Remote Sensing of the Biosphere

Committee on Planetary Biology, Space Science Board, Commission on Physical Sciences, Mathematics, and Resources, National Research Council

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THE NATIONAL ACADEMIES
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OF THE BIOSPHERE

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PREFACE

This report reviews the current state of understanding of the biosphere, discusses the major scientific issues to be addressed, and evaluates techniques, existing and in need of development, for this new science.

Although the science of the biosphere is an extremely broad subject, involving many federal agencies and research programs as well as scientists working in many diverse areas of investigation, this report is primarily concerned with developing the scientific capabilities of remote sensing for advancing the subject. The global nature of the scientific objectives requires the use of space-based techniques. Because of this space requirement, NASA finds itself involved in the subject in an important way. Charged with providing scientific advice to NASA for all its research programs, the Space Science Board commissioned its Committee on Planetary Biology to undertake a study that resulted in this report. The study is not intended to cover those aspects of biospheric research that are conducted from the surface of the Earth under the auspices of the National Science Foundation, the Environmental Protection Agency, the National Oceanic and Atmospheric Administration, the Department of Agriculture, and the Department of the Interior.

Although the report investigates the potential for space-based observations of the biosphere, the specifics of scientific programming are still to be developed.

A previous report, *Origin and Evolution of Life—Implications for the Planets: A Scientific Strategy for the 1980's* (1981), discussed research on chemical evolution, and the origin of life, and made a strong case for the development of a science of the biosphere

(the planetary system that includes and sustains life, consisting of the atmosphere, oceans, sediment, biota, and those solid surfaces in active interchange with life). The present document extends the discussion of the science of the biosphere by providing the goals and objectives for the NASA remote sensing programs.

The capability to look at the Earth as a whole has been developed only recently. The space program has made us aware of the unity and uniqueness of the surface of the Earth (perhaps most clearly seen in the photographs of Earth taken by the astronauts on the moon). The space program also has provided the technology to study the entire Earth from artificial satellites, and thus has been a primary force in new approaches to planetary biology. Space technology has also permitted comparative studies of planetary atmospheres and surfaces. These studies, coupled with the growing awareness of the effects that life has had on the entire Earth, are opening new lines of inquiry in science.

Ever since the first Apollo photographs of the Earth from space, it has become part of the public consciousness that we live on a unique planet that has the curious property of life. It is now commonly understood that life depends upon and is strongly influenced by the planetary environment. In the last few decades, a scientific community has developed that has recognized that life, in turn, has greatly influenced our planet. Our atmosphere, oceans, sediments, and solid surfaces are very different from what they would be on a lifeless planet. Life has influenced the Earth during its history; it continues to do so. Thus, from a planetary perspective, we now see that life influences and is influenced by its environments. These form a complex interacting system whose properties we barely understand.

The Committee on Planetary Biology concerns itself with a broad spectrum of scientific areas of interest to NASA, including areas directly relevant to the origin of life on the Earth, the early evolution of life, and terrestrial life today as a planet-wide phenomenon—chemical evolution, paleobiology, and global ecology. Examples of subjects of interest to this committee are (1) the history of carbon during the accretion of the Earth and other planetary bodies; (2) prebiotic synthesis in the atmosphere of compounds relevant to life; (3) the organic chemistry of an abiotic aqueous environment, such as a tidepool or pond; (4) the nature of the organisms that are responsible for the earliest Precambrian Stromatolites; (5) the effect of biota on the oxygen content of

the atmosphere from the beginning; (6) the factors controlling the pH of the ocean and the carbon dioxide content of the atmosphere from the beginning to the present; and (7) the influence of vegetation on the albedo of the Earth.

The subject matter is too extensive for a three-year detailed review. Chemical evolution, paleobiology, and planetary ecology were covered in the previous report *Origin and Evolution of Life— Implications for the Planets: A Scientific Strategy for the 1980's,* but not in great depth. Another relevant report, *A Strategy for Earth Science from Space in the 1980's and 1990's, Part II: Atmosphere and Interactions with the Solid Earth, Oceans, and Biota* (to be published), emphasizes biogeochemical cycles from the perspective of atmospheric science.

The major activity during the past three years has been to review potential NASA contributions to the understanding of planetwide biology. The committee finds that current funding for this research is woefully inadequate. It believes that the development of a space-based, global perspective of the biosphere is an integral part of the study of the origin and evolution of life. Thus, the committee recommends that *new* funds be found to support the global biology program, not that funds be transferred from other life science research.

We are poised at a unique moment in history. On the one hand, our technological civilization is affecting our planet on a global scale. On the other hand, space technology makes a global perspective possible for the first time. NASA's twenty years of experience in studying the Earth's vegetation, its solid surfaces, oceans, and atmosphere provide a unique capability. The time is ripe to begin the study of the Earth's biology on a planetary scale.

Although much has been done to lay the foundation for remote sensing, more research is needed to validate the techniques for studying the Earth's biosphere. Such research is essential for establishing the techniques as the major source of observational data for this new science.

Daniel B. Botkin
Chairman

ACKNOWLEDGMENTS

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INTRODUCTION

This report concerns the development of a science of the biosphere, which is the large-scale planetary system that includes, sustains, and is influenced by life. It presents a new perspective on life and on the connection between planetary characteristics and life, and it suggests that the study of the biosphere offers a major new scientific challenge for the next decade.

It has long been recognized that life depends on the unique characteristics of our planet. What is new and exciting is the recognition of the extent to which life influences the planet. The atmosphere, oceans, and sediments are very different from what they would be on a lifeless planet. Life has altered the Earth throughout its history, and it continues to do so. The abundance and distribution of life forms affect climate, energy balance, the cycling of chemical elements, and the chemistry of the atmosphere, oceans, soils, and many solid surfaces.

The biosphere is a difficult system to understand because biospheric phenomena (ecosystems, biomes, and so on) are characterized by time lags; by direct and indirect effects on the environment; by complex, mutually causal relationships between the living and nonliving components of the system; and by the evolution of new life forms. Episodic events have a great importance in the biosphere. The biota seem to be influenced by events in indirect

proportion to their frequency and direct proportion to their amplitude; large, rare events have an importance considerably beyond their frequency.

A science of the biosphere is necessary for understanding and mitigating the global effects of our modern technological civilization. We need to understand the implications of human activities, such as the atmospheric increase in carbon dioxide from land clearing and burning of fossil fuels; the increasing acid rain resulting from fossil fuel burning; desertification; and deforestation. We also need to learn how to mitigate these effects of our activities, so that we can revegetate deserts, reforest cleared areas, and manage our water resources and our crops and timber on a global scale.

THE ROLE OF NASA

Space technology makes the science of the biosphere possible. Remote sensing by aircraft and satellites, coupled with ground measurements, can provide necessary data over large areas and at frequent intervals.

The large amounts of data that need to be collected, their diverse nature, and the requirements for spatial and temporal resolution indicate that substantial computer capabilities, including computer analysis techniques, will be needed.

Because of the complexity of ecological systems, the science of the biosphere will require the development of theory and computer modeling. The science of the biosphere will also require the integration of many disciplines, including atmospheric sciences, biology, climatology, geography, and geology—in short, all Earthward looking sciences.

NASA has a long history of research, development, and use of remote sensing for the study of the Earth's biota. Most of this work has focused on crops, forest, and rangeland of economic importance. Such activities have been part of NASA's efforts since the early days of its existance. The research proposed here is a natural extension of a major activity of NASA. The techniques developed in the past for the study of crops, forests, and rangeland must be analyzed, validated, and extended to the study of all the terrestrial vegetation of the biosphere.

Thus, NASA is uniquely suited to play an important role in developing the science of the biosphere. NASA has considerable

experience in remote sensing and associated computer analysis systems, has developed effective interdisciplinary research programs, and has a global perspective gained through environmental satellites and planetary research programs that could be applied to the study of the biosphere.

The committee therefore recommends that NASA establish and implement a research program to study the biosphere. This program should employ remote sensing observations, complementary ground-based measurements, and an associated theoretical effort.

