing data acquisition efforts. The primary advantages are that this strategy leads to comprehensive long-term data sets and it provides a convenient method to determine the best sites for long-term measurements.

The disadvantages of using the second approach are that (1) the specific requirements of particular hypotheses would mean that a comprehensive long-term data base would not necessarily result, and (2) the chosen measurements would be merely a function of our ability to identify reasonable hypotheses--which themselves may be wrong or ephemeral. The advantage is that a scientific basis would be provided to justify and design a collection of long-term data bases.

If, however, both approaches lead to the same list, considerable confidence can be placed in that list and in our decision whether or not any measurements should be made.

It was also observed that there is an important class of population- and community-oriented research problems which require long-term ecological monitoring but which do not lend themselves to wholly site-specific, institutional, routine treatment. Rather, these problems, which ought also to compete for some portion of monitoring funds, seem best treated by individual principal investigators or resident research teams on a case-by-case basis. The enthusiasm and expertise which such individuals bring to research would be the surest and most cost-efficient prescription to ensure use and publication of the research.

Long-term measurements are essential for testing specific hypotheses that center on 4 basic issues of broad ecological interest. The first concerns global effects on populations and ecosystems, such as increasing CO_2 in the atmosphere, or climatic changes over decades and centuries.

The second concerns stability. Within this broad question we can frame 3 generic hypotheses: (1) Nature achieves a fixed equilibrium; (2) intrinsic processes of populations achieve equilibrium under fixed environmental conditions, but fluctuate under cha nging environment; and (3) intrinsic processes lead to fluctuations even when the environment is fixed. Rather specific hypotheses grow out of these generic questions, e.g., "The age-structure of long-lived animals in ecosystems undisturbed by man is stationary."

A third major category concerns population regulation. Specific hypotheses that require long-term observations include the following: (1) "Mortality in populations of forest trees is highly episodic with regard to both intrinsic (competitive) and extrinsic factors"; (2) "Seed and seedling mortality is predominantly caused by herbivory (insect or vertebrate), not by the physical environment.

A fourth major category of hypothesis centers on community structure. Hypotheses can be very specific, e.g., "The size of the herbivore fauna on an introduced plant increases at first, then (after 100 years) becomes asymptotic"; or "The new herbivores on a host plant are primarily drawn from those existing on congeners of the new host"; Environmental stress will result in increased nutrient exports from terrestrial ecosystems."

Over 40 hypotheses were evaluated, and an effort was made to determine the data sets required to test them. These data sets were compared to those identified by examining past research experiences. The two lists were virtually identical and a final one is presented below.

Enumeration of Desirable Long-Term Measurements:

A. Climatic:

Among the desirable long-term climatic measurements are a number which are routinely collected at weather stations. In some cases these stations represent too coarse a grid, and additional sites should be established for these measurements. Sites with long-term climatic records are particularly useful for monitoring programs of other agencies, including measurements of atmospheric constituents, toxic substances, organic and in-organic materials. Where this occurs, information among the biotic and abiotic factors can be most fruitfully and easily compared.

With the exception of snow depth, all of the following parameters should be measured continually:

1. Short wave insolation
2. Air temperature
3. Precipitation
4. Snow depth and duration
5. Dewpoint
6. Soil temperature at daily, seasonal, and yearly depths.

B. Chemical:

Unlike the previous list, the following chemical factors are measured at few sites. This limited research has proven over the last 50 years to be crucial for a number of studies. We recommend that the following be collected routinely at many locations:

1. Precipitation composition (pH, Ca, Mg, K, Na, SO4, Cl, NH4, NO3) collected weekly and data aggregated in monthly intervals.
2. Dry fall sedimentation, recorded continuously.
3. Erosion rate, recorded at yearly or longer intervals.
4. Soil nutrients, cation exchange capacity, organic matter, measured at 5 year or longer intervals.

5. Soil moisture, measured at monthly intervals, or more often.
6. Groundwater or first order stream hydrology and chemistry, measured at least quarterly.

C. Biological:

State Variables:

1. Composition and age-class distribution of dominant species in representative ecosystems and ecotones. Data may also be taken on all species, regulator, indicator, introduced, rare and endangered species. The frequency and intensity of measurements will be dependent on species and site.

2. Birth and death rates, migration, growth, and phenology of dominant species. Data may also be taken on all species, regulator, indicator, introduced, rare and endangered species. The frequency and intensity of measurements will be dependent on species and site.

3. Data on spatial dispersion pattern of dominant or selected species. The frequency and intensity of measurements will be dependent on species and site.

4. Amounts of dead material, such as standing dead and litter, by size, stage or decay, and species where appropriate. The frequency (1-10 years) and intensity is dependent on species and site.

5. Chemical content of living and dead material of selected species, collected at intraseasonal to 5 year intervals. At 5-10 year intervals, samples should be saved and archived for retrospective analyses.

6. Water stress measurements on selected species at appropriate intervals, depending on species, season, and site.

7. Seasonal measurements on the phenology of selected species.

Processes:

The measurement of processes is critical to many ecological studies, and, in fact, the identification of their significance has arisen from relatively recent investigations. However, measurements are more difficult on a routine basis than state variables. We recommend that, among the possible measurements, the measurement of primary production should be strongly encouraged even though the methods may vary considerably from site to site and vegetation type to vegetation type. In some communities, production may be estimated by litter fall or dendrometer readings. Others may require the harvest of biomass.

Consumption rates (herbivory, predation, parasitism) are also important factors which are likely to vary over long time intervals. Their measurement would be useful to many different but related research efforts. Once again, the techniques are time consu ming and require specialized expertise. Therefore, while these estimates of processes are encouraged, it is recognized that relatively few sites can conduct these studies on a routine basis. We recommend long-term measurements at a few sites for the following:

1. Primary production (e.g., direct measurement, dimensional analyses, dendrometers, harvest methods).
2. Litter fall and tree fall.
3. Consumption rates (herbivory, predation, parasitism).

Initial Conditions:

In addition to long-term measurements, there are a number of essential, one-time or infrequent periodic measurements which should be made to characterize the sites. These include:

1. Species lists from each community type.
2. Soil descriptions (profile, texture, structure, water availability, parameters).
3. Maps of geology, topography, soils, potential and actual vegetation.
4. Analysis of historical data (e.g., witness trees).
5. Recording of periodic and episodic events, both abiotic and biotic.
6. Provision for periodic (1-10 year intervals) aerial and ground benchmark photographs.

It is also important that sites be placed where first-order streams empty into lakes, since the sediments in these lakes constitute long-term records.

