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LIFE FROM A PLANETARY PERSPECTIVE:

FUNDAMENTAL ISSUES IN GLOBAL ECOLOGY

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LIFE FROM A PLANETARY PERSPECTIVE: FUNDAMENTAL ISSUES IN GLOBAL ECOLOGY

Conclusions of the Santa Barbara Conference on Ecology and the Chemistry of the Earth's Surface

D. B. Botkin

A group of twenty-three scientists from diverse disciplines met for one week at the University of California, Santa Barbara to discuss life from a planetary perspective. The scientists represented the major disciplines concerned with the Earth's biota, oceans, atmosphere and sediments, including geochemistry, atmospheric chemistry, chemical oceanography, limnology, forestry, terrestrial ecology, microbiology, biophysics, geography and remote sensing as well as mathematics. These twenty-three scientists met to discuss whether there was, at this time, a set of scientific issues concerning life and the entire Earth as a single unit, to set down the major tractable issues, and to suggest a set of activities that would promote the study of the issues identified.

This report summarizes their conclusions. It provides an overview and perspective in the Introduction, summary set of recommendations in Section II, and the bases and justifications for these recommendations in Section III.

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SECTION I: INTRODUCTION

We live in a unique epoch in the history of planet Earth. For the first time one species, man, has developed the ability to deliberately modify the environment on a global scale, and to observe and control the results of his actions within his own lifetime.

Our actions, up to this point, have been for the most part haphazard. We do, we observe and we think later of the consequences of what we do. For instance, we mine fossil organic carbon deposited by natural processes over millions of year. From it, we extract stored solar energy, releasing vast quantities of carbon (4 billion tons per year) to the atmosphere without regard to the consequences for the climate. In similar fashion, chlorine in gases used to disperse material from aerosol spray cans, or to provide the heat-transfer fluids of refrigerators, can diffuse throughout the stratosphere, driving ozone to lower levels of equilibrium with uncertain effects for the biosphere.

The effects may be subtle. Agricultural practice, favoring cultivation of legumes, may enhance the rate at which nitrogen is fixed by natural processes. In combination with nitrogen fixed inadvertently by combustion, or deliberately during manufacture of fertilizer, this may drive the biosphere to new biogeochemical domains, with yet unpredictable consequences for air, sea, soil and biota. The greatest feat of global engineering of all, conversion of 10% of total planetary land area to agricultural use, was carried out without regard to large-scale consequences.

Ecologists are accustomed to the study of systems on a small scale--a pond, a forest or an estuary for which one might hope to specify energy and material balances and to observe internal functions. The period of observation is necessarily limited, and indeed the system may be defined as an independent unit for at most a limited period of time. The temptation to assume steady-state is irresistable. We assume that the composition of the ocean is constant, that input of primary nutrients is balanced by output, and that the balance is maintained on all possible time scales. Yet this assumption may be seriously in error. The ocean may receive a 10,000-year supply of nitrogen during a time of glacial advance, and it may subsequently release this nitrogen to the atmosphere over long periods of time by denitrification in regions of upwelling. We are accustomed to thinking that the composition of the atmosphere is constant at least over relatively recent periods of terrestrial history. Yet this also may not be true. The level of CO_2 may have changed by factors of as much as 5 over the past 10,000 years in concert with changes in both the marine and terrestrial biospheres. Indeed, long time constant periodicities of the biosphere, modulated by CO_2 and other atmospheric gases, may have had a direct influence on climate. We need a deeper appreciation of the variability of the past if we are to provide a prudent vision of the future. Assessment of the short-range impacts of man is done best in this larger context.

We believe that NASA's program of life science should include a significant focus on ecological problems of global scale. What is the composition of the atmosphere? How is it maintained? What are the magnitudes of rates for exchange across the air-surface interface and how might they be modified by changes in external conditions? A satisfactory program must contain a proper balance of theory and observation. A catalogue of materials present in the atmosphere is no substitute for understanding. It is clear that understanding will require a combination of in-depth studies of selected habitats and the use of space observations to place these studies in a global context. NASA must exercise care in its choice of topics for study in this program. It would be easy to define as an objective the quantification of all gases which are present in the atmosphere to a concentration of 1 part in 10^{12}. However some gases are more important than others. Carbon dioxide has a special role due to its intimate relationship with the biosphere and its importance for climate. Nitrous oxide, methane and halogenated hydrocarbons are similarly important in light of their significance for the stratospheric ozone layer. Ammonia and volatile hydrocarbons such as isoprene can influence tropospheric chemistry, as may sulfur compounds such as COS, CS_2, SO_x and H_2S. An individual habitat may provide useful information regarding several substances and indeed coupling of C, N, S, and P may be so intimate as to preclude separation of these elements in any meaningful research program.

Emphasis may shift with increasing knowledge. It is our view, however, that at this time the atmospheric component of NASA's life-science program should emphasize studies of systems which may be expected to improve our understanding of the more abundant C, N, S and halogen-bearing gases of the atmosphere.

The atmosphere serves as an integrating system for the Earth's biota, operating on a time scale of several years. The ocean serves a similar function, though the time constant is here considerably longer, about 10^3 years. Definition of factors controlling the material balance of the ocean merits particular attention in the marine component of NASA's life science program. To this end, we recommend a strategy that should lead to better understanding of the rate at which important elements are transferred from land to sea. Problems in this area are of sufficient complexity to require new concepts in automated equipment and we recommend actions which might result in this development.

The biota on land show extraordinary diversity and here also change is the rule rather than the exception. We require better definition and classification of the areal extent of major elements of the land-based biota. Quantitative data on the current size of the carbon pool is required as a matter of some urgency, together with information on factors which influence change in both the living and the dead compartments. Particularly important components of the land biota--tropical forest, savanna, wetlands, etc.--merit urgent attention. The program should stress global considerations, although global objectives may dictate intensive study of selected environments offering particularly important insights into the global system.

The matters which we discuss here require a highly interdisciplinary approach. Studies of the global biosphere necessitate the combined talents of climatologists, atmospheric chemists, physical, chemical and biological oceanographers, microbiologists, geologists, ecologists, and others. The associations necessary to promote Global Ecology will not occur spontaneously. They require direction, and must be focused through appropriate scientific meetings, symposia, summer schools, cooperative research programs, etc. Our discussions at Santa Barbara may have as their greatest impact the intellectual and educational stimulus provided to the individual attendees. We urge that NASA build on the momentum of this meeting, and recommend institution of a Summer Program involving leaders of the various subdisciplines of Global Ecology. The Summer Program should seek to educate young scientists in the basic elements of this field, providing a forum for the cross-fertilization essential to progress in interdisciplinary research.

The planet Earth is a single biological system, but we have only recently had the opportunity to study it on a planetary scale. The transition was easiest for climatologists and atmospheric chemists. Their system is mixed efficiently on a relatively short time scale and much can be learned from studies at a few fixed locations. Oceanographers have a somewhat more difficult task. The mixing time for their system is about one thousand years. With regard to the land and its biota, Darwin had to embark on a long voyage to obtain even a glimpse of its diversity. Space observations, coupled with intensive studies, can provide a revolution in the way we look at and live with Earth. NASA's Office of Life Sciences has an essential role to play in designing an evolving strategy to meet the goals of Global Ecology.

SECTION II: RECOMMENDATIONS

The discussions held at the Santa Barbara conference led to a set of recommendations to NASA. These are presented in this section; the background to them and the justification is given in section III. These recommendations can best be viewed within a framework of long-, medium- and short-range goals. These goals are:

I. Long-Range

(a) A major objective is to understand how the biota and the biosphere change with time in response to the internal and external processes and perturbations.

(b) Models should be constructed which will predict the impacts of changing conditions on the global fluxes of energy and key compounds. By key compounds we mean those whose transfer from one reservoir to another is most likely to cause significant changes in the structure of the biosphere. The major reservoirs are the oceans, atmosphere, rocks, soils and the biota.

(c) The paleoecological record, and especially the Pleistocene should be examined in order to use the past to predict the future.

II. Medium-Range

(a) Delimit ecosystems and evaluate their contributions to global fluxes. Determine the major sources of key chemical compounds.

(b) Quantify the major contributions to the global biogeochemical cycles. Identify the chemicals which are at present in balance and those which are accumulating in one reservoir or another.

(c) Explore the causes and consequences of any major disturbances in the biosphere that occur naturally or are caused by human activities.

III. Short-Range

(a) Identify key compounds, major reservoirs, and most important ecosystems.

(b) Establish priorities for research and define appropriate programs. Programs should be flexible and responsible to new information and insight.

(c) Develop necessary measurement techniques and instrumentation.

(d) Identify catastrophic events worthy of immediate response.

IV. Immediate

(a) Establish an organizational framework for the implementation of the goals.

(b) Set up a summer program to train scientists in Global Ecology.

RECOMMENDATION 1

The study of the Earth's surface requires a unified approach at a global level. This unified approach is the combination and integration of geochemistry, geophysics, oceanography, atmospheric chemistry, climatology and ecology. THIS UNIFIED APPROACH MUST BE SUPPORTED BY FUNDING AT THE FEDERAL LEVEL. Such funding does not now exist because research is sponsored separately, by discipline, at a variety of institutions and agencies.