To accomplish this program presupposes (1) a commitment to the continued development and operation of global remote sensing satellite systems, which are not now assured by programs in NASA, elsewhere in the federal government, or in the private sector, and (2) an effective system for storage, retrieval, distribution, and analysis of data from these satellite systems for scientists within NASA, government laboratories, and universities both within the United States and around the world.

Validation is an essential step. We must understand the limits of existing techniques for supplying information concerning the biosphere. Accuracy must be determined and reliability assessed. These activities must include surface, airborne, and space measurements. Results will be important in providing direction not only in the area of sensor systems and processing techniques but also in the science that can be accomplished employing this new technology.

GOALS AND OBJECTIVES

The goals of a science of the biosphere are to understand the following:

- the nature of a system that supports life and allows it to persist;
- the influence of life on the Earth's energy balance, water, and biogeochemical cycles;
- the factors that control the storage and transport of energy and major chemical elements;
- the spatial distribution, temporal dynamics, and complex interactions of the various components of the biosphere;
- the relationships between biological systems and planetary environments, including the necessary characteristics of a planet that allow life to originate and evolve; and

- the effect of human beings on the biosphere in their present and future numbers.

The following material describes those research programs essential to accomplish these goals and establish the science of the biosphere. They should serve as the direction for research activities for the next decade.

Theory and Modeling

A science of the biosphere will require the development of theory and models. Because of the complex nature of the subject, the models will have to address several different scales of problems, including the energy balance of the Earth as a single unit; the flow of energy and cycling of chemical elements among the major components of the biosphere—the major terrestrial biomes, the ocean biota, the upper and lower ocean, the atmosphere, and the solid surface in active interchange with the biota; the dynamics of individual ecosystems and their interchange of energy and matter with the rest of the biosphere.

Some initial modeling efforts should be directed toward understanding the interrelationships among the carbon, nitrogen, sulfur, and phosphorus cycles, and the dependencies of these cycles on physical factors, such as global climate and atmospheric and oceanic circulation.

The history of the Earth represents a series of biospheric experiments. We can use the geological record to gain insight into the effect of major biological innovations on the biosphere and the effects of major changes in the environment (such as the distribution of continents) on the biota. The development of a science of the biosphere should make use of this Earth history to develop theory, especially making use of the following episodes: the late Proterozoic (800 to 700 million years ago); the Cretaceous-Tertiery transition; and the Pleistocene. Emphasis should also be placed on modern analogs of earlier biota, such as the study of certain gymnosperm forests as analogs of the pre-Cretaceous subtropical vegetation and microbial coastal hypersaline ecosystems as analogs to certain Precambian conditions.

An interesting theoretical question is, what is a "minimal" biosphere, i.e., what is the minimum size, complexity (in terms of the number of components and the number of pathways between

them for biogeochemical cycles), and the minimum number of species that can sustain life over long periods of time? Some modeling efforts should be developed to provide insight into this question.

Biogeochemistry, Energy, and Water Balance

A fundamental part of the science of the biosphere is the analysis of the major biogeochemical cycles. Twenty-four elements are required for life.* During the first decade of research, the primary emphasis should be on the cycles of carbon, nitrogen, sulfur, phosphorus, and the hydrologic substrate. The following questions should be addressed:

1. What are the sizes of the major pools of carbon, nitrogen, sulfur, potassium, and phosphorus, especially biological ones in active exchange with other components of the biosphere?

2. What are the major transport rates of the four elements from one component of the biosphere to another? Of special interest are the flux to and from biotic components, i.e., between land biota and the atmosphere; between marine biota and the atmosphere, from land biota to oceans (via rivers); from land and marine biota to short-term sediment storage.

3. What factors control these rates?

4. How much and in what ways does the cycling of one of these chemical elements affect the others?

5. What were the states of these cycles prior to anthropogenic perturbations?

6. What will be their future states?

7. What must be known to permit us to reverse or stabilize anthropogenically induced trends?

The carbon cycle is especially important because of the biological uptake and release of greenhouse gases, such as carbon dioxide and methane, that can affect climate, ocean chemistry, and mineralization. The fate of carbon dioxide released from the burning of fossil fuels and the destruction of forests and soils remains unclear; more carbon dioxide has been released than can be accounted for by the current content of the atmosphere, oceans,

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* H, B, C, N, O, Na, Mg, Al, Si, P, S, Cl, K, Ca, V, Mn, Fe, Co, Cu, Zn, Se, Mo, Ag, I.

sediments, and the biota. The first decade of research should place special emphasis on understanding the carbon cycle and the flux of carbon dioxide and methane.

The biota affect the Earth's energy balance directly and indirectly. The direct effects are those that result from the biological surface materials that influence the absorption, reflection, and reradiation of sunlight, and the transfer of energy from the Earth's surface to the atmosphere by the evaporation of water. The indirect effects are those that result from biologically induced changes in the biogeochemical cycles, as in the biological production of carbon dioxide and methane.

The biota, particularly land vegetation, affect the Earth's reflection of sunlight (albedo). The Earth's albedo is known with an accuracy only to a few percent, but a change in albedo of less than a few percent could have significant effects on the Earth's energy budget. We need to refine the estimate of the Earth's albedo and improve our understanding of the way that it is affected by biological activity.

More specifically, we need to (1) characterize the albedo of each major land cover type; (2) determine the rate of change of the Earth's albedo due to biological changes such as seasonal changes in land vegetation, and due to changes in the total areal extent of major land cover types (such as the effect of a decrease in the area of tropical rain forests).

The biota can affect the hydrologic cycle on a large scale. Land vegetation affects the percentage of rainfall that returns to the atmosphere by evaporation and the percentage that enters surface and subsurface runoff. We need to better understand the effect of the biota on the evaporation of water and the runoff to major rivers as these are affected by the type of biota that dominate an area, and as the state of these biota change over time.

Studies of the Land

We need to understand the spatial distribution and temporal dynamics of biomass. Terrestrial vegetation and soils aresources of storage of carbon, nitrogen, and other chemical elements required for life. Terrestrial vegetation has a rapid interchange of carbon dioxide, oxygen, and water with the atmosphere. Although it is

obvious that terrestrial vegetation and the atmosphere are coupled, we do not yet have sufficient quantitative understanding to predict the effects that a specific change in one will have on the other.

On the land, vegetation makes up more than 95 percent of the live biomass; therefore, we should determine vegetation biomass and net primary production (the changes in biomass). Measurement of net primary production is the first and fundamental step for calculating fluxes of oxygen, carbon dioxide, and other chemical elements and compounds.

Deforestation and desertification, as well as the erosion of soils, are currently major sources of change in the storage of carbon on the land. The rates of conversion of forests, the creation of deserts, and the loss of soil by erosion are poorly known. Remote sensing techniques could be applied to monitoring rates of conversion of forests and desertification.

Soils are a major site for chemical reactions important for the biosphere. Much of this chemical activity is conducted in anaerobic soils by microorganisms.

Field studies are required to determine correlations between dominant higher vegetation and microbial communities and activities. There is often a close relationship between microbes and fungi and higher plants, and the existence and activity of a certain kind of microbial community. Remote sensing, which determines vegetation cover type, should be used to infer the kind of microbial community. Along with other remote sensing measures (digital terrain information, soil moisture, and so on), this information could be used to determine the rates of decomposition and production of major compounds.

Microbes have a great influence on the chemistry of the biosphere. We need to develop a program of research to improve our understanding of these effects, including (1) to determine to what extent biologically mediated anaerobic processes are important in the deposition and weathering of metal ore deposits; (2) to quantify global methane sources; and (3) to study soil sulfur exchange. Laboratory research is required to establish methods to quantify the relationships among environmental conditions, the kind of microbial community, and the rates of activity.

A potentially important technique in the measurement of terrestrial biomass and net primary production is the measurement of the leaf area index (LAI). We need to improve the measurement

of LAI and the correlations among LAI, biomass, and net primary production. One of the first steps to do this would be to establish sites for studying at least three biomes; for example, coniferous forest, deciduous forest, and grassland. Within these sites, remote sensing of LAI could be tested against ground measurements, and the ground measurements of LAI correlated with direct measurements of biomass and net primary productivity. Other studies could address the variation in LAI within a biome, for example, to examine the variation within the boreal forest at geographic extremes, and to determine the extent of local site variation.