Site Characteristics:

There are several guidelines to follow in establishing new sites for long-term measurements. There are a variety of habitat conditions for which long-term measurements are useful. These include sites which are "representative" or typical of a region. But other special situations can make long-term measurements particularly useful. For example, a site lying in the drift path of a pollution source, or subject to a known past fire or logging history, or to the known exclusion of herbivores, would be of special interest. It is also advantageous to obtain long-term measurements which include undisturbed controls and sites which are subject to manipulation, so that the effects of the manipulation can be studied for decades. Finally, it is important to obtain long-term measurements from sites representing early, late, and mature successional stands.

Wherever possible, it would be advantageous to initiate long-term measurements at sites large enough to satisfy several of these criteria. In addition, it is important that terrestrial sites include whole watersheds wherever possible, and, in particular, that they include areas where first-order streams empty into lakes so that the lake sediments can be used to complement direct measurements.

Finally, wherever possible, long-term measurements should be made at locations where there is already active research by individuals or organizations.

Intra- and Intersite Coordination

Recommendations:

The optimal distribution for the collection of these data would be in ecosystems, under various developmental conditions, representing various combinations of environmental conditions. Therefore, the collection of these long-term datasets should not be limited to existing stations. However, the existence of an extant station provides continuity with previous records, helps safeguard the integrity of the biological communities, facilitates the data acquisition procedure, and provides the minimal required administrative assistance.

Provision must be made for documentation of the sample locations and intervals, for measurement procedures, and for subsequent data analysis and summarization. In addition, reliable sample storage must be provided either at the site or at some other suitable depository.

Final Summary Recommendation:

We recommend strongly the establishment of a program to collect a number of long-term ecological measurements at a series of sites. We have reached this conclusion from two lines of thought: first, we realize that there are central ecological hypotheses and issues which can only be answered or examined with long-term data sets; second, and just as important, we believe that a certain minimum set of long-term measurements can be determined to be important, whether or not they are attached now to issues or hypotheses of current concern. Our confidence in the list of what should be measured is strengthened because, in our discussion, the same list resulted both from reviewing past research experience and from examining the data required by hypotheses.

Therefore, we recommend that the National Science Foundation augment the funds in the Biological Research Resources Program so that long-term measurements can be made across the country, in an array of environmental and anthropogenic conditions. These measurements are important to present biological research and make the utilization of other research dollars more effective. The establishment of such measurements is a vital investment for biological research in the future.

FRESHWATER SECTION

Introduction:

Freshwater ecosystems respond sensitively to many changes in their terrestrial watersheds or overlying atmospheres as well as to those which occur directly in Aquatic Systems. Provided that the right parameters are measured, the interpretation of atmospheric, terrestrial, or aquatic data sets may allow us to detect and separate changes in atmospheric, terrestrial, or aquatic systems. We have therefore attempted to choose the types of measurements necessary to maximize information about all three regions.

The measurements must reflect a number of basic properties of freshwater ecosystems and watersheds. These include:

1. Measures of the structural and functional diversity and long-term stability of resident communities.
2. Knowledge of the autecology or genetics of member species.
3. Measurements of physical and chemical stability of the environment.
4. Measurements and calibration of sediments or other features likely to contain a wealth of paleoecological information.

There are major hypotheses regarding freshwater ecosystems which require long-term measurements. It was thought useful to mention some of these as examples. These hypotheses include:

1. Steady-state conditions (fluctuations of a trajectory within boundary conditions) are time variant.
2. Some intrinsic properties of populations (e.g., genetic makeup) change over long time series, even though population size and biomass may remain the same.
3. Structural and functional diversity and stability behave differently over long time series.
4. There are time lags (e.g., biological inertia) in response to environmental change visible over long time periods.
5. Physical-chemical stability in aquatic systems allows for high diversity (both structural and functional).
6. Anthropogenic effects will change all ecosystems and degrade many, in a unidirectional fashion over the next century.
7. Consumer organisms determine the structure of communities over long time periods.
8. Community indices (structural or functional) are not the most responsive indices to subtle environmental impacts.

Long-term measurements are useful for additional issues, including the following:

1. Basin sediment records provide a history of change which must be calibrated with time-series data.
2. Analyses of time series provide insights into trends, periodicities, autocorrelations, and random fluctuations which cannot be obtained from fixed-time data sets. (In this sense time series will provide a rich source of hypotheses on ecological changes over time.)
3. Sudden changes occur in ecosystems in response to rare catastrophic

events or as thresholds are reached and are of major importance in determining the long-term trajectory of freshwater ecosystems.

Site Criteria:

The criteria for the selection of monitoring sites for lakes, streams and wetlands can be grouped under 4 general headings:

1. Representative of important or major aquatic habitat;
2. Protection or control of the site in the past, present, and future;
3. Existence of early records; and
4. Feasibility of operation.

Included in the representative category are the watershed characteristics, geological setting, and the diversity of habitat types. Different freshwater systems respond in different ways. Therefore, a monitoring site should include a suite of lakes, streams, or wetlands of widely varying character for a series of stream orders. Although it is recognized that every monitoring site cannot include every desired type, the goal should be to include a series representative of the region. The following list suggests freshwater types from which a site-specific suite might be selected.

LAKES
Stratified
Unstratified
Acid bog lake
Meromictic
Eutrophic
Oligotrophic
Hypersaline or saline
Lake with long flushing time (decades)
Lake with short flushing time (years)
Range of sizes where appropriate

STREAMS
Second or third order watershed with all links (entire drainage net) in the watershed
A variety of watershed vegetation cover
Large rivers from 4th to 12th order

WETLANDS (Inland)*
Freshwater and saline reed swamps
Wet sedge and grass meadows
Shrub wetlands of various kinds
Swamp forests of various kinds
Sphagnum bogs
Large mixed wetlands

Wherever possible it is highly desirable for each freshwater monitoring site to include a suite of lakes including a stratified and unstratified lake, a second- or third-order stream network, and one or more wetland types. Additional types should be selected on the basis of the nature of the geographic location of the site.

Prior to selecting the site, regional surveys should be undertaken, if they do not already exist, so that the lakes, streams, and wetlands chosen for monitoring will be truly representative of the region.

The degree of protection or control of the site, past, present, and future, should be considered in its selection. Though no site can be guaranteed absolute protection, sites which have undergone or are likely to undergo major uncontrolled changes or disruptions should be avoided.

Preserves, state and national forests, and some large parks often contain desirable monitoring sites. In other cases the degree of protection may be less; but if the other criteria are met, these sites need not be rejected. Above all it must be kept in mind that the value of a long-term record increases with its length. Therefore, any factor which might prematurely terminate the record should be avoided.