RECOMMENDATION 2

A RESEARCH-ORIENTED SUMMER PROGRAM ON LIFE FROM A PLANETARY PERSPECTIVE SHOULD BE ESTABLISHED. This program would initially center around a University course which would bring together faculty from the many relevant disciplines to teach graduate students and other interested scientists the unifying principles required for an understanding of the biosphere. The course would also serve the purpose of bringing the faculty, representing what are now perceived as diverse disciplines, together. Preparation of this course would force the scientists to clarify the major issues in Global Ecology.

RECOMMENDATION 3

The NASA OFFICE OF LIFE SCIENCE SHOULD ENTERTAIN REQUESTS FOR GRANTS AND CONTRACTS BY INTERDISCIPLINARY TEAMS OF PRINCIPAL INVESTIGATORS TO DEVELOP A COMPREHENSIVE RESEARCH STRATEGY IN GLOBAL ECOLOGY. The complexity of the study of the biosphere demands the formulation of a detailed program plan by several teams of scientists that will be responsive to the recommendations in this document.

RECOMMENDATION 4

IN ORDER TO AVOID DUPLICATION OF EFFORT, NASA ACTIVITIES IN GLOBAL ECOLOGY SHOULD BE COORDINATED WITH THE EXISTING ECOLOGICAL PROGRAMS OF OTHER AGENCIES, NATIONAL AND INTERNATIONAL, (such as NSF's Long-Term Ecological Research Project, the United Nations' Man and the Biosphere Program, and the United Nations' Environmental Program).

RECOMMENDATION 5

The "GLOBE" RESEARCH PROGRAM SHOULD BE ESTABLISHED TO PROVIDE INFORMATION ON A GLOBAL SCALE ABOUT THE BIOTA OF THE EARTH. This includes the following:

(1) An accurate estimation of the area of the Earth's surface occupied by the major biotic entities. The estimates should be made using remote sensing and ground-based information.

(2) Methods should be developed for intensive ground-based measurements of short-term varying characteristics of the biota. These measures will allow determination of some of the major storage pools and transfer rates crucial to the chemistry of the surface of the Earth.

(3) A network of ground stations should be established to sample the spatial and temporal changes in atmospheric concentrations of CO_2 and other gases in the Earth's atmosphere near the ground: H_2O, CH_4, NH_3, NO_x, SO_x, CO, H_2CO, and some of a large number of organic volatiles produced by vegetation.

RECOMMENDATION 6

METHODS SHOULD BE DEVELOPED TO ESTIMATE THE CHANGES IN THE EARTH'S ENERGY BALANCE THAT WOULD ACCOMPANY MAJOR CHANGES IN THE EARTH'S BIOTIC ENTITIES.

RECOMMENDATION 7

A PROGRAM SHOULD BE ESTABLISHED TO PROMOTE THE DEVELOPMENT OF A DESCRIPTIVE THEORY OF THE FACTORS WHICH CONTROL THE CHEMICAL COMPOSITION OF THE BIOSPHERE. THIS THEORY SHOULD INCLUDE EXTENSIVE QUANTITATIVE MODELLING OF THE GLOBAL CYCLES OF THE EARTH'S MAJOR ELEMENTS.

RECOMMENDATION 8

A PROGRAM SHOULD BE ESTABLISHED TO RIGOROUSLY QUANTIFY FLUXES OF CARBON, NITROGEN, SULFUR, PHOSPHORUS AND MAJOR CATIONS TO AND FROM THE LAND VIA THE RIVERS AND THE OCEANS. This requires:

(a) Development of automated instrumentation for the sampling of the global input via the world's major river systems.

(b) Studies of the extent to which major changes in terrestrial ecosystems would alter the flux of vital chemical elements to the rivers and the seas.

(c) Studies of atmosphere-ocean exchanges, including input via dry and wet deposition, nitrogen fixation, losses via denitrification or sulfate reduction.

(d) Studies of the influence of the marine biota on the global cycling processes for C, N, S, and P and the impact of shifts in the chemical contents of the respective reservoirs on oceanic productivity.

(e) A test of the hypothesis that the oceans are in steady-state regarding the C, N, S, and P budgets and are not greatly influenced by major episodic events.

RECOMMENDATION 9

The relationship between ecological complexity and surface geochemistry is not known but it is the sense of this meeting that these relations may be very important. The ecological complexities, discussed elsewhere in this document, must be studied to elucidate these relationships. THEREFORE, WE

RECOMMEND A PROGRAM OF STUDY TO DETERMINE THE MINIMUM AND SUFFICIENT SYSTEM THAT CAN SUSTAIN LIFE OVER A LONG PERIOD (10,000 to 100,000 years). This will help explain why we observe so much biological diversity and what importance this diversity has for the Earth's surface chemistry.

RECOMMENDATION 10

A PROGRAM SHOULD BE ESTABLISHED FOR THE STUDY OF IMPORTANT ALTHOUGH INFREQUENT EPISODIC, LARGE-SCALE ECOLOGICAL EVENTS. This requires:

(a) Global monitoring by satellite remote sensing, to detect the events.

(b) Ground-based instrumentation to measure the chemical and biological consequences of these events. These instruments may need to be triggered only when the events occur; or be emplaced at the start of the event (e.g., aircraft drops into estuaries during floods).

(c) Consideration be given to deployment of teams of scientists capable of travelling quickly to study these events. We need to know whether this is an alternative or complement to (b); or whether we must rely on instrumental techniques.

(d) As an alternative to making realtime measurements during the event, we might get similar information by comparing state vectors before and after the event.

(e) Theoretical studies of the interactions of gradual trends with episodic events are a necessary part of the general development of models of global ecology.

(f) A steering committee empowered to determine which events should be monitored, and to act quickly to mobilize the study teams.

RECOMMENDATION 11

In order to understand geochemical fluxes across major ecosystem boundaries they must be studied in the context of ecological succession and the status, vigor or "health" of ecosystems. THEREFORE, WE RECOMMEND THAT GEOCHEMICAL STUDIES BE ACCOMPANIED BY ECOLOGICAL ANALYSIS OF THE RELEVANT BIOTIC COMMUNITIES AND THEIR DEVELOPMENTAL HISTORY. Such analysis cannot be undertaken except on the basis of sound taxonomic identification of the species involved.

RECOMMENDATION 12

WE RECOMMEND THAT A PROGRAM BE ESTABLISHED TO LINK PALEOECOLOGY TO STUDIES OF THE BIOSPHERE. AS PART OF THIS PROGRAM, THE PLEISTOCENE RECORD SHOULD BE EXAMINED TO DETERMINE THE RESPONSE OF MAJOR BIOLOGICAL SYSTEMS TO GLACIAL EVENTS.

RECOMMENDATION 13

Specific measures were discussed at the meeting for monitoring the status of an ecosystem in regard to its likely persistence, resistance to change, and ability to recover from changes. These measures of the status of an ecosystem, analogous to the "health" or vigor of an individual organism, may be possible, but require extensive development. WE RECOMMEND THE DEVELOPMENT OF SUCH TECHNIQUES, EXAMPLES OF WHICH ARE INCLUDED IN THE JUSTIFICATION.

RECOMMENDATION 14

THE NASA OFFICE OF TECHNOLOGY TRANSFER SHOULD BE REQUESTED TO DEVELOP BETTER MEASUREMENT TOOLS AND TECHNIQUES FOR REMOTE SENSING OF SUCH BIOSPHERE PROPERTIES AS THE OCEANIC MIXED LAYER, DISSOLVED NITROGEN IN SURFACE WATER, CARBON DIOXIDE, AMMONIA, METHANE, AND WATER VAPOR IN THE ATMOSPHERE.

RECOMMENDATION 15

A PROJECT SHOULD BE ESTABLISHED TO DETERMINE WHICH ECOLOGICAL VARIABLES CAN BE MEASURED FROM EXISTING LANDSAT DATA.

SECTION III: BACKGROUND AND JUSTIFICATION

Recommendation #1

The study of the Earth's surface requires a unified approach at a global level. This unified approach is the combination and integration of geochemistry, geophysics, oceanography, atmospheric chemistry, climatology, and ecology. THIS UNIFIED APPROACH MUST BE SUPPORTED BY FUNDING AT THE FEDERAL LEVEL. Such funding does not now exist, because research is sponsored separately, by discipline, at a variety of institutions and agencies.

Three things became clear to the participants at the meeting: (1) the major questions regarding the study of the Earth's surface chemistry and the effect of life on this surface chemistry can only be approached in a unified and interdisciplinary fashion; (2) important scientific issues are raised by interdisciplinary discussions such as those that occurred during the meeting; and, (3) enough is now understood about each of the relevant sciences so that a fruitful unified approach to understanding these issues can now be made.

Currently, research in the scientific areas related to planetary ecology is funded separately by discipline; moreover, funding within each of these areas is divided into subunits. For example, funding in ecology through the National Science Foundation is divided into several areas including ecosystem ecology, population ecology and evolutionary ecology. The participants at the meeting know of no source of funding that is devoted to a unified approach for the study of the Earth and its surface chemistry, and the effect of life on this chemistry. In fact, proposals at this level generally tend to be dismissed as inappropriate or tend to fall through the gaps between present specific funding programs.

The participants agree that studies at this unified level are a necessary background to an understanding of: the global impact of human activities; the history and development of the Earth as a planet; the effect of life on the planet; and, the characteristics of a planet necessary to sustain life over long periods of time.