Research on Fresh Waters and Wetlands

Rivers provide a major transport of chemical elements from the land to the oceans. This transport is a key step in many biogeochemical cycles. Few biological time series exist to document the coastal zone's past response to fluvial nutrient transients on a decadal time scale. We need to characterize the transport of disolved and suspended carbon, nitrogen, sulfur, phosphorus, and selected micronutrients by the 20 largest rivers since these seem to account for a major fraction of the total transfer. Special emphasis should be placed on the transport during large, episodic events.

Lakes are useful natural laboratories for determining the factors that control global aquatic primary productivity and the fate of fixed carbon, because lakes have well-defined limits, universal geographic distribution, and proven accuracy for the measurement of primary productivity. Studies of lake primary productivity, however, have lacked sufficient measurements of temporal and spatial variation. Satellite remote sensing creates an opportunity to look at lakes and their changes through time in a wholly new manner, as yet essentially unexplored in comparison to the use of remote sensing for agricultural crops or for oceanographic research.

Coastal wetlands may play a key role in the biosphere. Although they occupy a relatively small area of the Earth's surface, they are a major site for some biologically mediated chemical reactions, such as the production of methane, and of certain crucial steps in the sulfur cycle.

The study of fresh waters and wetlands should include (1) determination of the annual rate of transport of carbon, nitrogen, sulfur, and phosphorus from the land to the oceans via the world's

20 largest rivers; and (2) determination of the area covered and the geographic distribution of coastal wetlands. There is a need to develop remote sensing techniques to monitor monthly changes in vegetation cover, leaf area index, and biomass during the growing season for wetlands and to develop remote sensing detectors to differentiate major algae types that occur in wetlands from each other and from sediments. In situ studies are needed to determine under what conditions wetlands are a net source or sink of carbon and sulfur and to determine the rate of production of greenhouse gases (especially methane and carbon dioxide) from wetlands.

Oceanographic Research

Large areas of ocean, such as the central gyres, have relatively low rates of production per unit surface area, but account for a major fraction of total carbon fixation because of their large areal extent. In contrast, highly productive coastal and upwelling regions account for only 10 percent of the ocean area but probably 25 percent of the ocean net primary productivity; these areas provide more than 95 percent of the estimated fishery yield and may be a major carbon sink of atmospheric carbon dioxide.

The continental shelves also may be such a sink. In these highly productive regions, carbon may be transferred along food chains and deposited on the continental shelf in the excrement and dead organic matter of organisms. Changes in the production of algae on the continental shelves might therefore affect the rate of carbon deposition and the rate of transfer of carbon dioxide from the atmosphere to the ocean and then to the oceanic sediments. It is important that a better understanding be achieved for the rate of deposition of organic carbon on the continental shelves.

In addition, estuarine productivity per unit area is comparable to, or higher than, that of land systems, and much higher than all but a few marine regions. The greatest significance of estuaries seems to be (1) as a nursery ground for important animal species; (2) as a locus for anaerobic events that may be important in the nitrogen and sulfur cycles; and (3) as a filter through which most of the freshwater runoff from the continents must pass before it can enter the sea. All three roles relate intimately to high primary productivity of estuaries and coastal wetlands. It is important to develop a better understanding of the relationship between estuarine upwelling, shelf upwelling, and algal production, especially

the "spring plankton blooms," and to improve our understanding of the seaward extent of estuarine chemistry, the seaward extent of the transport of algae, and the importance of episodic environmental events on biological production on the continental shelves.

Current estimates of net primary productivity in the oceans allow no estimates of statistical variation, but are judged to underestimate actual rates by factors of 2 to 10.

There are two major reasons that large uncertainties exist in the estimate of marine carbon fixation: (1) the methodology used to estimate the rate in situ may be in serious error; and (2) the highly productive shelf regions exhibit a great range of spatial and temporal variability of biomass that has been sampled by classical shipboard programs.

To adequately map phytoplankton variation in high-concentration shelf areas, an instrument must be able to resolve about a kilometer of the ocean. Open ocean studies require a resolution of only 4 km. A measurement program for ocean productivity therefore requires a satellite system that can operate in two modes: (1) local area coverage of high resolution to about 1 km; and (2) global area coverage of lower resolution of about 4 km.

Satellite and aircraft remote sensing techniques, as well as moored biological buoys, have matured rapidly in the last 3 to 5 years, and sampling the spatial distribution and temporal variation of biomass in estuaries and on continental shelf regions is now possible. As a result, multiplatform (ship, buoy, aircraft, and satellite sensors such as CZCS) sampling strategies offer an opportunity to significantly reduce the variance in estimates of shelf phytoplankton abundance, carbon fixation, consumption, deposition, and their concomitant nitrogen and phosphorus fluxes.

Remote Sensing Requirements

A number of existing satellite remote sensing systems (including Television and Infrared Observation Satellites (TIROS), NOAA, Geosynchronous Operational Environmental Satellites (GOES), and Landsat) that acquire data in the visible reflectance and thermal infrared portions of the electromagnetic spectrum are crucial in the study of the biosphere. It is imperative that Landsat Thematic mapper sensors be maintained in orbit for the next decade in

order to provide continuity of data needed to improve our understanding of the biosphere. Research must continue on improved systems.

Aircraft systems are also important in remote sensing of the biosphere. Existing aircraft systems are essential both for photographic and multispectral sensor systems and analytical processing of research and development, and this program should be continued.

Considerable potential exists for research to be conducted with active microwave devices. These systems have shown some potential in research conducted to date to aid remote sensing studies of the surface under cloudy conditions, to penetrate deeper into terrestrial vegetation canopies, to detect higher leaf area indices than have been possible previously, and to detect directly total biomass and water content of terrestrial vegetation. Active microwave devices used on the Shuttle have also demonstrated the potential of these systems to produce data capable of detecting subsurface drainage patterns in sandy areas in extremely arid environments. The continued development of active microwave devices and the research required to test the full range of their potential to improve our ability to study terrestrial vegetation, soils, and hydrological phenomena should be encouraged.

Data Management

The fundamental research proposed here poses especially difficult and novel questions in the area of data management. Improved methods for obtaining, storing, processing, analyzing, and retrieving remotely sensed and other environmental data are required. However, the role that the science of the biosphere will develop is strongly dependent on the access of scientists to remote sensing data. Especially important is "data base management"—new systems need to be developed to facilitate the integration of different kinds of data, taken at different spatial and temporal scales. To this end, research on "artificial intelligence" systems should be expanded. It is important to develop data systems to integrate information from existing sensors; to improve techniques to register different sensors in different orbits to one another and to ground geographic coordinate systems. The large number of data that can be acquired by remote sensing requires that the following issues must be resolved: (1) which data sets should be archived; (2)

where these data sets should be archived; and (3) how they will be assessed and distributed. NASA must resolve how its resources will be applied to the archiving and distribution of data sets.

An especially important issue is the methods for establishing a network connecting scientists (including those in other countries) and the data bases at major institutions involved in biosphere research.

It is typical of federally sponsored remote sensing activities that more resources have been applied to the development of sensors and to fly missions than to providing for the processing, archiving, distribution, and analysis of data. To the committee's knowledge, essentially all projects in remote sensing relevant to the biosphere have had insufficient resources for the management of data. This is true today of Landsat-4 just as it has been true of all past Landsat missions. Any new project involving new missions must, as a basic part of the effort, provide adequate support for the coordinated processing and analysis of data.

Many potential users of remote sensing data lack the means to access the data. Previous data systems can be utilized efficiently only at a handful of universities in the United States. Additional funding for the acquisition and continued development of data systems that are readily accessible to university users is essential. Major issues in data management have been discussed in a previous report of the Space Science Board (*Data Management and Computation, Volume 1: Issues and Recommendations*, 1982), and the recommendations of that report are endorsed by the Committee on Planetary Biology and Chemical Evolution. In addition, the Committee on Planetary Biology is closely following and participating in the more detailed follow-up study by the Committee on Data Management and Computation, which is in progress.