Where long time series of data exist for undisturbed ecosystems, they can provide a solid basis for experimental manipulation of similar and adjacent ecosystems for a variety of purposes, for example:

(a) interference with normal cycles in order to determine causal factors, as in the drawdown of a prairie pothole during its high-water phase;

(b) manipulation to determine thresholds for change, as in experimental fertilization of oligotrophic lakes; and

(c) manipulation to determine the irreversibility of a change, or the time scale for recovery, as in the impact of various toxins upon oligotrophic lakes.

*Because the initial subgroups of participants in the meeting did not include one dealing with wetlands, a detailed monitoring program has yet to be outlined for these ecosystems. We recommend that such a program be developed.

The existence of early records of important ecological parameters at a site is an important asset. Continuation and augmentation of that record will have significantly greater value than a new record. However, the existence of such a historical record should not in itself be an overriding factor in the selection of the site.

The feasibility (probability of successful long-term operation of a site) will be enhanced by a number of related attributes which might be classed as research-related. The presence of an on-site or nearby field station or a university with an ongoing research program, demonstrated capacity for research leadership, and a body of data on the site area would certainly be a major advantage for a monitoring site. A site should be selected with an eye to its present or future attractiveness.

The development of a long-term record for a site which is interesting to research scientists will add synergistically to its research value.

Finally, it is clear that the individual needs of various aquatic ecologists for long-term measurements, whether physically, chemically, or biologically oriented, could be harmonized one with another. These measurements could also readily be harmonized with those of the terrestrial ecologists, so monitoring sites might best be watersheds containing streams and lakes. The lakes are particularly useful in providing an integrative sedimentary record, archived in situ, of secular events in the watershed which can be understood and calibrated by monitoring programs of the kind proposed.

Criteria for Measurements

Measurements must be of a sort which will allow separation of unidirectional and cyclic changes by time-series analysis, and detection of any time lags in response of the systems to outside influences. They must also allow a wide variety of ecological theories to be tested, including theories of stability, diversity, community structuring, and ecosystem development. Yet such measurements must be simple and reliable enough that those made at different sites or times by different investigators may be compa red with confidence. They must be stable enough that methodology is unlikely to change drastically over a period of decades. They must be of proven utility as sensitive indicators of ecological changes. Table 1 contains a list of criteria.

The studies outlined are aimed in general at measures that define conditions in successive years, so that changes over time can be followed on an annual basis over decades. However, it is readily apparent that sampling intervals would be determined by the parameters to be measured, in some cases by turnover times of abiotic parameters, in others by the sizes and life spans of organisms. The employment of sediment markers (such as radio-carbon, plutonium, the rise in Ambrosia pollen or, in some, additions of relatively inert materials such as brick dust) can serve to calibrate accurately the time-series implicit in the sedimentary record. In this connection it will be necessary to pay some attention to bioturbation and differential sorting of sediments. Cores already measured for some factors also need to be archived for the study of parameters which are later seen to be important and in need of close correlation with the earlier measurements.

TABLE 1

I. Categories of measurement

- A. Abiotic
- B. Biotic
  1. Structural
  2. Functional

II. Criteria for measurements

- A. Techniques must be relatively stable (e.g., for a decade); if they are changed, then the new techniques must be calibrated against the old.

B. Techniques should be proven to be useful in evaluating and/or predicting biotic changes.

C. Sampling intervals should be within known biotic turnover times.

D. For static measurements (which include both abiotic and biotic-structural measures), materials should be labeled carefully, catalogued and stored (e.g., watershed airphotos, sediment cores, samples of known plankton or benthos.

E. Dynamic (biotic-functional) measures should be by techniques that can be accurately repeated (e.g., 14C fixation or benthic respiration at specified temperature using carefully documented technique).

*All data should be catalogued and stored for ready retrieval.

The need for standardization of measurement techniques cannot be overemphasized. Not only does the historical record become much more useful if the data set is homogeneous in terms of technique, but also the analysis of time series by existing powerful mathematical techniques is possible only if the data are standardized and of equal quality. In particular, the usefulness and adaptability to rigorous mathematical analysis of time series increases with the length of the series. Therefore, the concept of building a time series of data should be viewed as an investment in knowledge which grows much like a monetary investment whose value increases by compound interest.

After extensive discussions about rate measurements, it was concluded that, although these are questions about all techniques currently in use, some rate measurements should be included. The main emphasis, however, should be on static (structural) assessments because these can be rechecked later from stored samples. There are also many technical pitfalls in measurements such as those utilizing radioisotopes, but these can be taken care of by adequate documentation of methods. It is recommended that a few rate measurements be continued over a long period for the sake of continuity even though better methods may become available.

The rate measurements should be made over an entire year at appropriate intervals. Such intervals need be only every 3 or 4 years. The rates to be measured are production and turnover of producer (autotroph) and micro- and macro-consumers (heterotroph). General examples are: phytoplankton production by 14C, microbial activity by 14C glucose at tracer levels, community production and respiration in running waters by upstream/downstream measurements of oxygen or pH, and of stream processing (including decomposition of natural or artificial organic substrates).

Recommended Monitoring:

Measurements on aquatic systems will be those that characterize climate and weather; watershed; hydrology; physical and chemical characteristics of water; biota; and historical records. These are outlined below for watersheds with aquatic habitats, lakes, streams and the biological features of lakes and streams.

They do not comprise a wish list. All are measurements which we expect to be essential for thorough evaluation of many of the diverse hypotheses likely to be formulated in the foreseeable future and to require time-series data for adequate testing. We recommend a regularly revised handbook of appropriate techniques, inter-calibrated as new or other techniques are adopted (preferably by the investigator first using them).

I. Watersheds

A. Base data--watershed

1. Location - latitude and longitude, altitude
   country, state, county
   political jurisdiction

2. Degree of protection--wilderness area, national park, nature conservancy area, status of mineral rights, etc.

3. Area

4. Contour map to show relief

5. Soil parent materials - types, extents, depths

6. Underlying soil types - extent, development of humus layers, profile development

7. Watershed cover - bare ground, vegetation, productivity, sources of pollution, fire history, land use patterns, etc., as established by aerial photos* with ground control, by maps of various kinds, documentary sources and personal inquiry

8. Historic and prehistoric records - documents, maps, photographs, tree rings, fire scars, personal inquiry, etc.

*Aerial photos and imagery of various types and scales should be arranged every 5 years or as needed to cover the anticipated period of long-term monitoring.

B. Parameters to be measured

1. General records of major watershed changes, site-specific as necessary.

2. Chemistry of bulk precipitation (dry and wet fallout), in several collectors (protected from vandalism and contamination) on an annual basis for chemical budgets:
    a. Total P
    b. Total N
    c. NH_4-N
    d. NO_3-N
    e. Total alkalinity or acidity (by sealed system titration)
    f. pH
    g. SO_4
    h. Specific conductivity (corrected to standard temperature).