We believe that this unified approach can provide an area for major scientific advances in the next decades and should be supported by funding at the federal level.

Recommendation #2

A RESEARCH-ORIENTED SUMMER PROGRAM ON LIFE FROM A PLANETARY PERSPECTIVE SHOULD BE ESTABLISHED.

There are several reasons to establish such a course. First of all, the participants agreed that the activities begun at this meeting, including the interdisciplinary discussions about a unified approach to the Earth and its surface chemistry, should be continued by a similar group. It was suggested that one of the best ways to maintain and continue this discussion would be through the development and establishment of a summer course. The attempt to devise a course would force the scientists to better define and clarify the issues and the information available at the present time.

Because it was agreed at the meeting that a unified approach to the Earth's surface is now possible and is important, it follows that a group of research scientists should be trained with this perspective. At this time we do not know of any major institution where such training can be obtained. Therefore, we advocate the establishment of such a course and the training of graduate students in this interdisciplinary approach.

The short course should be run by an executive committee that oversees not only the course but its preparation during the year as well. The membership in the executive committee and the faculty of the course should change, but slowly enough and in a manner to retain consistency.

Recommendation #3

The NASA OFFICE OF LIFE SCIENCE SHOULD ENTERTAIN REQUESTS FOR GRANTS AND CONTRACTS BY INTERDISCIPLINARY TEAMS OF PRINCIPAL INVESTIGATORS TO DEVELOP A COMPREHENSIVE RESEARCH STRATEGY IN GLOBAL ECOLOGY.

We believe that if NASA simply invites proposals in global ecology, most of the responses will be along traditional disciplinary lines, as most scientists will respond by simply trying to obtain funding for what they are already doing. To achieve the global and interdisciplinary effect, NASA needs a program plan. We believe a step between this report and a funding program is required. A good program plan calls for as much careful work as a good proposal, and is only likely to come from people who have a strong stake in the outcome. The program plan should be written by an interdisciplinary group that includes those who would like to be a part of the work themselves.

Recommendation #4

IN ORDER TO AVOID DUPLICATION OF EFFORT, NASA ACTIVITIES IN GLOBAL ECOLOGY SHOULD BE COORDINATED WITH THE EXISTING ECOLOGICAL PROGRAMS OF OTHER AGENCIES, NATIONAL AND INTERNATIONAL, (such as NSF's Long-Term Ecological Research project, the United Nations' Man and the Biosphere Program, and the United Nations' Environmental Programme).

Ecologists concerned with populations and ecosystems have long recognized the need for site-specific observations and experiments over periods of a decade or more. They are required to generate and to test hypotheses concerning: the structure, function and development of populations and ecosystems; and, the energetic and geochemical fluxes that occur across ecosystem boundaries.

Four workshops have been held by the National Science Foundation and

The Institute of Ecology between 1977 and 1979 to examine this need and to provide an intellectual and practical justification for developing a government-funded program of Long-Term Ecological Research (LTER). The program scope of LTER contains two related thrusts: (1) a series of core research questions that should be examined with standardized measurement procedures at a modest number of primary sites throughout the country; and, (2) and aggregate of local studies and sites for investigator-specific research, which could take place at the primary sites or at other locations. The goal of both approaches is to provide an extended observation period for research on particular populations, communities and ecosystems.

The aims of the LTER program and that in which we are engaged are extremely similar both intellectually and operationally, although we are considering a larger, planetary scale of investigation. Both groups are concerned with the recognition of landscape units and measurement of the geochemical fluxes across their boundaries. Both have the problem of monitoring regular cycles, gradual successional trends, and sudden episodic changes of considerable magnitude. Moreover, the summation of long-term ecosystem changes examined by LTER parallels the broader-scale changes with which this workshop is concerned. We believe, therefore, that there should be close coordination between the program that we propose and the LTER program now under development by the NSF.

Recommendation #5

THE "GLOBE" RESEARCH PROGRAM SHOULD BE ESTABLISHED TO PROVIDE QUANTITATIVE INFORMATION ON A GLOBAL SCALE ABOUT THE BIOTA OF THE EARTH.

To implement the long and medium range goals of global ecology, a research program which utilizes the global perspective is essential. As an example of such a program we describe a GLOBE (Global Long-Term Observation of Biogeochemistry and Ecosystems) Experimental Program, in which remotely-sensed data from airborne and spaceborne systems is combined with ground-based field measurements. We have made an effort here to develop this recommendation in greater detail than others in this document because much of the preliminary work has already been done. This program is designed to answer three very basic research questions about the biosphere: (1) what is the area of the Earth's surface occupied by various vegetation types?; (2) what is the distribution pattern of these vegetation types?; and, (3) what is the spatial and temporal variation in important ecological characteristics such as canopy leaf area and biogenic molecules?

(1) Area of the Earth's Surface Occupied by Various Vegetation Types

Terrestrial ecologists have approached the study of vegetation by classifying areas of the land surface into broad categories, often defined by the physiognomy of dominant species[1,2]. Inasmuch as the dominant vegetation is an expression of environmental conditions, these vegetation maps are maps of ecosystems, including and reflecting variation in soils. An estimate of the worldwide land area covered by each vegetation type is fundamental to our understanding of the relative size and role of the biosphere in the surface chemistry of the Earth. The area of these categories multiplied by the mass of vegetation and soil carbon measured in carefully selected sample plots chosen as representative of these categories will yield an estimate of the size of the biotic pool of living and dead material in each category and ultimately the world. Similarly, the sizes of the pools of nitrogen, phosphorus etc., could be calculated for the above- and belowground portion of land ecosystems.

One might guess that the task of determining areas might be easier than making accurate measurements of ecological parameters at representative field sites. Unfortunately, the reverse is true. Our current precision in making areal estimates is limited by inaccuracies in mapping (typically ± 100%) rather than by errors in measurements in the sample plots in the field, (typically ± 20%). For example, Cole and Raup[3] have found coefficients of variation in the chemical content of sites in the temperate deciduous forest category of 50% . Schlesinger[4] found variation in the soil carbon pool of temperate forests of 33%. The chemical content of a unit area of a temperate forest is known with greater accuracy than the area occupied by vegetation types. The total land area of the world is well known (149×10^8 ha), but variations in the areas of vegetation categories is much greater[5]. Even within North America, our estimates of cultivated farmland vary by a factor of two[6].

Some of the variation in area is the result of different classification schemes used by different workers. Presumably, consistent definition of types would improve our estimates of area. Table 1 presents a list of baseline vegetation units, as well as other land covers and features of interest, which we have identified as a starting point.

Remote sensing technology will be essential to any improvement in the areal estimation of these vegetation units. The present state of the art for land-use/land-cover determination using Landsat digital technology provides classification accuracies at approximately the ninety percent level for general vegetation classes similar to those described in Table 1. Although less well-explored, synthetic-aperture radar (SAR) can be used in a similar way to map the areal extent of various canopy types from either airborne or spaceborne platforms in areas of the Earth's surface subjected to constant cloud cover.

Obviously, it is not possible to estimate the Earth's entire surface by satellite mapping. Even if it were possible to construct a mosaic of remotely-sensed images of the entire terrestrial Earth surface, the computer processing time required to extract the information from such a vast array of data points is not within the realm of hardware capabilities foreseeable for several decades.

Instead we must adopt a sampling approach to areal estimation. In such a scheme, the first step is stratification of the Earth into regions or zones within which mixes of vegetation units are reasonably consistent. On the simplest scale, the delineation of such regions will involve the compilation and analysis of world vegetation as it exists, at all scales. Further delineation may occur with environmental stratification--for example, division of forested areas into those of high relief, low relief, upland or lowland etc. Unique geologic terrains might also be differentiated where such substrates are expected to have an impact on the distribution of vegetation types. Climatic stratification would also be possible and desirable. Within such regions, sample segments would be allocated in either a random or systematic fashion. Remotely-sensed imagery of segments selected is obtained and processed to differentiate vegetation classes, and

Table 1

BASELINE GLOBAL UNITS OF VEGETATION/LAND COVER

Predominant Vegetation Types

1. Evergreen forests (broadleaved)
2. Coniferous forests
3. Broadleaved deciduous forests
4. Cut forests, burned or bare ground
5. Savanna woodlands
6. Grasslands
7. Croplands
8. Deserts

Other Surface Features

9. Fresh-water wetlands
10. Salt-water wetlands
11. Estuaries
12. Coral reefs
13. Urban
14. Glacial ice
15. Upwelling and other ocean fronts
16. Open ocean
17. Sea level
18. Timberline
19. Permanent snow line

the proportions are scaled up to reflect the entire stratum. These, in turn, are aggregated until the global level is reached.

The design and execution of a system to inventory world vegetation is probably within the present capability of NASA. The Large Area Crop Inventory Experiment (LACIE) demonstrated a global capability to sample large regions of the Earth using the Landsat satellite system, to process relevant remote sensing data for such large areas in an automatic fashion, and to prepare estimates of crop yields, which meet pre-defined accuracy criteria. The critical difference between a LACIE-type program and a vegetation inventory program will be in the phase of field data collection needed for system calibration. This will be costly and will require considerable international cooperation.