Funding for basic and applied remote sensing research at NASA centers and more particularly at universities across this country has been reduced to a level where the nation stands to lose a major analytical capability. NASA should be aware that this capability, once lost, cannot easily be regained. Today, the processing and analysis of advanced remotely sensed data require complex, highly sophisticated hardware systems and associated software, as well as experts in remote sensing familiar with the science of the biosphere. This will most often require interdisciplinary efforts. NASA must find the resources to sustain and

encourage such efforts both within NASA centers and universities and through cooperative research between NASA centers and universities.

AN INITIAL PROGRAM

The previous section described the scientific objectives for a research program in biospheric science. While all of these objectives need to be accomplished eventually, they should be addressed in an orderly, phased manner, with the fundamental quantitative measurements (e.g., area extent, biomass density) being first. Establishing a science of the biosphere is a difficult task because of the large number of complex and interacting systems. Thus, the basic measurements in each of the main study areas need to be pursued together; i.e., a balanced approach to gathering the basic data is the prime requirement. In order to advance this subject from a phenomenological basis to a true science, emphasis must also be placed on the concurrent development of theory and modeling.

Thus, from the list of scientific objectives, the committee has excerpted an initial program that should be the first step in this science. The elements of this program follow:

I. Theory

• Develop computer simulation models of the biospheric cycles of C, N, S, P as a function of the state of the biota, climate dynamics, interactions among these cycles.

• Begin to develop models that use the fossil record, and model five transitions in Earth history: (1) Archean-Anaerobic biosphere, (2) transformation of the atmosphere from reducing to oxidizing by phonosynthesis, and the appearance of aerobiosis, (3) Late Proterozoic transition from single to multicellular organisms, (4) the colonization of the land, (5) Cretaceous-Tertiary transition, (6) Pleistocene ice ages.

These models should focus on changes in biogeochemistry as a result of major changes in taxa.

II. Land

• Measure total area covered and geographic distribution of major biomes.

• Measure the rate of change of distribution of major biomes.

• Measure biomass density for each biome.

- Vegetation production (annual): (1) Use leaf area index as key variable relating vegetation reflectance to biomass and biological production. (2) Test active microwave techniques to measure biomass; canopy moisture; soil moisture.

III. Fresh Waters and Wetlands
- For the 20 largest rivers, determine annual rate of transport of C, N, S, P from land to oceans.
- Determine area covered and geographic distribution of coastal wetlands.
- Determine production of greenhouse gases from wetlands (methane and carbon dioxide).

IV. Oceans
- Determine carbon fixation in coastal upwelling and continental shelf areas (annually).
- Determine carbon fixation in central ocean (annually).
- Determine deposition rate of organic carbon on continental shelf.

V. Remote Sensing
- Maintain the continuity of advanced Earth remote satellite sensor data.
- Maintain—this is imperative—the thematic mapper sensor in orbit for the next decade.
- Develop calibrated sensors capable of high spectral resolution measurements in the 0.4- to 2.5-μm region.
- Develop calibrated, active microwave sensors at wavelengths from millimeters to 1 m.
- Develop sensors to detect emissive infrared wavelengths in the 2- to 5.5-μm and 10- to 12-μm ranges.
- Conduct fundamental research on extracting quantitative information about the biosphere from remotely sensed data.

VI. Data Management
- Develop data systems to integrate information from existing sensors (on biophysical properties of vegetation, soils, water, and so on) that operate in many regions of the electromagnetic spectrum.
- Improve techniques to register different sensors in different orbits to one another and to a ground geographical coordinate system.

- Obtain funds to increase the processing and dissemination of thematic mapper data for the scientific community.
- Develop distributed data base systems.

SOME SPECIFIC EXAMPLES

While it is not the purpose of this report to specify an implementation strategy for this science, the committee presents here some illustrations of how investigations might be conducted that would lead to a progressive understanding of elements of the biosphere. Consider, for example, the most studied and best known of the biogeochemial cycles—the carbon cycle.

A current major issue is the "missing carbon problem." An estimated 5.67 billion metric tons of carbon are released each year from the burning of fossil fuels. However, only 3.07 of this increase is found in the atmosphere. The rest must either go into the ocean and its sediments, or into land biota. A first hypothesis is that the missing carbon must be taken up by land vegetation. The argument in this case is that increasing carbon dioxide concentration increases vegetation growth rate and, therefore, should increase the rate of uptake by land vegetation. A second hypothesis is that the rate of loss of biologically stored carbon in land vegetation through human land clearing exceeds the increase due to the fertilization effect of an increased carbon dioxide concentration in the atmosphere. Following from this hypothesis, the land vegetation would be a source of carbon to the atmosphere, rather than a sink. At this time, information at hand does not allow us to resolve this issue. We do not even know the direction of change of stored carbon in land vegetation. Figure 1.1 illustrates our understanding of the global carbon cycle.

There are many reviews of the global carbon cycle, and these include estimates of the total biomass or carbon storage in the major land vegetation types. These estimates are qualitative generalizations based on few measurements and many assumptions. Furthermore, some of the estimates are not independent; they depend on previous estimates and use the same literature values.

Two methods have been used to estimate biomass and productivity. In the first method, biomass and productivity per unit area for major vegetation types are multiplied by the total estimated land area occupied by each type. Global estimates derived in this manner vary greatly. Estimates of total terrestrial plant biomass
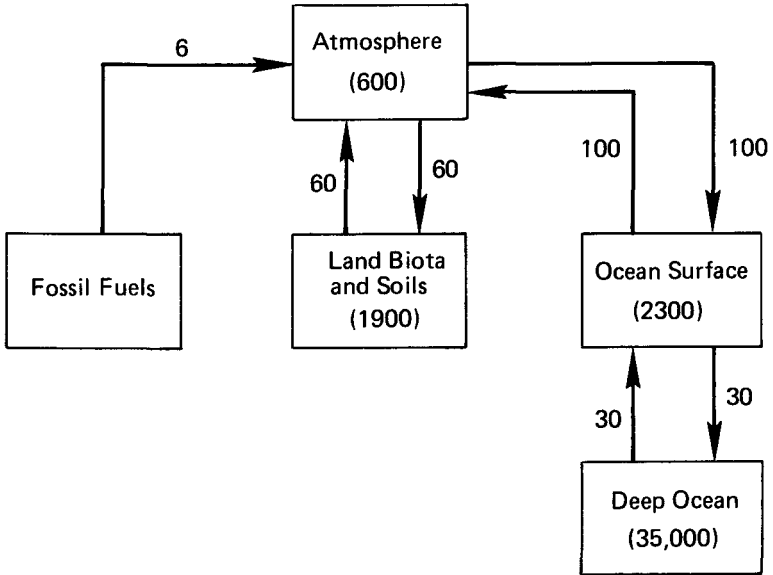
FIGURE 1.1a   Global carbon cycle—classical view.

range between 450 x 10^{15} g C and 1000 x 10^{15} g C, a difference of more than twofold. Without remote sensing, the extremely poor data available now for both areal extent and per unit area measures of biomass and net primary production limit our ability to improve these estimates.

The second method is based on the correlation between biomass or biological productivity and climatic indices, such as temperature and precipitation, or temperature and evapotranspiration. Maps of average climatic conditions are then used to generate maps of biomass and productivity. Such estimates are also limited by the small number of data available as a basis, by the lack of a means to estimate statistical variation, and by the fact that the result is a map of potential productivity, or potential biomass assuming a fixed state of vegetation on the land surface, and not a map of actual productivity or actual biomass.