3. Climate and weather, daily, from National Weather Service data and Climatological Summaries:
    a. Air temperature - max./min.
    b. Humidity- max./min.
    c. Rain and snowfall
    d. Solar radiation - visible spectrum
    e. Wind - direction and speed

II. Lakes

A. Base data

1. Bathymetric map - for length (unobstructed fetch), width, area, mean and maximum depth, hypsometric curve, volume, shoreline development, insulosity, and calculation of retention time.

2. Shore types - location and extent

3. Bottom types - location and extent

4. Inlets and outlets - sources of water and where it goes

5. Thermal characteristics - mixis, heat budget

6. Trophic type

7. Relationship to topography, soil parent material, soil type, vegetative cover, land use, pollution, etc.

B. Parameters to be monitored--temperate, dimictic lake as example

----
Parameter   Spatial (sampling intervals)   Desired Minimum
----
1. Heat budget by
   a. Temperature profile
      (1) Ice-free period   1 meter intervals (to 0.1•ûC)   bi-
weekly   June, early
                                10 soundings on larger
lakes   Aug., Sept.
      (2) Ice-covered period   meter (to 0.1•ûC) 5 soundings   monthly 2-3 weeks
                                on larger
lakes   before breakup
   b. Thermocline depth   bi-
weekly   early Aug.
   c. Ice and snow data
      (1) Appearance of ice
date of

freezeup

(2) Disappearance of ice
date
of breakup

(3) Thickness of ice 5-10 places monthly once-max.

(4) Depth of snow 10 places monthly
once-max.

2. Hydrology

a. Water level (relative Continuous
4 per year
local datum) or
daily incl. max.
(seiches
and min.
damped)

b. Discharge
- inlets Continuous
2 per year
- outlets or daily
max. & min.

c. Ground water level (consider only where necessary, on a site-specific basis)

3. Lake circulation patterns (currents or internal seiches) where appropriate on a site-specific basis.

4. Solar radiation Exposed location
Continuous continuous

5. Water chemistry

a. Dissolved oxygen profile

b. Major chemical properties Surface only Spring overturn

Dissolved 1 meter During

both   Every 3 yrs.
inorganic   periods of
carbon   circulation;
                                                             and at height
"Dissolved"   summer and
organic   winter
carbon   stratification

Particulate   1 meter   During
both   Every 3 yrs.
organic   periods of
carbon   circulation;
                                                             and a height
Total "dissolved" P
summer and   "
                                                             winter

Particulate
P   "   "
NH4-
N   "   "
NO3-
N   "   "

"Dissolved"
"   "
organic N

Particulate
N   "   "

Total
alkalinity   "   "
or acidity (by sealed
system titration)

pH
"   "
So4
"   "
Chlorophyll
a   "   "

c. Minor chemical properties
Mg
"   "
Na
"   "
K
"   "
Cl
"   "
Total
Fe   "   "
Total
Mn   "   "

d. Suspended solids   During
both   Every 3 yrs.
(particulate matter)   periods
of   before
circulation;   breaking
and at height
summer and
winter
Clastic material (sand, silt,
clay)   stratification   "

$CaCO_3$
"   "
Organic carbon (see under
(2))   "   "

e. Transparency, color light
Annually   Every 3 yrs.
Secchi disc   June,
July,   August
transparency   August

Light profile   1
meter   "   "
by Si solar   or less
cell

Absorbance (350 nm) 1 meter " " profile on filtered water

Color of water 1/2 Secchi " " (Forel-Ule scale) depth

6. Sediment properties to be measured in surface few cm (varying with sedimentation rate) at 5-10 year intervals except perhaps where sedimentation rate very rapid. Sediments should be archived intact, either frozen or at 4•ûC, for later analysis (perhaps by agencies such as EPA or ERDA).

   a. Physical properties
      - sand/silt/clay
      - organic matter
      - $CaCO_3$
      - mineralogy of clastic (and perhaps carbonate) fractions

   b. Major elements - Si, Fe, Ca, Mg, Na, K
   c. Biophile elements - C, N, P, S
   d. Trace elements - Pb, As, Br, Zn, Cd, Hg, Co, Ni, Mn, Cu, Se, Te, V, Mo, Sc
   e. Radioactive isotopes - ^{137}Cs, ^{239}Pu, ^{90}Sr
   f. Trace organics - do gas chromatography scans for those things we know, and keep the printout for later identification of unknown peaks
   g. Fossil pigments - site-specific where likely to be useful

---

III. Streams

A. Base data
   1. Place in stream network--first, second order, etc.

2. Relationship to topography, soil parent material, soil type, vegetative cover, land use, pollution, etc.

3. Relationship to lakes and wetlands studied

B. Parameters to be measured (include inflows to and outflows from lakes)
   1. Stream morphology (headwater to mouth)
      a. Bank full channel cross section. Measured at three bench-marked locations (with scour chains also) at least once a year at low flow. (Better twice a year before and after the major flood period.) Nature of banks (rock, till, outwash, sand, etc.)
      b. Channel gradient and major channel debris. Annual mapping of 100 to 1,000m is preferable, but at least following major flood events (once baseline is established),e.g., 5 or 10 year floods.
      c. Sediments. General mapping of sediment distributions (gravel bars, etc.) at least every 2 to 3 years, preferably annually. Also characterize sediment composition at same time interval.
      d. Riparian vegetation survey, at least every 2 to 3 years.

   2. Stream discharge
      a. Continuous chart (hydrograph)
      b. Record base, the water year (Oct. 1 to Sept. 30) so as to be compatible with existing U.S.G.S. records.

   3. Stream water temperature
      a. Continuous chart (preferably with integrator): at least daily maximum and minimum temperatures, at water flow gauging stations.
      b. Record base, the water year or possibly a specific discharge year (peak flow to peak flow or base flow) or a detritus year (leaf fall to leaf fall).

   4. Solar radiation--integrate by ozalid papers or other integrative technique at several appropriate sunny and shady locations.