(2) Distribution of Vegetation Types

In addition to estimates of the surface area of the Earth within various vegetation/land cover classes, the global distribution pattern of such classes also represents essential information for global ecology. As an example, consider the construction of a nutrient budget for a large watershed such as the Mississippi. In such a research problem it is not enough to simply obtain the proportion of the watershed occupied by various vegetation types. It is also clearly essential to learn the actual spatial pattern of the types, and how they are interconnected by the hydraulic network of ground and surface water and by the atmospheric flow pattern of gases, aerosols, and particulates.

As one objective of the GLOBE Experimental Program, we therefore recommend a satellite mapping of the Earth into very broad but consistently defined units such as those listed in Table 1. The global map will require updating at least at five year intervals. Changes in the area occupied by the various global units through time should also be estimated by this mapping program. Certain key changes should be assessed by focusing upon the edges of advancing or retreating snow-line, timberline and desert.

It is important to realize that the mapping of the global vegetation cover is a fundamentally different problem from areal estimation. Areal estimation is most profitably approached through multi-stage sample design using varying degrees of resolution, whereas mapping implies the choice of a map scale in which information is to be presented at a specified degree of resolution.

The capability to map the global distribution of broad vegetation units in an accurate, cost-effective manner does not currently exist. Present and planned satellite systems (such as Landsat, Multispectral Resource Sampler, SPOT, etc.) have the spectral capability to differentiate such units, but wall-to wall processing of the high volumes of data these systems generate is simply not within the realm of present technology. However, the need for such a vegetation mapping capability is great, and is a long-term objective of the GLOBE Experimental Program.

(3) Measurement of Global Ecological Parameters

The essential linkages among land, atmosphere and water are qualitatively known in regard to major pathways and transformations, however, pool sizes and the rates of turnover are not. Yet to establish the relative importance of various physical, chemical and biological processes that affect the destiny of man and life in general, the pool sizes and turnover rates must be better estimated.

To assess the rates of transfer among the global units and the atmosphere, a variety of important but difficult--or presently impossible--measurements are desireable. Examples of these are listed in Table 2. Any of these measurements would be helpful in furthering global ecological science; some together could answer important unresolved questions. Such measurements will require sub-monthly or monthly data collection. A few measurements, such as canopy leaf area, will require measurement timing consistent with growing season.

These measurements are best made at a fixed time of day (such as 11 a.m.), but the exact time should reflect factors such as shadowing and cloud cover. Some additional measurement may require data of the same area as a function of the time of day.

Measurements of surface albedo, emissivity and surface temperature, even at approximately monthly intervals, would be extremely valuable data in computing regional and global energy budgets. Since vegetation, snow cover, and surface temperature vary in their seasonal characteristics, periodic sampling is required. With careful analysis of a few years' data, the sampling intervals might be lengthened, greatly reducing the cost of analysis.

A number of the global environmental variables in Table 2 are related to vegetation characteristics; these are starred in the table. Such variables will be monitored most effectively by a stratified sampling program based on vegetation types and areas.

Canopy Leaf Area

Of all the possible structural characteristics of vegetation, one of the most immediately useful is canopy leaf area per unit of land area. The layers of projected leaf surfaces range from 0 on deserts and ice caps to a maximum of 20 in redwood and fir forests of the Pacific Northwest. For a particular global unit of vegetation under a range of environments, the International Biological Program has reported that New Primary Productivity is closely related to canopy leaf area. Over a fair range of leaf areas, canopy exchanges of water vapor, carbon dioxide, and even mineral cycling are linear functions. Where major changes in climate or chemical transfers are occurring, the canopy leaf area is likely to respond.

Soil moisture, even when measured at the surface can be important information when linked with knowledge of the temperature of decomposing litter. Losses of organic matter from drained or drying peatlands are particularly related to the amount of soil moisture. Canopy leaf area is also related to soil moisture.

Knowledge of the height of vegetation, canopy leaf area, and general life forms provides a means of estimating the pool size of living biomass (or carbon), and through re-measurement, the net changes in the pool size.

Biogenic Molecules

Much could be learned from sampling and global mapping of the biogenic gases with atmospheric residence times less than about a decade. Such gases exhibit spatial and temporal fluctuations in concentration that provide information on source strength as a function of position and time as well as on atmospheric transport processes. The long-lived gases, by way of contrast, are uniformly mixed, at least in the troposphere, and are not useful candidates for observation from space.

Table 2

ECOLOGICAL PARAMETERS RECOMMENDED FOR GLOBAL MONITORING

1.* albedo and emissivity

2. surface temperature (±1 °C)

3.* surface and soil moisture (±5% of dry weight)

4.* canopy leaf area (±10%)

5.* height of vegetation (±10%)

6. glacial ice depth (±10%)

7. precise selected measurement of sea height and river height (±10% cm)

8.* atmospheric concentrations of selected biogenic gases: CO_2(±0.1%) CH_4(±5%), H_2O(±5%), NO_x(±5%), CO(±5%), total atmospheric pressure.

9. depth of mixed layer in oceans

10.* chlorophyll abundance in ocean (specified segments)

* Related to vegetation characteristics

Remote measurements of any of the following would be valuable: H_2O, CO_2, CH_4, NH_3, NO_3, NO_x, SO_x, CO, H_2CO, atmospheric pressure, anthropogenic pollutants, and any of a large number of organic volatiles produced by plants and microbes. For most of these gases, measurements of changes in concentration close to the ground would be the most valuable. Information on the height profile of the gas would be useful but not essential. The required precision depends on the residence time of the gas in the atmosphere. CO_2 measurements are particularly important. The living matter on Earth is composed of molecules of reduced carbon fixed through the photosynthetic process which removes CO_2 from the atmosphere. Conversely, the decay processes oxidize dead organic matter to CO_2 which is released to the atmosphere. The long-term balance of the photosynthetic and decomposition processes will determine changes in atmospheric CO_2. Hence, a monitor of atmospheric CO_2 near the surface will allow one measure of the net change in the mass of the biosphere, with proper allowance for additions from fossil fuels.

Since photosynthetic processes change daily and seasonally, and vary across the surface of the globe, any long-term remote sensing of atmospheric CO_2 levels should integrate CO_2 measurements made at monthly intervals at different latitudes into an overall atmospheric CO_2 balance, using models of atmospheric circulation.

Measurement precision will be critical for some of these biogenic gases. For CO_2, the requirement is to detect changes in concentration of a few tenths of one percent. Less precise measurements of most of the other gases listed would be satisfactory.

Ocean Fronts

The ocean has a relatively continuous surface temperature broken by specific frontal movements. One set of fronts is associated with upwelling areas, the other with large-scale eddies that break off from major ocean currents. Synoptic temperature measurements from space could be used to study these major systems. The most useful minimum time scale for repeated observations would probably be about 5 days.

Long-term observations of the extent and thickness of sea ice would be useful in determining if we are in a period of net storage or loss of sea ice.

Conclusion

With an understanding gained from this kind of experimental program, other related projects in mass transfer of sediment and minerals through rivers, ocean production and sedimentation, and the impact of species depletion, become more tractable.

Such an approach provides a real focus and stimulus for the development of an integrated science of global ecology.

Recommendation #6

METHODS SHOULD BE DEVELOPED TO ESTIMATE THE CHANGES IN THE EARTH'S ENERGY BALANCE THAT WOULD ACCOMPANY MAJOR CHANGES IN THE EARTH'S BIOTIC ENTITIES.

It is well-known that vegetation affects the Earth's albedo and micrometeorology. Surprisingly we do not have good quantitative knowledge of either subject. The albedo measurements of the Earth are accurate only to a few percent, but a change in albedo of a few percent could have significant effects on the Earth's energy budget. We recommend that a program of research be established to refine the estimate of the Earth's albedo and we recommend that remote sensing techniques be applied to this task. There is virtually no information on the change of albedo due to changes in vegetation in the recent past, or during the entire Pleistocene. In recommendation 4, it was emphasized that remote sensing from a space platform could improve the current areal estimate of vegetation types and serve to monitor possible changes in the future. Here we note that such measures are crucial to an understanding of the Earth's energy budget.

The effect of vegetation on microclimate has not been extensively studied. The only notable example is the recent study of the Sahel by Charney[7], which indicated that vegetation may exert a major impact on the local climate, especially in areas where the existence of vegetation is marginal. For example, in desert border regions, a decrease in vegetation cover in an area results in a higher albedo. This leads to a decrease in the radiative heating and an increase in the radiative cooling of air.

Since the cooler air tends to sink, this suppresses cumulus convection and its associated rainfall. Hence the decrease of vegetation results in a decrease in rainfall, setting up a positive feedback which creates more arid land unsuitable for vegetation. Charney et al.[8] suggest that overgrazing in the Sahel might have led to as much as a 40 percent decrease in the rainfall of this region.

On a global scale, the biotic effect on the radiation budget of the Earth's atmosphere is more subtle. A number of biologically-related trace gases contributes substantially to the "greenhouse effect." These, in order of importance, are CO_2, O_3, CH_4, and N_2O. The net effect of all these gases is to keep the atmosphere warmer that it would otherwise be. One primary concern in global ecology is the design of a strategy to counter the increase of atmospheric CO_2 due to fossil fuel burning and its greenhouse effect on climate. A careful global analysis of the effect of the biota on the Earth's energy budget can suggest strategies to mitigate the effects of anthropogenically induced climatic change. For example, in the current atmosphere the abundance of methane is 1.5 ppm (by volume), and this compound contributes about 0.5°C to the greenhouse effect. Methane is much more efficient in absorbing solar radiation than CO_2. This is because CH_4 has a stronger absorption band at 7.8 microns, and this band is located close to the atmospheric "window" region. Methane is primarily produced in marshes and swamps, which occupy only 2% of the land area. If all marshes and swamps were filled and converted to other uses the net effect on Earth's radiative balance would be significant. Of course there would be other, possibly adverse, environmental effects due to the suppression of atmospheric methane. This is just an example of coupled global ecological interrelationships that should be examined.