Three sources of error are important in the existing estimates. First, field studies often have large errors associated with them and may misrepresent true values of biomass and productivity. Second, average values for biomass and productivity may be incorrect. A tremendous local variability in biomass and productivity, coupled
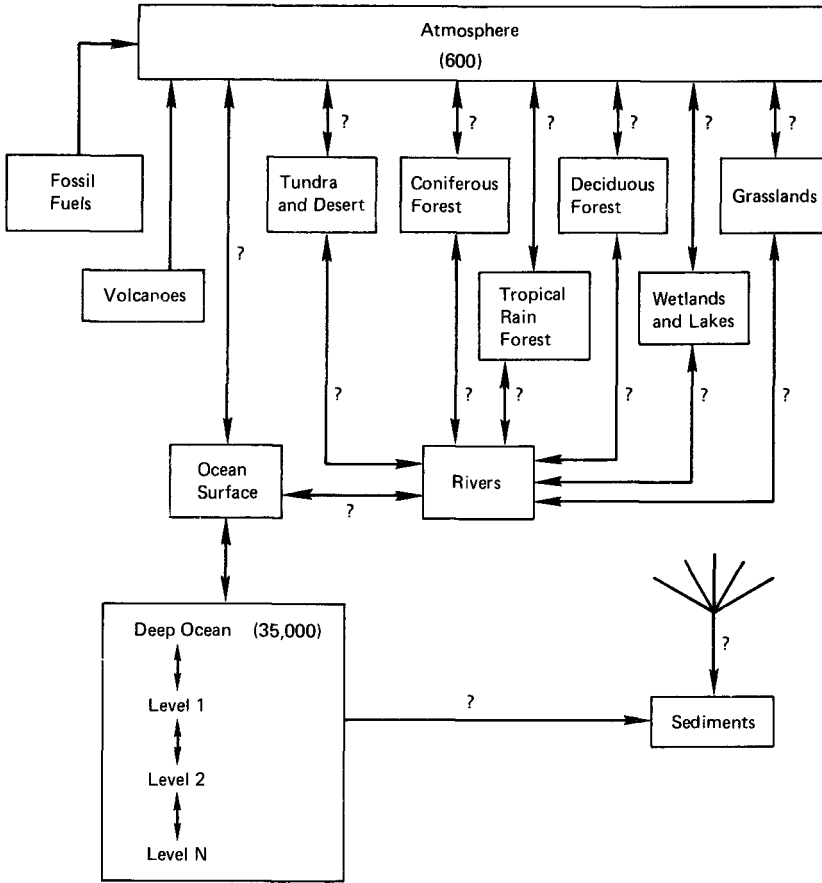
FIGURE 1.1b   Global carbon cycle—biosphere view.

with a spotty geographic distribution of field studies, makes the determination of biome averages very difficult. Third, the areal extent of biomes has been a rather subjective determination, with boundaries between biomes set arbitrarily. Moreover, forest clearing, desertification, urbanization, and other changes have altered the areal coverage of biomes faster than international statistics and land use maps can be updated. The limitations affect both of the first two methods.

   These sources of error are well illustrated by past estimates of the total area and biomass of the boreal forest. This is one of the world's major biomes. Some estimates suggest that the boreal forest makes up approximately one-sixth of the total live organic

TABLE 1.1 Recent Global Estimates (Averages and Ranges) of Net
Primary Productivity and Biomass of Boreal Forests

	Area, 10^6 km^2	Productivity, tons/ha/yr	Biomass, tons/ha
Lieth (1975)	12	6.5 (3-12)	(200-500)
Whittaker and Likens (1975)	12	8 (4-20)	200 (60-400)
Rodin et al. (1975)	23	6.5 (4-10)	190 (80-370)
Ajtay et al. (1979)	9	8	245

SOURCES:

Ajtay, G.L., P. Ketner, and P. Duvignead. 1979. Terrestrial primary
    production and phytomass, pp. 129-181 in B. Bolin, E.T. Degens,
    S. Kempe, and P. Ketner (eds), The Global Carbon Cycle. Scope
    13. John Wiley and Sons, New York.
Lieth, H. 1975. Primary productivity of the major vegetation units
    of the world, pp. 203-215 in H. Lieth and R.H. Whittaker (eds),
    Primary Productivity of the Biosphere. Springer-Verlag, New
    York.
Rodin, L.E., N.I. Bazilevich, and N.N. Rozov. 1975. Productivity of
    the world's main ecosystems, pp. 13-26 in D.E. Reichle, J.F.
    Franklin, and D.W. Goodall (eds), Productivity of World
    Ecosystems. National Academy of Sciences, Washington, D.C.
Whittaker, R.H., and G.E. Likens. 1975. The biosphere and man, in
    H. Lieth and R.H. Whittaker (eds), Primary Productivity of the
    Biosphere. Springer-Verlag, New York.

carbon storage (Table 1.1). Essentially all but the most recent
estimates of the biomass and productivity per unit land area of
boreal forests in North America are based on studies conducted at
just two sites, in New Brunswick and Quebec provinces of Canada.
Current estimates of biological productivity for the boreal forests
of the world have been calculated by multiplying these values on
a unit land area basis by estimates of total land area covered
by boreal forests. Estimates of the land area covered by major
vegetation types vary from 9 to 23 x 10^6 km^2 (Table 1.1).

As with the boreal forest, information used to calculate com-
ponents of the global carbon cycle derive ultimately from the
compilation of intensive studies of single ecosystems.

In order to resolve the question of the "missing" carbon, we need to improve the measurements of biomass and its rate of change as a basis for developing models of the global carbon cycle. Realistic models, which adequately represent the complexity of the biosphere, must then be developed so that useful predictions of the changes in the carbon cycle can be made. First-generation global carbon models were so highly aggregated that all carbon in terrestrial vegetation was represented as one compartment.

The committee suggests development of global carbon models that are driven by a satellite data base. Key capabilities developed in the remote sensing community make this potential attainable if satellite data are used to drive ecosystem-level models designed to accept satellite inputs. Figure 1.2 illustrates the sensors, data streams, and modeling required for such a venture. The committee suggests coupling satellite-derived measurements of vegetation structure (LAI, biomass) with satellite measurements of surface climate (albedo, temperature, soil moisture). When these data are combined with satellite definitions of the areal extent of each biome, mechanistic models of key energy and mass exchange processes of the vegetation could be defined. Land-atmosphere exchanges of carbon, water, and energy could be calculated directly and inferences to N, P, and S exchange made. At an ecosystem level, net primary production (NPP), accumulated living biomass, and detritus could be calculated.

A program could establish test sites in biomes exhibiting major differences in components of the carbon cycle. Examples of sites within terrestrial biomes for such studies might be the following:

1. Boreal forests whose geographic extent is large.

2. Coniferous forests across climatically steep gradients such as the Pacific Northwest where LAIs of 1 to 15 are documented with similar range in NPP.

3. Transition zones between short and tall grass prairies as in the Konza prairies of North America.

4. Agricultural areas where seasonal productivity is accurately measured.

5. Desert and tundra where extreme climate reduces carbon cycling to near zero.

6. Tropical forests with high carbon, energy, and water cycling rates.

REAL WORLD

GLOBAL
CARBON
MODEL

PLATFORM / SYSTEM
SELECTION
● Met Sats
● Landsat
● AVHRR
● ESMR
● TM
● MSS
● CZCS

ENERGY OUTPUT

Global Model

● Carbon Pool and
  Fluxes in

  – Land
  – Ocean
  – Atmosphere

Data Acquisition

Preprocessing

● Radiometric
● Geometric
● Atmospheric
● Band Ratio
● Clustering and
  Classification

Multiple Data Bases

Remotely Sensed Data

In Situ Measurements

Archive Data

Library Data

Ecosystem Model

● Net Primary
  Production
● Living Biomass
● Detritus

Data Analysis

● Labeling of Biome
  Areas and Types
● Biomass Estimation
● LAI
● Surface Moisture
  Estimation
● Surface Temperature
  Estimation
● Albedo

Process Models

● Photosynthesis
● Respiration
● Decomposition
● Evapotranspiration

FIGURE 1.2   Example: Remote sensing for global carbon modeling.

In a similar manner, the dynamics of primary production in the oceans could be analyzed. Satellite-based measurement of ocean surface temperatures and a greenness index have been developed that correlate well with measured primary production rates. Large-scale mapping of these variables could provide a dynamic and spatially accurate measure of ocean productivity. Additionally, ocean surface hydrologic and energy budget calculations could be overlayed on this map.