   5. Stream chemistry--(considerable debate can be generated over this category, but it seems that stream ecologists, like limnologists, have measured many chemical parameters which are never related to any ecological questions. Therefore, relegate most chemical parameters to the specific study category, i.e., related to a specific ecological question).

a. Nitrogen (N): continuous monitoring of at least total dissolved N and NO3. If not continuous, then 24-hour measures according to the major discharge and temperature regimes essentially seasonally (say 5-10 samples per year at different stages on the hydrograph, including high and low extremes). Weekly or monthly instantaneous measures are almost useless.
b. Phosphorus (P): total dissolved. Requirements the same as for N.
c. Dissolved organic carbon (DOC). Requirements the same as for N.
d. Alkalinity (organic and inorganic) and/or calcium ion. Requirements the same as for N, although continuous data would probably be of limited-use.
e. Particulate organic carbon (and nitrogen and phosphorus) highly desirable, at least over 24-hour periods at a range of discharges. Do at least one series over 24 hours at base flow, and one over 24 hours at the opposite time to base flow (summer or winter).
f. Do dissolved oxygen in large streams only (perhaps also in slow flowing smaller streams with high organic carbon).

6. Groundwater discharge--only on site specific basis.

IV. Lakes and Streams

Biological Parameters

Group	Sampling	Analysis	Frequency	Other Notes
Phytoplankton	Integrated trophogenic Zone	Species Size-Frequency Numbers Biomass	Annual at: Spring over-turn early August, Fall overturn Winter	
Zooplankton	Integrated water column	"		
Benthos: lake:	Profundal Grabs	"	"	
	streams: Erosional & deposition-al substrates	"	Annual at: Late Autumn Mid-Summer	Methods ac-cording to Elliott

			(Nearest low flow)	(1971)
Periphyton	Natural Substrates	Species Biomass	Every 3 yrs. lakes, mid-summer; streams, Benthos schedule	
Macrophytes	Photo mapping with ground truth	Species Distribution Biomass	Mid-Summer Every 6 years	
Fish	Various capture	Species size-frequency	3 years	
	Mark & recapture in small lakes,		3 years	
	acoustic surveys in large lakes	Biomass Scale samples		
Birds & Mammals	Surveys (Site Specific)	Species Numbers Resident Time	Site Specific	
Genetic long &		enzyme	Annually	i.e.,
a selec-				
Structure	short lived			
poly-		zooplankton		
	species	morphism		
and fish				
Paleolimnology	Core	species and number for cladocera algae, pollen chironomids		
	Sedimentation		Annually	Techniques
not developed				
	Trap			
	Stratigraphic Marker	Reference for Bioturbation	24 years	

Additional Notes:

1) Every 6 years an intensive survey of littoral zone to be made.
2) Additional rate and process measurements to be made as reliable techniques become available (see comments in criteria for measurement).

Conclusion:

It is important to detect and understand the ecological significance of long-term changes in the structure and function of populations and ecosystems. Therefore, the properties of freshwater ecosystems should be examined on a long-term monitoring basis at permanent sites well-chosen for their ecological interest and with good facilities, so that a variety of hypotheses and questions, far more diverse and powerful than we can now imagine, and testable and answerable only by means of long-term records, can be studied satisfactorily. Some of these hypotheses and questions will be concerned with both natural and anthropogenic secular trends, whose effects can only be separated by data collected over considerable periods of time.

MARINE SECTION

General Conclusions:

We want to underline the principal points set out in the introduction to this document and to reemphasize the importance of long-term ecological monitoring in marine systems to detect both trends in, and variances of, critical ecological parameters. Such measurements are essential because many ecological processes are so slow that only a long-term investigation can shed any real light on the functioning of an ecosystem. Our primary concerns are with system stability and resilience, and our proposed measurements are primarily directed towards an understanding of these. The steps set forward in the following discussion deal with such fundamental ecological parameters that they provide only the barest minimum of what any responsible program must examine.

Because of the importance of quality control in the measurements, we feel strongly that monitoring should, wherever possible, be carried out in conjunction with ongoing or related past projects by reputable individual investigators. Investigators are mortal, and their investigations even more so, and there will be some cases where the need to obtain continuing site-oriented data sets will shift responsibility to particular marine and estuarine laboratories. Further, in some cases, such as climatic and ae rial monitoring, our recommendations clearly require the cooperation and involvement of other agencies currently taking such measurements. The monitoring for which we are calling should not be dependent upon the present existence of an investigator or institution now interested and prepared to do the work. In the few instances where individual investigators or institutions have not already expressed an interest in initiating long-term measurements, we urge that NSF establish an ad hoc committee to determine how liaisons among individuals, government agencies, and scientific institutions should be developed. This committee should evaluate specific recommendations and requests to undertake measurements we have indicated are needed.

We want to make particular note of the potential usefulness of aerial photography by color-reversal infra-red techniques, which can provide a relatively inexpensive but invaluable archival record of ecological systems which cannot later be duplicated. To have had such a record from the past 50 years would have provided an incomparable database which is now sorely lacking.

Conclusions Regarding Specific Habitats

Open Ocean:

Although we shall discuss seabird populations, we do not deal explicitly with other vertebrates, such as marine mammals and fishes. These are quite obviously of major importance both aesthetically and commercially, so much so that of the long-term measurements which we would propose for these groups are already being taken by some agencies. We can only emphasize that such measurements are essential.

At this time, open sea organisms can be given very approximately, a typical period for their lifespan and a spatial size for the patchiness and migration cycles of their populations. Fig. X illustrates approximate temporal and spatial relationships for the North Sea. In the figure, ecological interactions operate along the diagonal. It is impractical to seek sampling schemes as described by points along the diagonal in this figure, but that line divides sampling regimes into an upper portion concerned wi th overall population levels and a lower region specifying their distribution in space and time. One could extend the figure into other dimensions to include the size structure of populations and a full specification of species importance. For fish populations, current large scale efforts required for yearly stock assessments from commercial catches provide information in the upper left quadrant Fig. Y. For zooplankton, the Continuous Plankton Recorder gives results in the same quadrant as a basis for zoogeographical studies. A very high inherent variability necessitates accumulating large sets of data (or mechanical averaging techniques as with the CPR) to reduce variances so that year to year trends can be distinguished. Experience indicates that smaller data sets (corresponding to points) near the diagonal (Fig. X) can generate information that is useless for discerning significant, non-castastrophic, changes.

This applies particularly to phytoplankton where small numbers of measurements of chlorophyll or productivity (by 14C uptake) are unlikely to yield useful long-term data. The use of aircraft to measure light spectra on regular flights has been proposed previously (SCOR, 1973), and extension of this technique is one of the specific recommendations of this conference.