Recommendation #7

A PROGRAM SHOULD BE ESTABLISHED TO PROMOTE THE DEVELOPMENT OF A DESCRIPTIVE THEORY OF THE FACTORS WHICH CONTROL THE CHEMICAL COMPOSITION OF THE BIOSPHERE. THIS THEORY SHOULD INCLUDE EXTENSIVE QUANTITATIVE MODELLING OF THE GLOBAL CYCLES OF THE EARTH'S MAJOR ELEMENTS.

The phenomena of global ecology and global biogeochemistry involve a large number of interrelated processes. Such highly interconnected networks exhibit system properties that cannot be predicted from a knowledge of the subsystems which have been considered to be convenient objects of study. Therefore global studies will require a theoretical effort to build system models and integrate the findings of more specific investigations. Such theory is needed to provide a basis for examining the issues discussed in the introduction and in the other parts of this report.

The present state of our understanding provides a delineation of the major spatial compartments and some information on the flux pathways and flux rates. We can also divide biophysical processes into oxidation-reduction reactions within the compartments and transport between compartments.

The compartments are:

Oceanic	Atmosphere	Terrestrial
Estuarine and shelf	Troposphere	Biota
Mixed layer	Stratosphere	Soil
Deep ocean	Outer Space	Crust
Sediment		Mantle
Mantle		

Chemical and physical background allows us to catalog the possible oxidation-reduction reactions. Geochemical and ecological information allows us to identify the magnitudes and pathways of the major redox reactions.

Some of these, suchas photosynthesis, are not possible without the direct participation of living organisms. Others although they are predicted by thermodynamics, are kinetically limited unless catalyzed by organisms.

Starting with the available information, the tasks of the theory groups are:

1. To assemble data on the pools of reactants, the redox processes, the organisms involved in the redox reactions, and the fluxes between compartments. Missing data should be brought to the attention of the appropriate experimentalists who can attempt to fill in the missing steps.
2. To construct global models, using empirical generalization to study linkages. For example, biological nitrogen fixation always requires an enzyme containing molybdenum. This leads to the question: what is the effect of the global molybdenum cycle on the global nitrogen cycle and therefore on other global chemical cycles, such as carbon?

   There are several categories of models. The first kind attempts to deal with the flux of materials as just described in the nitrogen and molybdenum example. A second kind would attempt to deal with the global distribution of the biota and the effects on the Earth's energy budget that accompany changes in the size of diffe ent ecosystems. It would focus on the quantities of organic compounds stored in ecosystems, as well as the production and removal of gaseous compounds to and from the atmosphere. A third type of model would focus on energetic transfers at the Earth's surface and between the sun, Earth and space. A fourth model would focus on "information" transfer at the Earth's surface as in the transference of biologically active chemical compounds, the transport of spores, seeds and other reproductive units, and the immigration and emigration of animals.
3. To test the predictive features of the model by constant interaction with experimental groups. The construction of these models should be sensitive to the insights of subsystem specialists, yet should not be so restrictive that one is unable to go beyond their specific paradigms.

This theoretical effort could probably be carried out at universities. It is important that theorists periodically meet with those in experimental programs for an exchange of information. The effort may later expand into major computer programs but it is difficult to predict a timetable.

Recommendation #8

A PROGRAM SHOULD BE ESTABLISHED TO RIGOROUSLY QUANTIFY FLUXES OF CARBON, NITROGEN, SULFUR, PHOSPHORUS AND MAJOR CATIONS TO AND FROM THE LAND VIA THE RIVERS AND THE OCEANS.

In order to provide a specific example of an approach to this topic, the participants at the meeting focused on one case study: the flux of nitrogen from the rivers to the oceans. Current textbooks and reviews present diagrams of the nitrogen cycle which imply that the cycle is well understood. However, this is far from true, because even the most basic fluxes are poorly known. Among recently published estimates there is at least a three-fold range for average annual input of nitrogen from rivers to the oceans, and we believe that the data upon which such estimates are based are too imprecise to permit further refinement. Not only specific flux rates, but the factors that control the entire nitrogen balance of the oceans, are poorly understood. Discussions at the Santa Barbara meeting made clear that the nitrogen in the oceans is probably not in a steady-state, and that the inputs that can be accounted for are less than the estimated outputs. A major, basic question is therefore opened: what controls the long-term nitrogen balance of the oceans?

It is highly likely that the global marine nitrogen cycle is affected substantially by major glacial events. Certainly the processes of soil displacement and vegetation denudation by advancing glaciers, the variability in terrestrial runoff, and the exposure and subsequent reflooding of major estuaries and continental shelf regions would significantly alter the fluxes of nitrogen both to and from the ocean, and the reservoir of nitrogen within the oceans. It may be that during periods of glaciation the oceans provide a sink for nitrogen, while during interglacials they act as a source. Thus it may also be true that a "balance" in the nitrogen cycle can only occur over periods of 10^5 years, and that glaciations play a crucial role in replenishing nitrogen in the oceans.

Prior to the origin of oceanic life, nitrate was formed abiotically in the atmosphere and delivered to the oceans where it contributed to the deep ocean reservoir of nitrate. We cannot, however, derive from first principles a reasonable model that can predict the current oceanic reservoir of nitrogen. We do not even know how constant this reservoir is over time spans which approach the length of interglacial periods. Thus upon examination from the perspective of the Santa Barbara meeting, a topic which appears, superficially, to be well known becomes a major unknown. We believe that comparable gaps in our knowledge of other global chemical cycles will appear upon similar examination.

Conclusions and Recommendations

The study of processes that transport biological nutrients from rivers to oceans is an important scientific endeavor. This requires:

(a) Development of automated instrumentation for the sampling of global input via the world's major river systems. In this regard we feel that the potential of physical methodologies (e.g. laser/raman/infrared spectroscopy, fluorescence/scattering measurements) has not been satisfactorily exploited for oceanographic measurements.

(b) Studies of the extent to which major change in terrestrial ecosystems would alter the flux of vital chemical elements to the rivers and the seas.

(c) Studies of atmosphere-ocean exchanges, including input via dry and wet deposition, nitrogen fixation, losses via denitrification or sulfate reduction.

(d) Studies of the influence of the marine biota on the global cycling processes for C, N, S and P and the impact of shifts in the chemical contents of the respective reservoirs on oceanic productivity.

(e) A test of the hypothesis that the oceans are in steady-state regarding the C, N, S and P budgets and are not greatly influenced by major episodic events.

We envision the following sequence of events for this program:

i. Creation of a small group of interdisciplinary scientists who would identify, in detail, the various components of a measurement strategy necessary for obtaining ocean input of the major nutrients from rivers. By components we mean: the selection of appropriate rivers; the sequence for making the measurements at the different rivers, both with respect to time and position; and, the most suitable measurement methodologies for acquiring the data.

ii. Support of research efforts that would allow for the development of novel instrumentation suitable for data acquisition on river inputs. Attractive measurement capabilities should not only undergo definition studies but also be field tested.

iii. Solicitation and support of field research from the scientific community in response to an issuance of a "dear colleague" letter that describes, in detail, the research plan "River-Input" project. It is expected that the initial field effort will be restricted to a few selected rivers.

iv. Move forward in compiling a complete and total inventory of the major biological nutrients from the world rivers using automated land-based as well as remotely-sensed instrument methodologies.

Recommendation #9

The relationship between ecological complexity and surface geochemistry is not known but it is the sense of this meeting that these relations may be very important. The ecological complexities, discussed elsewhere in this document, must be studied to elucidate these relationships. THEREFORE, WE RECOMMEND A PROGRAM OF STUDY TO DETERMINE THE MINIMUM AND SUFFICIENT SYSTEM THAT CAN SUSTAIN LIFE OVER A LONG PERIOD (10,000 to 100,000 years). This will help explain why we observe so much biological diversity and what importance this diversity has for the Earth's surface chemistry.

What planetary characteristics are necessary for the long-term persistence of life on the Earth or any planet? What is the minimal system that can sustain life over long time periods? From chemistry and physics we know that the minimal system that can support life for long periods must have two characteristics: a flux of energy and the cycling of all the chemical elements required for life[9].

Minimal systems that have these properties of energy flux and complete chemical cycling are composed of at least several interacting populations and their non-biological environment. The smallest candidate for such a minimal system is an ecosystem--a local community of interacting populations and its local non-biological environment. The term "ecosystem" is applied to areas of the Earth differing greatly in size, however, from the smallest pond to a large forest. For a single ecosystem to be a minimum unit for the long-term persistence of life, the ecosystem must be essentially independent of all others in the sense that all chemical transformations needed for maintenance of its member populations occur within the system. Such a system would be closed in terms of matter although necessarily open to the flow of energy.