The approach suggested in Figure 1.2 has several key advantages over current capabilities. It provides near-real-time measurement of land disturbance frequencies and changing meteorological conditions. It also provides direct verifiable measurement of existing vegetation and surface conditions over large terrestrial and

oceanic areas, rather than point samples extrapolated to unmeasured locations. While this example illustrates the advances that could be made in global carbon cycling, the committee sees similar advances in other fields, such as biogeochemistry of nitrogen, phosphorus, and sulfur. The common denominator that the committee advocates is a new synthesis of remote sensing, ecological modeling, and quantitative ecosystem analysis.

2.
INTRODUCTION TO
PLANETARY BIOLOGY

This report addresses the development of the study of the biosphere, which is the entire planetary system that includes, sustains, and is influenced by life. This science offers new scientific challenges of great intrinsic interest and forms a necessary base for many practical issues. Life affects the Earth's atmosphere, oceans, and solid surfaces; it does not adapt passively to the physical and chemical constraints imposed by the surface of the planet. We now know that life has greatly altered the planet on a global scale: the Earth has far more oxygen and far less carbon dioxide in its atmosphere than other terrestrial planets; the formation of many sedimentary rocks can be attributed to organisms. A central issue of a science of the biosphere is the extent to which the surface, atmosphere, and hydrosphere result from biological rather than abiotic processes. Understanding the role of life as a planetary phenomenon includes knowing the extent to which life can modify a planetary surface.

A science that chooses the globe as its fundamental unit faces extraordinary scientific difficulties. The kinds of questions that can be asked about dynamics at this level are not immediately obvious. Nor is it clear how to formulate theories or experiments for a system of this size—considering biological systems on a planetary scale is new and scientifically very exciting, but initially we lack appropriate paradigms.

Space science and technology can greatly accelerate our understanding of global biological processes by providing observations

of spatially distributed and large-scale processes. Once relationships between processes on the ground and quantities that can be sensed from space are firmly established, aircraft and satellite observations can extend our knowledge of local and regional sites to global information.

In this report, the committee summarizes the current state of knowledge of the biosphere and discusses how the science may be advanced by the application of remote sensing technology, development of new ground-based sensors, techniques for managing large data sets, and the development of appropriate theory.

WHY STUDY THE BIOSPHERE?
BASIC PRINCIPLES OF GLOBAL ECOLOGY

The biosphere (an older use of the term "biosphere" was the total amount of living organic matter on the Earth; in this document "total biomass" has this meaning) is the entire planetary system that contains and supports life. It includes all of the biota and those portions of the atmosphere, oceans, and sediments that are in active interchange with the biota. The biosphere extends from the depths of the oceans to the summits of mountains and into the atmosphere.

A system that can support life over long time periods must have two characteristics: a flux of energy, and the flux and cycling of all the chemical elements required for life. The chemical elements must be available in appropriate chemical form, at adequate rates, and in appropriate amounts and ratios to ensure growth and reproduction of organisms. The Earth's biota includes an estimated 3 to 10 million species. These exist as sets of spatially distributed, interacting populations. Each population has its own growth characteristics and, typically, a temporally changing requirement for chemical elements, compounds, and particulates. Thus, the ecological and physiological mechanisms that control the flux of elements at appropriate rates and times are complex. A local set of interacting populations is an ecological community. A community and its local nonbiological environment is an ecosystem. An ecosystem is the smallest unit that has the characteristics necessary to sustain life. The biota are organized into geographically distributed classes called biomes, which are types of ecosystems.

The rates at which critical chemical elements must be cycled to support life are far more rapid than most geologic processes. Yet, the extent to which ecological systems can control the exchange of gases with the atmosphere, ions with the hydrosphere, and solid particulates with both atmosphere and hydrosphere is largely unknown. To identify the processes that control the composition of the atmosphere and hydrosphere, we have to understand exchange processes between ecosystems and abiotic global reservoirs of major components of the biosphere.

The fluxes of elements into and out of solid and liquid phases represent processes of great significance for biological survival. In turn, biological processes affect the chemistry of these elements in both sedimentary and aquatic environments. For example, the concentrations of dissolved trace metals, inorganic phosphorus, silica, nitrate, and carbonate in seawater and ocean basins are known to be strongly affected by marine biota. Living things mediate the deposition of almost all limestone today. Among the minerals of major interest with respect to their interaction with the biota are specific mineral phases of carbonates, sulfides, silicates, phosphates, iron, and manganese oxides. The extent to which these minerals are uniquely produced by living cells at moderate temperatures and pressures is not fully known.

THE NATURE OF LARGE-SCALE BIOLOGICAL SYSTEMS AND THE INFLUENCE ON THE EARTH

The study of the biosphere requires a new scientific discipline and a new, highly interdisciplinary perspective. This assertion can be supported by the following argument: the simplest, null hypothesis, which we will refer to as the "life as a peculiar form of ice" hypothesis, states that the occurrence of biotic systems can be predicted simply from a few physical measurements. If this were true, no knowledge of biology would be required to predict the effects of climatic change on the biota, except statistical correlations between present distributions of life forms and the present average climate. Such a model cannot be sustained for two reasons. The first is a consequence of evolution; the second of ecology.

First, it has been clear since the development of evolutionary biology in the mid-nineteenth century that the distribution

of species is determined by evolutionary as well as environmental factors. Second, although this is less well known, biotic systems have time lags, positive and negative feedback, and other characteristics that lead to their ability to alter the environment, and to affect their own subsequent states.

HOW LIFE AFFECTS THE ENVIRONMENT

Life has major effects on the biosphere. For example, some have suggested that human land clearing has changed the climate; that human land clearing has increased the surface albedo of the Earth by 0.06, which would be sufficient to cool the Earth's surface temperature by 1 or 2°C and account for the temperature difference between the present and the "climatic warming" of approximately 4000 years ago.

What is required to support this hypothesis? First of all, we must have an accurate measure of the emissivity and reflectivity and other components of the energy budget of natural vegetation. Second, we must have a way of making a reasonable estimate of the aerial extent of major vegetation types today and at the start of land clearing. Third, we must have reasonably accurate estimates of the actual land clearing.

We lack this information. While this information can and has been collected accurately at specific study sites, we lack the capability of extrapolating the results to regional or larger areas. Once we had this information, we would then have to set it within an integrated biosphere context, in which the relative importance of other factors could be evaluated, such as the effect of a regional change in albedo on global climate; the effect of the regional change in vegetation cover, seasonal and annual flux of carbon, nitrogen, phosphorus, and sulfur; the effect of the fluxes on the atmosphere (via greenhouse effects of carbon dioxide) and on ocean productivity, via the transport of nutrients from the previously forested regions via rivers to the oceans. Thus, we see that this conjecture requires an understanding of biological, oceanographic, geological, and atmospheric characteristics, and the coupling among them.

A planetary perspective suggests that organisms can have effects on the biosphere out of proportion to their mass or relative abundance. For example, diatoms are now a major factor in the flux of carbon from the atmosphere to ocean sediments. Diatoms are abundant along the continental shelf and can grow extremely

rapidly: a population of diatoms can double in four hours. Diatoms are particularly important in the burial of carbon because, with siliceous shells, they sink readily in contrast to other forms of phytoplankton.

The evolution of diatoms demonstrates that biological innovation has influenced biogeochemical cycles. Other major biological innovations that have had major biogeochemical significance include the origin of photosynthesis, the origin of higher plants and animals on land, as well as the origin of human beings.

The quantitative importance of some biological innovations can be examined by using modern analogs to simpler/primitive conditions. For example, hypersaline lakes, such as Mono Lake, California, provide a modern analog to some early environments. In such systems, one can ask questions such as, How does the recycling of nitrogen change if nitrification and excretion by higher animals are excluded from the ecosystem?