It is important to consider measures corresponding to lower sections of Fig. X as an alternative to measures which fall in the upper left quadrant of Fig. X. The spatial distribution of pelagic plankton may display regular features or may vary seasonally in a predictable fashion. Laboratory studies and large scale ecosystem experiments indicate that environmental stresses alter species composition, sometimes resulting in changes in the size structure of the plankton rather than in their total biomass. The technology is available to measure such spatial and size distributions. These measures of trophic structure may prove to be more sensitive indicators of long-term changes than general biomass estimates. They may also require less effort in terms of the (expensive) operations at sea.

```
        | l0 3                                                      Fish
        |                                                           /
        |                                                        /
        |                                                    /
```

```
        | 10 2                                              /
        |                                               /
Km.     |                                       Zooplankton
        |                                          /
        | 10 1                                /
        |                                /
        |                       Phytoplankton
        |
        | 10 0
        |
        |
        |
        |------------------------------------------------------------------------------------

                10 0            10 1            10 2            10 3            10 4

                                                Days
```

Fig. X. A schematic and simplified representation of a food chain in terms of typical space and time scales of variability.

```
        |                                                         |
        |                                                         |
        |                               Commercial--------------------------------
        |                               Fish stats                |
        |       - - - - - - - - - - - - - - - - - - - - - - - - - -Fish- - - - - -
- - - -
        |                                       |                 |
        |                                       |                 |
Km.     |                                       |                 |
        |                        |              |                 |
        |
CPR
-----------------|-------------------------------------
|                  |    |                                 |
        |        - - - - - -|   Zoop - - - - - - - - - - - - - - -|
        |                   |    |                                |
        |                   |    |                                |
```

```
        |                   |    |                                |
        |                        |                                |
        |                        |
        |
        |-------------------------------------------------------------------------------------------
                                                Days
```

Fig. Y. Examples of data collections which are sufficiently extensive to smooth out small-scale variations and form a suitable series for long-term studies.

A second specific recommendation of our group is that, at Georges Bank or similar sites where comparatively high-quality, long-term data on fish production and population structure exist, a long-term study be undertaken to measure species structure and distribution at the primary and secondary trophic levels. More precisely, this would involve, in light of present technology, continuous or semi-continuous underwater measurements of phytoplankton fluorescence and both phytoplankton and zooplankton size distributions (by particle counter methods). This would be augmented by the usual oceanographic measurements (e.g., temperature, salinity, light intensity, nutrients by auto analyzer, etc.). In addition, these techniques should be regularly calibrated for size and species composition by comparison with direct counts from samples.

In estuarine and in-shore situations the smaller areas involved can decrease the spatial coverage requirement, but there can be more rapid and larger fluctuations in physical and chemical factors (such as salinity) which will increase the requisite frequency of sampling. In such shallow areas, the benthos interact more substantially with the aquatic part of the system than in the open ocean, and, consisting of longer-lived organisms, the benthos exhibits fewer high frequency variations than the sea water column. Therefore, in these areas, the benthos may provide the best indication of long-term changes in the system. We shall return to these near-shore benthic systems in the next section.

Sea bird populations offer an especially attractive subject for long-term population studies of organisms dependent upon the ocean and as indicator organisms of oceanic ecosystem states, because they are long-lived, widely dispersed during most of the year, but concentrated during the nesting season. Also, they are relatively readily visible in comparison with organisms living beneath the ocean surface. We suggest monitoring sea bird populations on nesting grounds by methods which might involve aerial photography of nesting sites. The advantage is that, in terms of the spatial-temporal scale presented for the oceanic plankton systems, birds are a population or trophic level of very wide extent that can be measured in a very small space during nesting. It is also possible to measure avian population levels during non-nesting seasons with transects over principal feeding grounds either from airplanes or from ships. This would have the advantage of including species that feed in one area (e.g., Georges Bank) but nest far away (e.g., Wilson's storm petrel which nests in the Antarctic).

In either case, birds represent a high trophic level that interacts with and integrates effects of the environment over a huge area that could not be readily monitored directly. Many sea birds feed only at sea and only at the surface where the effects of air-sea interactions are maximal. Birds could be especially useful for answering questions about marine pollution since they, being air breathers, do not equilibrate with sea water and may accumulate pollutants. Thus they would be suitable for long-term studies of pathology, behavioral changes or body burdens of pollutants. For interpretation of such studies, data on long-term population trends would be essential. Furthermore, such long-term data would also be invaluable for studies of bird populations as examples of long-lived oceanic organisms or of long-lived animals in general. The data could help answer questions about regulation of bird populations, relation of populations to food supplies, and other questions dealing with the oceans and population ecology.

Although we have not been specific with regard to other vertebrates, we point out here that similar indications apply to pinnipeds, and that a long-term study similar to that outlined above for birds would be most valuable for such mammals.

Rocky Intertidal Ecosystems

The North American rocky intertidal has been shown to be a particularly useful site for long-term studies which can provide answers to fundamental biological questions. Preservation of such areas is important not only for aesthetic and conservation reasons, but for fundamental scientific research.

It is possible not only to describe the structure of this community in terms of the distribution, abundance, size, and diversity of organisms present, but also to understand the forces organizing the communities. Experimental tests of hypotheses concerning the mechanisms determining the observed structural patterns are eminently feasible and have yielded invaluable information about general ecological processes and principles. However, short-term studies in this community do not allow us to evaluate questions concerning long-term stability properties of the system, either with regard to the persistence of populations at any location through time or the response of the system to perturbations. Since such information is critical to answer many population c ommunity and ecosystem level ecological and evolutionary questions, long-term monitoring of these systems is absolutely necessary.

The types of long-term data that are critical are (a) physical and (b) biological.

(a) Physical information includes primarily daily climatic data: wind speed, wind direction, air temperature, water temperature, number of hours of sunshine, precipitation. and wave stress. This information is valuable only when taken in conjunction with the biological information indicated below.

(b) Important biological data are of three general types:

(1) A photographic record of selected areas, taken annually. This should include color reversal infra-red photographs taken from an appropriate altitude (below 500 feet) and ground photography from areas being surveyed as indicated below. This provides one measure of the states of ecosystems.

(2) Annual quantification of patterns of space occupation, abundance and size of spatial dominants, and selected critical information about predators and herbivores. These provide a second estimate of the states of rocky intertidal ecosystems.

(3) General information on recruitment rate of such species as the major "space holders" such as barnacles, mussels, and dominant algae.

On coral reefs (and some rocky subtidal areas) photographic methods can be used to follow every colony or individual of a species on selected sites, thereby providing precise information on growth, recruitment, mortality, and biotic relationships through time. The long-term information is particularly needed on coral reefs where some corals may live for hundreds of years. Small areas on the order of 2m x 10m should be monitored every year. Line-transects should be used to monitor larger areas at each of several depth zones each year. For large-scale coverage aerial flights should be used to provide percent coral and algal cover over entire reef systems every five years. In conjunction with the above detailed studies, water temperature, salinity, turbidity, and suspended sediments should be measured (continuously) if possible).

In addition to the following of recruitment in the monitoring sites described above, panels of more than one size should be placed in the study area to follow monthly recruitment and subsequent successional patterns.