In reality ecosystems seem to differ both in their rates of certain chemical transformations and in the transfer of matter and energy between the ecosystem and the atmosphere, oceans and sediments. For example, coastal salt marshes appear to carry out a large portion of the conversion of sulfur-containing organic compounds to hydrogen sulfide and sulfur oxides--transformations necessary for the complete cycling of sulfur through the biota. Compounds made and released in excess in one ecosystem can be utilized by other, sometimes widely separate, ecosystems. Hydrogen sulfide and sulfur oxides can be transported long distances through the atmosphere or oceans and utilized in ecosystems far from salt marshes. The oceans, atmosphere and sediments serve as both storage and transport mechanisms for the products and exudates from individual ecosystems.

It may be that the interconnections among ecosystems are necessary because local ecosystems rarely or never have all the capabilities for complete chemical cycling. If this were the case, the minimum unit necessary for the long-term persistence of life would be a set of ecosystems, possibly the entire biosphere. Thus at this time all that can be said about the minimum size of a real system capable of sustaining life for long periods is that it can be no less than one ecosystem and might be as large as the entire Earth's biosphere. The biosphere is our only example of a truly long-term, persistent life-support system. However, some would argue that a few very small laboratory ecosystems, as small as a single bottle containing green plants, soil, decomposing micro-organisms, air and water are sufficient systems. The range of sizes for a minimal system that can support life for long time periods is uncomfortably large and unsatisfactory scientifically. Thus the determination of the minimum size of the system that can support life for long periods is a central and intriguing issue confronting global ecology.

The Problem of Complexity

The question of the minimum size of a life-sustaining system is not merely a question of volume, but of structure. What is the necessary structure of such a system? Chemical and physical constraints do not by themselves give us insight into the necessary size or structure of a unit that sustains life over a long time. In fact, given only chemical and physical constraints one can imagine that a unit which supports life over long periods could be rather small and simple. One could imagine an ecosystem containing two species in which individuals of one converted radiant energy to chemical energy and small compounds to macromolecules required for growth and division (as in photosynthesis) and individuals of the other transformed these large molecules to small recyclable compounds. However the biosphere includes more than two million species, and most ecosystems include thousands to tens of thousands of species. Furthermore, these species differ greatly with respect to their mechanisms for transforming food and energy, as well as their abundance, individual size, life cycle characteristics and the specificity and subtleties of their interactions. Species are distributed as complex interacting communities showing striking spatial heterogeneities at scales from microns to hundreds of kilometers. In addition, communities show temporal heterogeneities involving changes in community structures that occur at time intervals that range from minutes to thousands of years.

Does complexity increase the probability of the persistence of life, or is complexity merely a curiosity--an historical accident in the sense that it is the result of phenomena that take place given a system that supports life over long periods, but are of little consequence to the system properties including its persistence? The relation between events at the temporal and organizational scale of evolution and those at the level of ecosystem events remains an unknown and an important area of inquiry.

The relationship between complexity and stability is an issue that pervades contemporary ecology. A decade ago it was considered a truism that complexity increased stability. Recently, mathematical models have been used to demonstrate that simpler systems may be more stable than complex ones, at least for one definition of stability and one class of mathematical formulations[10]. The actual effect of complexity on the stability of life-sustaining systems remains unknown.

Recommendation #10

A PROGRAM SHOULD BE ESTABLISHED FOR THE STUDY OF IMPORTANT ALTHOUGH INFREQUENT, EPISODIC, LARGE-SCALE ECOLOGICAL EVENTS.

The traditional approach to ecology, limnology, and geochemistry has been based on the assumption that Earth systems exist in a relatively steady state and that changes occur gradually providing smooth transitions to new equilibrium states. There is increasing evidence that these assumptions must be modified because of the importance of sudden, large-scale, spatially and temporally delineated events. These require high density data collection and rapid data handling if they are to permit the development of theoretical understanding. Large-scale fires such as those of the Boundary Water Canoe area in Minnesota and The Quetico Wilderness in Canada, which have a frequency on the order of decades, and the eruption of Mt. St. Helens, are examples of large-scale episodic events which have many ecological ramifications.

These episodic events can occur at a wide range of space and time scales. We see fluctuations of periods of years, decades, centuries and millenia--from a severe winter to an ice age. Such events appear to have an impact far out of proportion to their frequency and duration.

Many episodic events are only predictable statistically. Especially, if the space and time averages are over large enough domains, episodic events exhibit regular patterns. However, precise predictions of the time of earthquakes, fires or volcanic eruptions is still infeasible.

It is in this context that the earth sciences are adopting a different view of the world; complementing the average picture of our systems with an emphasis on the occasional and usually unpredictable events which have such a marked effect on the balance and the structure of our environment.

There are problems associated with the study of episodic events. Primarily, of course they cannot be predicted with any precision. Conventional research is planned over many months and funded for a specified period of time. Such events as a volcanic eruption or a major fire cannot be scheduled into the typical research framework.

Secondly, sudden large-scale events are usually associated with violent and dangerous conditions inimical to the collection of data. For example, flux from estuaries may be dominated by transports during major storms when sampling may not be possible with present techniques. Yet without storm data any estimated flux averages are invalid.

A further difficulty, especially important for biotic systems, is that the response to sudden large perturbations can be very dependent on longer term trends. Thus El Niño, the cause of the changes in upwelling which occur occasionally off Peru, was absorbed by the anchovy ecosystem until harvesting of these fish reached a level where the stress of this physical perturbation resulted in the virtual elimination of the fish stocks. The importance of studying long-term trends has been discussed elsewhere in this report.

Many natural systems, however, have evolved so that sudden perturbations rather than being destructive, appear necessary to maintain their diversity. Examples are storms on coral reefs or tree falls in tropical forests. Man's elimination of these occasional events can lead to longer and more nearly disastrous consequences. Forest fires are the best documented example where fire suppression turned out to be a challenge to the forest ecosystem and altered the normal patterns of cyclic succession[11].

We now appreciate the role of these episodic events in determing the flux of materials through systems, and in defining the changes of structure within such systems[12]. It is apparent that our present understanding of the quantitative aspects is confined to relatively small-scale systems in space and time. But we know that these concepts must be applied to larger scales. Furthermore, we realize that man has the ability to produce relatively rapid temporal alterations at the largest spatial scales. These events cannot be considered separately from the intermediate scales, nor from the longer-term natural trends. From this basis we recommend:

(a) Global monitoring as made possible by satellite remote sensing to detect the events.

(b) Ground-based instrumentation to measure the chemical and biological consequences of these events. These instruments may need to be triggered only when the events occur; or be emplaced at the start of the event (e.g., aircraft drops into estuaries during floods).

(c) Give consideration to the deployment of teams of scientists capable of travelling quickly to study these events. We need to know whether this is an alternative or complement to (b); or whether we must rely on instrumental techniques.

(d) As an alternative to making realtime measurements during the event, we might get similar information by comparing state vectors before and after the event. This approach has already been used for stratospheric aerosols and volcanoes. For river input and hurricanes, we could take an inventory of sedimentary reservoirs within the riverbed before and after the hurricane. For forest fires, similarly, let us inventory the vegetation. Looking for changes in the state of the system allows a more leisurely time-scale, and provides useful information while we wait for a catastrophe.

(e) Theoretical studies of the interactions of gradual trends with episodic events are a necessary part of the general development of models of global ecology.

(f) A steering committee empowered to determine which events should be monitored, and to act quickly to mobilize the study teams.

Our recommendation contains measures for dealing with the unpredictable and often violent nature of episodic events. It is expected that further refinements will emerge as the program is implemented.

In summary we propose a different view of the world from the one implicit in scientific or social ideas of a steady state. We recognize that unpredictable episodic events are not to be treated as "noise," or as deleterious, but as regular, essential and often advantageous components of the environment. The general problem is not that man imposes change, but that we have sometimes made changes we did not foresee and do not wish. The immediate question is to understand the consequences of our present capability for large-scale and relatively rapid change when these are put in the context of a natural world with its own inherent episodic character.

Recommendation #11

In order to understand geochemical fluxes across major ecosystem boundaries they must be studied in the context of ecological succession and the status, vigor or "health" of ecosystems. THEREFORE, WE RECOMMEND THAT GEOCHEMICAL STUDIES BE ACCOMPANIED BY ECOLOGICAL ANALYSIS OF THE RELEVANT BIOTIC COMMUNITIES AND THEIR DEVELOPMENTAL HISTORY. Such analysis cannot be undertaken except on the basis of sound taxonomic identification of the species involved.

The basic statements that underlie this recommendation are two: (1) ecological succession implies geochemical evolution; and, (2) geochemical evolution constrains further ecological succession. Ecological succession is the development of an ecosystem in time following a catastrophic change.

There are two kinds of ecological succession, primary and secondary. Primary succession occurs as in the aftermath of a glaciation, when there is no residue from a prior ecosystem. Secondary succession occurs as after a fire, when there are stored seeds and soil organic matter that constitute a significant residue from prior ecosystems.