Some biomes play unique roles in the biosphere. For example, salt marshes and other areas rich in anaerobic sediments may be a major source of reduced compounds, such as hydrogen sulfide and molecular nitrogen. A significant change in the area of these systems could alter atmospheric concentrations of methane and change the Earth's surface temperature. A period in the Earth's history characterized by a much larger area in shallow seas and bays and therefore with much more marshland might be significantly warmer than the present Earth, other things being equal. The area of the Earth's surface in shallow seas and bays has changed significantly. During the glacial maxima of the Pleistocene, most of what is now the continental shelf was either exposed land or shallow seas. Thus, one can speculate that at the glacial maxima there were considerably larger areas of marshes, and perhaps this was one factor leading to a warming of the Earth and the initiation of an interglacial period.

What would be required to test this hypothesis? One would first of all have to obtain a reasonably accurate estimate of the current area of marshes, a reasonably accurate estimate of the production of methane of these marshes, as well as of the other sources of methane; and a measure of the effective albedo of salt marshes. In addition, one would need to estimate the effective albedo of the Earth at a glacial maxima, which would require improved information on albedo of the major biomes and an estimate

of their areal extent during the glacial maxima. We do not now have sufficiently accurate information about any of these factors.

Some ecosystems have long time lags. For example, once certain forests are established, they may persist after climatic conditions have changed to the point that the same kind of forest could not regenerate in the same area.

Direct and indirect effects, the existence of ecological time lags, the historical occurrence of biological innovations, and the mutual causal connections between the biota and the environment suggest that the influence of the biota on the biosphere is complex, and life cannot be viewed at a planetary level as if it were a "peculiar form of ice." How then do we approach the study of the biosphere? First by considering the properties of ecosystems, a basic unit of the biosphere.

LIFE AS A HIERARCHICAL PHENOMENON

Life can be studied at a series of levels, all of which are interconnected, and two of which seem particularly significant: the organismic level and the planetary level. In the past, most ecologists have concerned themselves with interactions among local sets of organisms and their local environment. From this perspective, life is viewed as an organismic phenomenon in which individuals are aggregated into populations and populations (groups of individuals of the same species) into communities (sets of interacting populations). The population and community form proper scientific objects for ecology.

Viewing life as a planetary phenomenon introduces a new ecological perspective, which raises a family of new questions. Living things are seen as processors affecting atmospheric, geologic, oceanic, and chemical properties.

A hierarchical view of life yields important insights into planetary ecological processes. Life responds to change over a large range of time and space. The same local ecological system may respond on five-minute time pulses of nutrient input in rainfall and to a climatic change over thousands of years. To understand life requires a perspective that spans the entire range from organisms to biosphere and from minutes to eons. The time scales of importance depend on the choice of appropriate questions and techniques.

ECOLOGICAL STABILITY IN ECOLOGICAL SYSTEMS

The need for a variety of scales becomes clear when one considers perturbations or episodic events in ecological systems. What appears destructive at one level—for individual organisms—may be necessary for the persistence of an ecological community over a longer time scale. Many natural systems have evolved so that sudden perturbations, rather than being destructive, appear necessary to maintain biological diversity. The continuing stability of certain ecological systems, such as the grain producing grasslands, is critical for the survival of human beings. Since we have no adequate understanding what leads to stability of natural systems, research is needed to identify and then collect the relevant data from which a theory of the stability of ecosystems can be derived.

Ecosystem function is generally used to mean the sum of all processes required to sustain life: biological productivity, chemical cycling, and energy flow. The persistence through time of ecosystem function implies some kind of stability, but the factors determining stability are not known. During the development of ecology in the twentieth century, stability in ecological systems has been defined and used in practice as analogous to stability of mechanical systems. That is, an ecosystem has been assumed to have a single equilibrium state, to which the ecosystem returns following disturbances. An example is a conifer forest subject to a forest fire, which then undergoes natural reforestation, supposedly returning to the exactly same equilibrium conditions that existed before the fire. This equilibrium state has generally been considered to be the most desirable condition, as well as the most likely to persist over time, and in that sense, an optimal condition. This mechanical analogy has proved inadequate. In fact, there is evidence that ecosystems must fluctuate—that they must move through a set of states—in order to persist over long time periods. Other evidence suggests that ecosystems are not characterized by a single optimal equilibrium condition, but by a series of relative equilibria interrupted and maintained by periodic disturbances (e.g., seasonal changes, fires, migrations, hurricanes).

In addition to natural fluctuations, human civilization and technology has introduced an array of changes. Some of these changes have transformed entire landscapes to new steady states,

others have threatened to destroy irreversibly the regulatory mechanisms essential for ecosystem persistence. The extent to which productive ecosystems are perturbable or even destructible by imported propagules, such as fungal spores, by climate changes, by insect pests, or by removal of key species, is unpredictable at present. On the other hand, the environmental costs and long-term effects of maintenance of the present stability of ecosystems by means of chemical control of diseases and pests are equally unknown. Directional and irreversible changes that threaten the stability of ecosystems are also connected with human activity, including deforestation, desertification, and burdening the environment with toxic substances such as industrial and municipal wastes.

Viewing life as a hierarchical phenomenon helps clarify a number of ecological issues. An ecosystem may be stable over a short-time period of 10 or 100 years and return to some prior state following perturbation. Concurrently, that ecosystem may be subjected to long-term changes in climate to which it does not respond in a stable fashion, but moves away from its previous stable state and toward a new configuration. The biosphere requires a new perspective that includes the possibility of both local stability and global instability. Viewing life as a planetary phenomenon introduces new theoretical problems that must be addressed.

CRITICAL SPECIES

In the biosphere, some species are more important than others. A species is important in the present context if its elimination would cause significant changes in the ecological systems, of which it is a part. For example, some nitrogen-fixing algae in the central oceans are key species. Only one or two species are known to fix nitrogen in these regions. The extinction of one of these could have major effects on the viability of other species and the biogeochemical cycle in the open ocean.

Other species are not critical because they are redundant in a certain sense—other species can carry out the same chemical and energy transformations. For example, when the chestnut tree was eliminated from the mid-Atlantic forests by an introduced blight, other tree species—red maple and certain oaks—merely increased in abundance. The extent to which any species is crucial—a key species—remains an important question.

Human activities during the past 200 years have greatly increased the rate of extinction of species. The role of threatened species and the effects of their losses are not known; it is possible that threatened species are critically important to ecosystems function and therefore must be protected. The sea otter is an example of a threatened key species. Monitoring populations of particular species may therefore constitute a most sensitive indicator of change of an ecosystem over time.

THE SPATIAL DISTRIBUTION OF ECOLOGICAL PROCESSES

Little is known about variation within or between biomes, but there is reason to believe that spatial heterogeneity is essential to the stability of the biosphere. Heterogeneity may be important at many different scales, ranging from microns (as in the anaerobic microsites for bacteria in aerobic environments) to many hundreds of kilometers (as in forest boundaries). Sometimes ecological boundaries are easily recognized because rate processes change dramatically. The accompanying Landsat scene of Mt. Kilimanjaro shows five major types of ecosystems; each at a different elevation band (Figure 2.1). Timberline boreal forests and the edges of crater lakes have easily defined boundaries. Even in cases where boundaries seem gradual or vague on the ground, such as the evergreen coniferous forests of North America that border on agriculture and pasture lands or deciduous hardwood forests, the border generally can be identified with precision to within a kilometer or less from the air or from space. Images using the Advanced Very High Resolution Radiometer (AVHRR) sensor show these boundaries clearly (Figure 2.2). In other cases, for example, the open ocean, the appropriate area to be taken as a functioning ecosystem is unclear.

Another property of most ecosystems is the maintenance of a large chemical potential difference between its zones: the oxygen-producing and oxygen-utilizing aerobic zone, and the anoxic and anaerobic zone. The transitions between the anaerobic and aerobic zones are often at sediment-water interfaces or within the sediment. Vertical stratifications with underlying anaerobic and overlying aerobic zones is not only common (e.g., in salt marshes, lake sediments, and forest profiles), but probably required for ecosystem sustenance. These aspects of ecosystem organization

LANDSAT IMAGE E·2367· 06582 I·24·76

FIGURE 2.1   Landsat scene of Mt. Kilimanjaro.

and changes through time are poorly understood. No natural ecosystem is entirely independent of others: gases, ions, and particulates in suspension, propagules, and other matter transfer between ecosystems.