Salt Marshes

Long-term studies of whole ecosystems can provide data that the monitoring of individual populations may not since the sensitivity of ecosystem components to changes in environment varies over a wide range and in manners that are not predictable at present. For example, studies of moderate pollution in tidal salt marshes in Massachusetts have shown that fiddler crabs are very sensitive to hydrocarbon pollutants, but not to metals; amphipods are not sensitive to pollutants, but respond rapidly to changes in fish predation; the grasses are affected by neither hydrocarbons nor metals at moderate levels, but respond dramatically to changes in nitrogen supply.

Tidal marshes are useful systems for studying long-term changes because: (1) they are located at the interface between land and sea where effects of changes in both systems can be seen; (2) they are important in the productivity of important fish and shellfish of coastal regions; (3) they are relatively simple systems in which some aspects of structure and function can be monitored from a considerable distance. There are two aspects to long-term studies that must be emphasized. First, there is a need for continued close examination of a few examples of marshes along the coast. This amounts to a statement in support of intensive work that is now going on at Woods Hole, New London; Delaware, N. Carolina, Georgia, and Louisiana. In addition to current research, there is a need for some standard measures of the area, biomass, and productivity of salt marshes. More specifically, we suggest the use of aerial photography, at as low an altitude as possible, to monitor marsh area and the structure of the plant co mmunities. Such monitoring should be done annually at the time of maximum production late July or August) with color-reversal infra-red film. It should be done simultaneously with direct ground measurements of productivity and biomass, using harvest techniques. It would be reasonable to take such measures at 2-week intervals for 6 weeks to be certain of defining the maximum standing crop and to best calibrate the aerial photographs. The direct harvest measures could be carried out as a part of the ongoing programs at the laboratories mentioned above and would serve as a part of the controls for experimental manipulations already underway.

It would also be useful to have another set of photographs made in late winter or early spring to examine how events such as ice rafting, wind transport of sediment, and tidal erosion affect the structure of the marsh system. since we know that this structure has, in turn, a very significant effect on marsh production.

Finally, we suggest that these same flights might photograph subtidal areas of sea grasses for data on the changing extent of these communities. This can be successful, if done at low tides with suitable light conditions and negligible wind, and it would provide data almost completely lacking at present.

As in the rocky intertidal section, we underline the need for certain specific climate and related variables, in particular tidal parameters, wind factors, air and water temperature (max./min.), sunlight, precipitation, runoff, insolation, and ice occurrence.

THE ESTUARINE SYSTEM

Many questions have been posed regarding structural and functional changes in estuarine systems over time. Are there long-term trends in temperature, salinity, and turbidity? How are these trends affected by channel dredging and power plant discharges? Are nutrients, toxic materials, or pathogens accumulating? How will these affect plant productivity, dissolved oxygen distributions, fishery harvests, or recreational usage? It is essential that a substantial data base be accumulated on a number of estuari es over a time period sufficient to answer these questions.

Estuaries, however, are characterized by rapid changes in many factors in the temporal and the spatial dimensions. Regular tidal oscillations, irregular wind stresses, and sporadic freshwater inputs affect the salinity and turbidity. Insolation and air mass movements control the water temperature. Plant nutrients may come predominantly from the river, the sea, or by regeneration from the sediments at different times; the amounts available for phytoplankton may or may not be limiting. Rates of primary productivity and the dominant phytoplankton species vary widely in space and time. Food material for secondary productivity may be primarily riverine allocthonous, locally produced phytoplankton, or detritus from salt marshes or sea grasses. Migratory animals move in and out of the estuary, and dissolved oxygen may range from supersaturation near the surface to immeasurable levels at the bottom at the same time and station. The qualitative relationships between these factors are generally understood, but the quantitative relationships are critical, basic ecological questions. Furthermore, because of the significant impacts of man upon many of our largest estuaries and because of the simultaneous services expected from estuaries, understanding these interrelationships has high priority as an applied ecological endeavor.

There are a large number of central questions implied by the above brief list of interacting factors. Data are now being gathered for some of these factors, for example, the seasonal cycles of abundance, size distribution, and growth of commercially important fishes, or the concentrations of known toxic materials downstream from industrial discharges. Of the many other factors for which long-term data should be collected, priority must be given to those bearing on critical ecological questions.

Data must be gathered by way of careful sampling programs which take into account the spatial gradients and short-term temporal fluctuations in order to permit detection of long-term cycles or drifts. Generally speaking, a large estuary will require sampling at more stations and at more depths in the water column than a small estuary. Distributions may be adequately defined by a series of mid-stream stations in a narrow estuary, whereas transects may be required in a wide estuary. Sampling frequencies are related less to the size of the estuary than to the estuary flushing rate, its biological activity, and the specific nature of the factor being measured.

In view of the differences among estuaries, only preliminary suggestions may be made regarding sampling frequencies (Table 2). Assuming an adequate number and appropriate distribution of stations and depths, temperature, salinity, and turgidity should be measured at least twice a year at times of maximum and minimum freshwater inputs. Optimum frequency would probably be 10-13 measurements per year at each depth and station. These measurements would permit detection of cyclical patterns or long-term trends in estuarine circulation, sediment loading, and light penetration.

Optimal sampling frequency for dissolved oxygen, plant nutrients, and chlorophyll is similar, 10-15 times per year, but the minimum frequency consists of one sample per season at each depth. These measurements will permit detection of significant changes in biological activity within the estuary such as gradual eutrophication or summer-time oxygen depletion of bottom waters. The minimum frequency for determination of phytoplankton and zooplankton abundance and species composition is quarterly; much better evidence of changes to the planktonic system will be obtained from 15-25 samples per year for zooplankton. Changes in species composition will probably be a much more sensitive index of environmental changes than chlorophyll concentrations. Measurement of chlorophyll concentrations will permit the distinction between inorganic and organic contributions to turbidity. In certain estuaries the contributions to total estuarine productivity contributed by sea-grasses or local salt marshes should be determined at least every three years to detect changes in the relative importance of these sources.

Preliminary suggestions regarding sampling frequency necessary to characterize and recognize long-term changes in estuaries.

Parameter	Sampling Frequency (no./yr.) Optimum	Minimum
Temperature	10-15	2
Salinity	10-15	2
Turbidity & light penetration	10-15	2
Dissolved oxygen	10-15	4
Plant nutrients (N, P)	10-15	4
Chlorophyll	10-15	4

Phytoplankton species	15-25	4
Zooplankton species and abundance	6-12	4
Extent and productivity of marshes and sea-grasses	1	0.3
Macro-benthic animals	2	1
Sediment type	1	0.2
Sediment chemistry and organic matter	1	0.2
Toxins (metals, pesticides, PCB's . . .)	1	0.2

A survey of macrobenthic animals should be made at least once per year; their populations will tend to integrate short-term fluctuations and thereby are ideal for establishing long-term changes. Determination of sediment type (mineralogy, sediment size distribution), chemistry, and accumulations of toxins should be made at least twice per decade to detect secular changes.