Recent studies[13] have made clear that the development of an ecosystem over time is accompanied by changes in the geochemistry of the landscape and its ecosystems that constrain further ecological succession. Rapidly growing and developing ecological systems, such as occur soon after a catastrophic clearing or after a fire, take up large amounts of chemical elements and store them. In contrast, steady-state or degrading ecosystems are leaky to chemical elements and tend to lose them. Furthermore, there is a long-term change in soil that is the result of fluvial processes as affected by biotic metabolism. These long-term changes in soils tend to be unidirectional and lead to a decrease in the soil fertility. Studies in Australia, New Zealand and North America suggest that when soils remain in place for very long periods, (on the order of tens of thousand to hundreds of thousands of years), sufficient time passes for the fluvial erosional processes to degrade the fertility of these soils. This is what is meant by geochemical evolution constraining further ecological succession.

Examples

On deglaciated landscapes the magnitude of the nitrogen cycle in an ecosystem depends on the early introduction of N-fixing organisms--often legumes with associated Rhizobia. Later successional communities exploit, and are dependent on recycling, these early additions of N--with leaching losses being made up by N in atmospheric precipitation.

As ecosystems accumulate biomass during early phases of succession they sequester many elements--chiefly the biophile ones such as C, N, S and P. In this way geochemical fluxes are temporarily reduced, but once biomass accumulation ceases these fluxes will be restored. In many very long-lived ecosystems biomass will eventually decline owing to acidification, leaching and nutrient depletion (perhaps of trace elements as in Australia and New Zealand), and geochemical fluxes will be enhanced by the re-mobilization of sequestered elements.

Biomass accumulation accelerates leaching of soil, which in certain circumstances (coarse, noncalcareous parent material) leads to a soil acidification which conditions further development of the biota. Eventually, in wet climates, acid leaching may lead to the development of an iron pan, soil waterlogging, development of peatland vegetation, and the mobilization of redox-sensitive elements such as Fe and Mn. Lake sediments may provide a record of Mn mobilization by accumulation, in certain horizons of the profile of large amounts of this element. However, a gradual increase in lake productivity owing to flushed in nutrients may lead to anoxia in bottom waters, the re-mobilization of inwashed Mn, and finally its export from the lake.

If we are to establish geochemical fluxes accurately, it will be necessary to establish the nature and boundaries of ecosystems, sometimes (e.g. in wetlands) on a fairly fine scale. This can be done most effectively by plant community (or biotic) analysis and description, based on sound biological taxonomic identification of the species involved. The person who can best recognize the habitat differences that are likely to be important to the geochemist interested in chemical fluxes is the field ecologist who knows the patterns of the vegetation! Comparative plant community analysis is fundamental to comparative geochemistry.

Recommendation #12

WE RECOMMEND THAT A PROGRAM BE ESTABLISHED TO LINK PALEO-ECOLOGY TO STUDIES OF THE BIOSPHERE. AS PART OF THIS PROGRAM, THE PLEISTOCENE RECORD SHOULD BE EXAMINED TO DETERMINE THE RESPONSE OF MAJOR BIOLOGICAL SYSTEMS TO GLACIAL EVENTS.

While some events occur on time scales of decades to millenia, still others appear on time scales of 10^4 to 10^8 years. Such long-term events have had a major hand in shaping the world as we know it. Inferences drawn from the study of fossil ecosystems, can expand our appreciation and understanding of the biota over this long time scale.

Geologically, small-scale events of global and ecological significance overlap the millenial scale. In the fossil record, numerous such events can be found in a wide array of situations. This presents the opportunity for studying and comparing events that are infrequent by the standards of scientists' lifetimes, even though they can be seen much more dimly than when they are studied contemporaneously.

The details and even final state of recovery of ecosystems from perturbations may well involve a large stochastic component; certainly both the observed fossil record and evolutionary theory converge on this view. This may make prediction of the behavior of some ecological variables difficult, while prediction of others may be more tractable. Studying the fossil record of paleoecological perturbations, especially if closely correlated with studies of global ecological processes today, might give important clues as to the components most likely to be predictable, or more generally as to the range of variation to be expected of certain components. For example, does diversity return to the same level after perturbation? Does productivity? What about the number of trophic levels, or other measures or components of community structure? Do energy sources ever shift from autotrophic to detrital? Evidence bearing upon such questions may be drawn from fossil record, some of it directly, some of it indirectly via theoretical linkages.

The Pleistocene fossil record and the history of glaciation are particularly important and interesting in the linkage between paleoecology and the study of the Earth's contemporary surface chemistry. This is because the attempt to explain the rise and fall of the glacial ages has long intrigued scientists and is still without a generally accepted explanation. Also, any theory linking the biota to the surface of the Earth must be consistent and ultimately must be capable of explaining the Pleistocene glaciations and the interglacial periods, in terms of the distribution of the glaciers, the climatic changes that led to these distributions, and the biotic changes that occurred throughout the Pleistocene and perhaps influenced the glacial ages.

The mapping of terminal moraines has been accomplished. It is unlikely that much will be gained by more field work on this question, with the possible exception of some locations in Siberia. The areal extent of existing glaciers is also rather well known. What is needed now is a time series analysis of the worldwide change in glacial extent over the next 10-100 years.

The work involved includes both contemporary studies and studies of fossil records. The required studies are as follows:

(a) The response of glaciers to climatic variables is poorly understood. We require detailed time series analysis of the extent and rates of change of contemporary glaciers along with data on temperature, albedo, precipitation, and other climatic variables to assess glacial response to climatic forcing.

(b) The areal extent of modern and Pleistocene glaciers are known but we do not know the ice thickness. Some estimates of this thickness have been made through such means as calculating the pressure required for rocks imbedded in the glaciers to score bedrock within the ice path. Other estimates are based on the uplift of former shorelines.

The terrestrial picture derived from mapping terminal moraines has been augmented by studies of deep-sea oxygen isotope stratigraphy which suggest as many as 22 glacial stages during the last 900,000 years[14]. The volume of the ice sheets may be estimated by (1) studies of sea level changes, or (2) studies of changes in the oxygen-18 to oxygen-16 ratio of the ocean.

(c) Coral terraces give us an index of when and at what height sea level was stable for a few hundred years. Coral is one of the few materials we may date accurately in the range of one to three hundred thousand years. Coral terraces provide information about sea levels that are higher than today. About 125,000 years ago, eustatic sea level was 2 to 20 meters higher than today.

Dating uplifted reefs gives us an estimate of the time when sea level was relatively high, but below that of the present time. By correlating data around the globe from many emergent coasts, we find that the sea level record appears to be punctuated by relatively high levels at 135, 108, 82, 60 and 40 thousand years ago which did not reach either the present levels or those existing 125 thousand years ago.

Much of the sea level data comes from tectonically active regions where flights of uplifted coral terraces provide a detailed albeit discontinuous record of sea level changes. Broecker et al.[15] compared an emerging island to a strip chart recorder with sea level controlling the pen. When sea level was high, a coral reef terrace was drawn onto the island only to be stranded as the island continued to emerge and sea level fell. The next high then drew another terrace below the level of the earlier one. To reconstruct such a record, detailed knowledge of the tectonic history of the region is necessary but often lacking. There are basic uncertainties regarding the constancy of uplift rates. The long-term picture is some combination of episodic uplift followed by a period of subsidence. The sea level record obtained from tectonically active areas needs to be supplemented by better studies in tectonically stable areas utilizing drilling and coral dating.

(d) The total amount of continental ice is directly related to the volume change of the ocean. The ice is depleted in oxygen-18 and the oceans are enriched in oxygen-18 during glacial times. Oceanic isotope changes are recorded in the shells of foraminiferal $CaCO_3$. Species living in the deep waters are least affected by temperature changes and thus are the best recorders of ice volume changes. Surface dwelling foraminifera are the best recorders of temperature changes between glacial and interglacial times. A major uncertainty in the link between deep-sea isotope stratigraphy and ice volume is our lack of knowledge about the average oxygen isotopic composition of the Pleistocene glaciers. Attempts to determine this indirectly assume knowledge of the controls of calcification by foraminifera in response to changes in temperature and salinity. More work here is urgently needed.

<u>Summary</u>

In summary, the paleoecological record should be linked to studies of the contemporary surface chemistry of the Earth. The Pleistocene record is of crucial importance, both in our need to understand the causes of the glacial and interglacial periods and also as a test of any theory one might devise for the control of the Earth's surface chemistry and energy budget and the influence of the biota on these factors.

The discussion to this point suggests several measures that would be useful and several scientific advances that might result. It would be useful if we could map coral terraces from space to determine: (1) how fast corals grow in response to a rising sea level; (2) whether one can estimate the isotopic composition of glaciers; (3) whether periods of glacial advances are correlated with high carbon dioxide concentration in the atmosphere; (4) the effect volcanoes have on climate; and, (5) whether one can map post-glacial uplift from space.

Advances We Might Make

1. For key plankton species determine what controls their calcification.
2. Can we map coral terraces from space?
3. Determine how much of episodic uplift associated with earthquakes on an island is temporary and how much is permanent--Episodic Strike Team.
4. How fast can corals grow in response to a rising sea level?
5. How can we better estimate the isotopic compositions of Pleistocene glaciers?
6. Are periods of glacial advance correlated with high CO_2 concentrations in the atmosphere?
7. What effect do volcanoes have on climate?
8. Can we map post-glacial uplift from space?
9. Determine the response of contemporary glaciers to climatic variables.

Recommendation #13

Specific measures were discussed at the meeting for monitoring the status of an ecosystem in regard to its likely persistence, resistance to change, and ability to recover from changes. These measures of the status of an ecosystem, analogous to the "health" or vigor of an individual organism, may be possible, but require extensive development. WE RECOMMEND THE DEVELOPMENT OF SUCH TECHNIQUES, EXAMPLES OF WHICH ARE INCLUDED IN THE JUSTIFICATION.

<u>The Idea of Index of the State of Ecosystems</u>

For any ecosystem we cannot claim a complete understanding of interactions or properties that would permit us to predict explicitly its capacity to resist any but the mildest of perturbations. Nevertheless, if we could demonstrate that species composition and relative abundance were not significantly changing during a particular time interval we could assert that no significant disturbance had occurred during the interval.

Unfortunately, complete censuses by species are time-consuming, expensive and either destructuve of the ecosystem or subject to gross sampling errors. Even species lists, which for many purposes are almost as useful as complete ecological censuses, are expensive in time, skill and money.

Therefore, if we could find an advanced technology which would permit rapid assessment of the degree to which an ecosystem has been significantly altered during a time interval, then we would be able to monitor the global ecosystem with sufficient thoroughness and speed to forestall, or at least predict, ecological changes. This is particularly true for changes that occur gradually or result from relatively inconspicuous events. There is a possibility that such a technology could be developed.

(1) <u>AGAP: An Aerosol and Gas Analyzer of Patterns</u>

We recommend that the development of a capacity to measure and characterize very small quantities of gases and aerosols be part of NASA's program. One approach might be to use an aerosol and gas analyzer of patterns. This is suggested by the commonly observed fact that many organisms have characteristic odors, which change as a function of their physiological state. Ecological communities also have characteristic odors--a woodland pond has an odor different from that of a forest, marsh, or desert. These odors can be attributed to gases and aerosols emanating from the surfaces of objects in the ecosystem and its surroundings.

If these volatiles could be collected automatically and codified, they would represent a "fingerprint" of the ecosystem. This information would be useful since any drastic change in such an odor print could be taken as an indicator of serious change in the ecosystem. Conversely, an unchanging odor would indicate a lack of deeper changes in the same way that constant body temperature indicates a lack of physiological changes in a mammal. We propose a network of instruments that would provide a continual global ecological monitoring system. This system might consist of several unmanned Aerosol Gas Analyzers of Patterns (AGAP). Each AGAP would consist of a sample-taking device designed to avoid contamination by distant odors, a spectrometric analyzing device, and a device to digitize and transmit the resultant information to a computerized data system. This data system should signal any drastic changes in AGAP's environment to the operators.

The Relationship Between AGAP and LANDSAT Types of Remote Sensing

Remote sensing from satellites can provide information on type, areal extent, color, and surface temperature of ecosystems. AGAP would contribute on-site information to aid in the evaluation of remote sensing data. Also, changes in AGAP data might be used to focus the attention of remote sensing devices on particular locations. AGAP would be a source of intensive local information which may add meaning to the remote sensing data. It is our belief that a combination of remote sensing and an AGAP-type of device would provide a major step forward in our ability to study the Earth's surface.

The value and novelty of AGAP would be its role as a sensor of the current status of ecosystems. It has not been feasible thus far to measure this in a sufficiently rapid and objective way for scientific research purposes.

Therefore, we recommend that NASA develop a coordinated measurement program, linking an AGAP-type device with remote sensing. To implement this recommendation it will be necessary to develop an AGAP unit, calibrate the instrument in experimental ecosystems, and interphase the AGAP with LANDSAT-type data analysis systems. The next phase of the program would involve site selection and installation, resulting in an AGAP network in the field. Once a network is in operation, research scientists from many disciplines can use the data which is being collected in a variety of applications.

(2) Mass Spectrometry

An extension of the concept of an AGAP device is the development of the following mass spectrometer. Existing high-resolution high-sensitivity mass spectrometry has some characteristics particularly suited to analytical evaluation of the atmosphere in or around all ecosystems, the stratosphere and beyond. It has the advantage that it would provide information of a permanent sort which can answer present questions and also serve as a benchmark source at some later date when questions arise as to changes over time in the concentrations of atmospheric compounds.

We recommend the recording of all individually detected masses in the range of 1,000 AMU rather than specific identified masses representing known compounds. This is because we do not know all of the compounds which are important and will be of interest in the future but if a record is kept the data will be there.

We also recommend high-resolution mass spectrometry rather than combined chromatographic-mass spectrometric instrumentation because it will make possible identification of compounds the chemistry of which (and therefore the chromatographic characteristics of which) are presently unknown. The composition (and chemistry) of low molecular weight volatiles can be inferred directly from M/e data whereas the combination of chromatography and mass-spectrometry would leave room for uncertainty.

High resolution will permit distinction between isobars in lower mass ranges and various organics in higher mass ranges. For example, the difference in mass between $^{14}N_2{}^{16}O$ and $^{12}C^{16}O_2$, both with nominal masses of 44, is about one part in 5,000. Both are atmospheric constituents and could be separated chemically or physically before analysis but this requires additional processing and also does not allow for recording information regarding other constituents, presently unrecognized, with nominal mass 44. The $^{12}C^{32}S$ radical, for example, also would appear at mass 44.

This level of resolution at masses up to 50 would account for most inorganic constituents and beyond mass 50, most organic compounds to be found in the atmosphere (aside from particulates).

The mass spectrometric monitoring of atmospheric constituents at high-resolution and high-sensivity and the preservation of this information would make it possible to get the information we think we need now and the information which at some future date we will wish we had gotten.

On a less quantitative plane it will provide a "fingerprint" of various environments, making possible the recognition of change.

(3) Diagnosis of the "Health" of Ecological Communities

Another approach to measuring the status of an ecosystem lies in biochemical measures like the following. Such an analysis might take advantage of the ubiquity of some biochemical reactions that are important in the regulation between the anabolic and catabolic enzyme systems that regulate all living cells. These can give a status of the system on both a long- and short-term basis. This approach has the advantage of providing an objective measure that can be used to replace the vague, subjective and qualitative notion of the status or "health" of an ecosystem.

(a) Adeno-phosphate ratios

A short-term assessment could be made using measurements of the ratios of ATP, ADP and AMP. These have been shown to correlate very closely with the growth rate of bacterial mericultures[16]. Thus, the ratios serve as a measure of activity, growth, and reproductive potential in both invertebrates and vertebrates; and in various ecosystems[17].

(b) Stored metabolites

Stresses that induce longer-term effects on the biota can be measured in terms of the changes in pools of endogenous storage materials. These cellular components are stored during periods of adequate nutrition and catabolized during periods of starvation. The various endogeneous storage materials appear to be consumed in a definite sequence with starch-glycogen fastest, triglycerides second, and waxes last.

Starches can be used as indicators of plant nutritional status. Glycogen storage indicates the nutritional status of bacteria and animals.

In the eukaryotes, from yeast to humans, high nutritional status results in triglyceride synthesis and storage, so this can be used as a measure of the condition of the ecosystem.

(c) Exopolymer production

A third class of measures, specifically reflecting prokaryote "health," involves the synthesis of extra-cellular polysaccharide polymers and the response to an incomplete nutritional environment or to protozoan predation[18]. It is possible to assay these polymers by measurement of unique components in hydrolysates such as methylated sugar or uronic acids. Such methods are being developed.

(d) Signature compounds

A critical area for research is the development of ways to measure the activities of particular groups of organisms so that fluxes between components in the ecosystem can be followed. This is particularly important for interactions between micro-organisms, where individuals cannot be readily isolated. We suggest the development of analysis by "signature" compounds such as lipids, which can be isolated from various microbial sub-communities. These compounds, if extracted, purified, and measured, could give measurements of the biomass and metabolic activities ("health") of the microbiota[19].

It is difficult at this stage of development to see how these techniques could be automated for remote sensing, however experiments could lead to correlations with gas exchanges such as H_2 disappearance, CH_4 appearance, N_2O disappearance etc., whose concentrations could be remotely monitored. This discussion leads to the following recommendations.

1. These and other biochemical methods should be developed and used to supplement other measurements. The development would include more sensitive assays--by chemistry and instrumentation.
2. The specificity of the biochemical methods should be improved--finding the unique components or pathways that should be measured for each specific group of organisms.

3. More convenient and rapid methods for measurements should be sought. (For example, woody storage of starches in vascular plants).

Recommendations #14 and #15

THE NASA OFFICE OF TECHNOLOGY TRANSFER SHOULD BE REQUESTED TO DEVELOP BETTER MEASUREMENT TOOLS AND TECHNIQUES FOR REMOTE SENSING OF SUCH BIOSPHERE PROPERTIES AS THE OCEANIC MIXED LAYER, DISSOLVED NITROGEN IN SURFACE WATER, CARBON DIOXIDE, AMMONIA, METHANE, AND WATER VAPOR IN THE ATMOSPHERE.

A PROJECT SHOULD BE ESTABLISHED TO DETERMINE WHICH ECOLOGICAL VARIABLES CAN BE MEASURED FROM EXISTING LANDSAT DATA.

The Earth Resources and Global Ecology communities share a common requirement as shown in the common measurement needs and mission objectives described in the final report of the Landsat D Thematic Mapper Technical Working Group Final Report[20]. These include:

1. Acreage estimates for crops
2. Acreage estimates for rangeland
3. Acreage estimates and stand densities of forests
4. Inventory of watershed/water resources for water management
5. Land use classifications

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