Intertidal and Subtidal Soft-Sediment Systems

The spatial and temporal homogeneity of a few undisturbed shallow-water benthic sites (Fig. X) allows long-term monitoring at low cost. These studies provide the control data required to test hypotheses concerning the explanations for shifts in community structure in other environments. The fact that soft sediments are frequently the repository for chemical inputs from land makes these environments sensitive indicators of subtle anthropogenic changes in marine systems. For example, changes in muddy bottom communities in Long Island Sound and Narragansett Bay would be difficult to interpret without the long-term studies in Buzzard's Bay that show relatively little change from year to year. These long-term studies have also been used as the basis for interpretation of fossil communities. Another example is the sudden major shift in subtidal community structure at stations in Chesapeake Bay following hurricane Agnes. Monitoring since 1961 suggests that one equilibrium community may have been replaced by another. In each of these cases the work has depended largely on an individual investigator and has suffered from gaps in the data as a result of shifts in support and changes from one investigator to another.

Long-term monitoring at any of these sites requires at least three replicates 1/25 M2 samples taken seasonally each year. Species composition, relative abundance of size structure should be determined for all of the macrofauna. The screen size for sampling macrofauna should be small enough to sample all the individuals of the major taxa such as polychaetes, molluscs, etc. Temperature and salinity should be measured and sediment samples should be frozen and stored each year. The selection of sites will, in part, depend on how carefully the areas have been sampled previously.

Long-term studies of recruitment in these environments are needed to determine if shifts in community structure result from changes in patterns of larval dispersal and the life histories of component species. These measurements can be made with defaunated sediments and can be done at somewhat longer intervals--perhaps at least twice a year at five-year intervals.

Deep-Sea

The deep sea benthos is thought to be the most constant environment on earth. Measurements on the dynamic properties of these systems are vital to an understanding of the determinants of community stability. Any of these measurements requires long-term monitoring, since few existing measurements indicate germinating times on the order of decades. Since deep-sea communities are relatively homogeneous over broad depth zones, a small-scale infrequent sampling program can have considerable generality. We recommend intensive sampling every 5 years at the 3 sites where the major portion of the fauna can be identified because the fauna is sufficiently known--the permanent stations at 1800 M and 3600 M off New England and the San Diego Trough. Five replicate 1/4 M2 samples processed through 0.3MM screens will provide an adequate representation of the major taxa such as molluscs, polychaetes, and peracarid crustacea. In addition, sediment samples should be taken with one portion used in immediate analyses and the other portion frozen and stored.

In addition to the monitoring of community structure through time, studies of succession on defaunated areas of benthos would be particularly valuable. Initial studies indicate that rates of response of communities following perturbation are very slow. Sediments at each of the 3 sites above should be defaunated on as large a scale as feasible and sampled annually. These experiments will provide data on the success and rates of colonization and growth in individual species in a relatively constant environment. The regular monitoring of communities in surrounding areas provides the control data for these long-term experiments.

LONG TERM ECOLOGICAL MEASUREMENTS CONFERENCE PARTICIPANTS

Daniel B. Botkin, Chairman
The Ecosystems Center
Marine Biological Laboratory
Woods Hole, Massachusetts 02543

Kenneth Cummins
Department of Fisheries and Wildlife
Nash Hall
Oregon State University
Corvallis, Oregon 97331

Margaret Davis
Department of Ecology and Behavioral Biology
University of Minnesota
Minneapolis, Minnesota 55455

Connie Delwiche
Soils Department, Hoagland Hall
Land, Air and Water Resources
University of California
Davis, California 95616

George Fishman
Operations Research
Phillips Annex
University of North Carolina
Chapel Hill, North Carolina 27514

Jerry Franklin
3200 Jefferson Way
Corvallis, Oregon 97331

David Frey
Department of Zoology
Indiana University
Bloomington, Indiana 47401

David Gates
4093 Natural Science Building
University of Michigan Biological Station
Ann Arbor, Michigan 48104

Eville Gorham
Department of Ecology and Behavioral Biology
University of Minnesota
Minneapolis, Minnesota 55455

Frederick Grassle
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts, 02543

Edward Kuenzler
Department of Environmental Sciences and Engineering
School of Public Health
University of North Carolina
Chapel Hill, North Carolina 27514

Simon Levin
Ecology and Systematics--Langmuir
Cornell University
Ithaca, New York 14850

John Magnuson
Laboratory of Limnology
Department of Zoology
University of Wisconsin
Madison, Wisconsin 53706

Jane Menge
Biological Laboratory
Harvard University
Cambridge, Massachusetts 02138

Robert Ragotzkie
Sea Grant College Program
University of Wisconsin
1800 University Avenue
Madison, Wisconsin 5370B

David Reichle
Environmental Science Division
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, Tennessee 37830

Paul Risser
Department of Botany and Microbiology
University of Oklahoma
Norman, Oklahoma 73069

David Schindler
Fresh Water Institute
501 University Crescent
Winnipeg, Manitoba R3T 2N6
Canada

Daniel Simberloff
Department of Biological Science
Florida State University
Tallahassee, Florida 32306

Matthew Sobel
School of Organization and Management
Yale University
57 Hillhouse Avenue
New Haven, Connecticut 06511

John Steele
Marine Laboratory
P.O. Box No.101
Victoria Road, Torry
Aberdeen AB9 8DB
Scotland

John Teal
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543

Observers:

David Edgington
Ecological Sciences Section
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439

Nicholas Fisher
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543

John Hobbie
The Ecosystems Center
Marine Biological Laboratory
Woods Hole, Massachusetts 02543

William Reiners
National Science Foundation
1800 G Street. N.W.
Washington, D.C. 20550

Kenneth Sherman
National Marine Fisheries
South Ferry Road
Narragansett, Rhode Island 02882

William Sievers
National Science Foundation
1800 G Street, N.W.
Washington, D.C. 20550

James States
Ecology Consultants, Inc.
P.O. Box 2105
Fort Collins, CO 80522

Paul Whitson
National Science Foundation
1800 G Street, N.W.
Washington, D.C. 20550

George Woodwell

The Ecosystems Center
Marine Biological Laboratory
Woods Hole, Massachusetts 02543

Copyright ©1998 Long-Term Ecological Research
Please contact Patricia Sprott with questions or comments about this website