The major routes of interecosystem transfer have seldom been made explicit. The fluxes of matter and energy between ecosystems via the fluid phases, the atmosphere, and the hydrosphere have been studied and described by atmospheric scientists, oceanographers, and geochemists with a vocabulary and in contexts different from those familiar to biologists. Similarly, the fluxes within ecosystems have been studied by biologists with a vocabulary and in contexts unfamiliar to other scientists.

The relative importance of material exchange for the stability of ecosystems is not known. A general theoretical context for material flux, evaluation of data, and prediction of future states has never been developed. Without a balanced strategy for a science of the biosphere, any study of the particular effect of some portion of the Earth's biota on the atmosphere and climate, such as human effects on ozone and carbon dioxide, will almost certainly fail.

BIOGEOCHEMICAL CYCLES

During the past century, human activity has altered the physical and chemical conditions of the planet—changing atmosphere, oceans, and landscapes on a global scale. The alteration of global biogeochemical cycles by human activity has reached a critical stage: states of individual cycles have begun to move outside their historical ranges. Current concern over the intensification of acid rain and the increase in atmospheric carbon dioxide illustrates the urgency for developing a science of the biosphere. Such a science will need to consider global biogeochemical cycling.

The Major Biogeochemical Cycles

Biogeochemical cycles involve chemical elements that are taken up and released by the biota. Twenty-four elements are required by living things. There are generally divided into the macronutrients, required by all forms of life in large quantities, and the micronutrients, required by some forms of life or required in small quantities by all life forms. In addition to the elements required

by organisms, the biota also process elements that are toxic, such as lead and mercury.

The cycling of these elements in the biosphere is poorly known. The fluxes between major components of the biosphere are rarely known to accuracies of less than an order of magnitude. Frequently, the factors that control the fluxes are unknown. The sizes of major storage "pools" are poorly known. The level of knowledge is insufficient to assess the outcome of human alteration of the biosphere, or to understand how the cycles are maintained in a way that leads to the long-term persistance of life on Earth.

The carbon cycle is a good case in point. Because of its central role in organic matter, and because of the concern with the possible effects of an increase in carbon dioxide content in the atmosphere on climate, the carbon cycle is the best studied of all biogeochemical cycles. Yet, in spite of decades of study, we still do not know the fate of a large fraction of the carbon emitted into the atmosphere from the burning of fuels.

Early models of the global carbon cycle suggested that observed atmospheric carbon dioxide buildup could only be explained if the net flux of carbon was from the atmosphere to the land and the land's biota were a net sink for the added carbon dioxide. Because laboratory experiments show that plants grow faster in air enhanced with carbon dioxide, some scientists have argued that the unaccounted-for carbon dioxide is fertilizing the growth of woody vegetation and is being stored in the land. Other ecologists believe carbon dioxide does not limit terrestrial plant growth in most natural systems, and therefore would not increase vegetation production or increasecarbon storage. In addition, it is argued that the rate of deforestation would be sufficient to reverse any trend toward net carbon storage on land. This controversy remains unresolved.

Uncertainty centers on the role of terrestrial ecosystems. Two factors govern the level of carbon storage. First is the alteration of the land cover, such as the conversion of forest lands to agriculture or agricultural lands to desert, which results in a net release of carbon dioxide to the atmosphere. Several analyses suggest that the net flux of carbon may be *from* altered land areas to the atmosphere and the magnitude may be 20 to 50 percent of that released through the combustion of fossil fuels.

The second factor governing the rate of carbon storage is the possible change in net biological productivity, especially due to
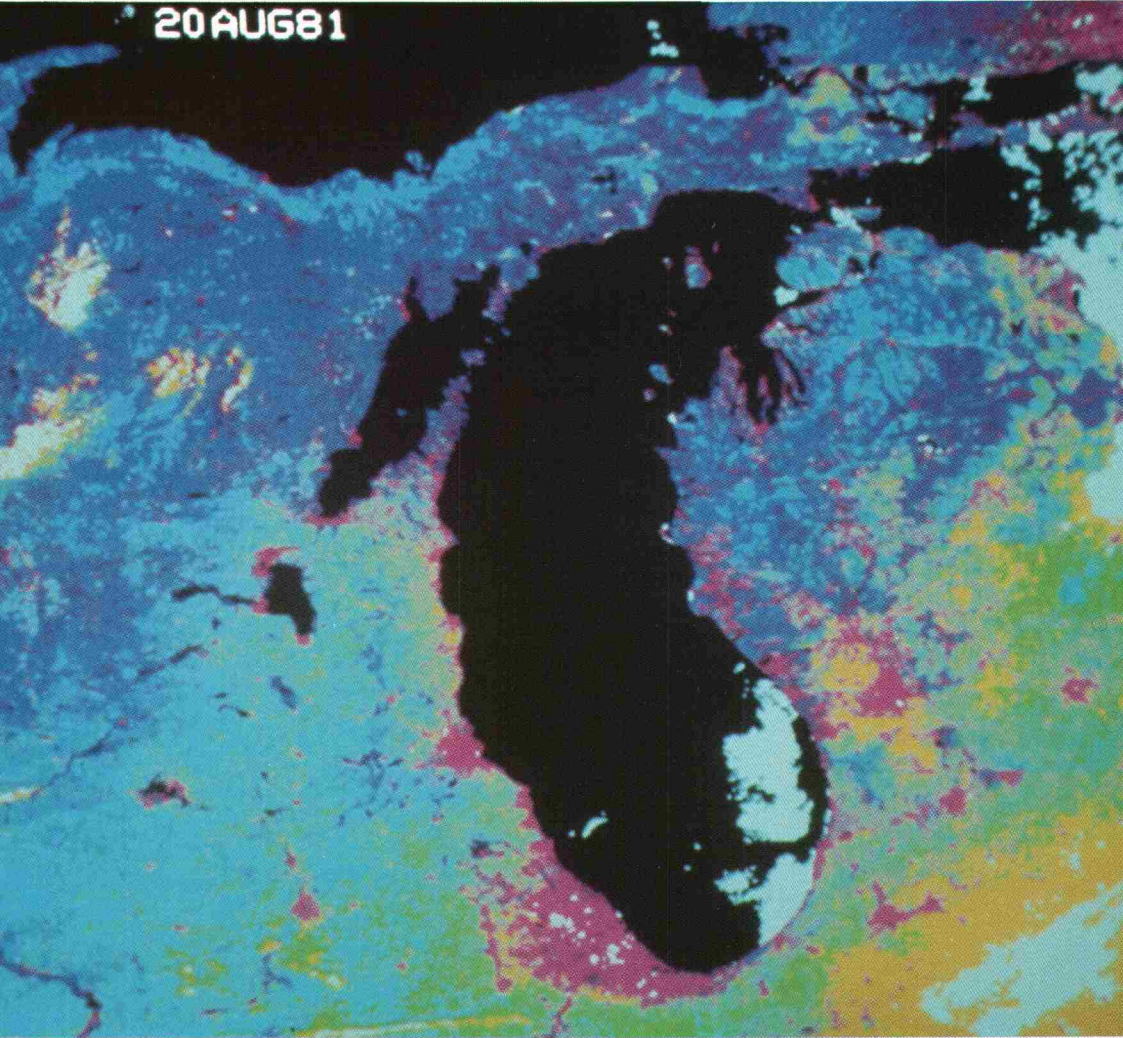
FIGURE 2.2 AVHRR sensor scene showing boundaries of different ecosystems.

human activities. The interaction of several biogeochemical cycles and between these cycles and climate may also have important, yet poorly understood, effects.

For example, consider the interactions between carbon and nitrogen. In addition to adding carbon dioxide to the atmosphere, the burning of fossil fuels releases large amounts of nitrogen oxides. Some of this nitrogen becomes available to biota through precipitation. There is some debate as to whether this could stimulate carbon fixation and carbon storage.

Wood harvests can reduce the biotic storage not only of carbon but also of nitrogen, phosphorus, and other chemical elements. Nitrogen is lost through harvest-accelerated erosion, through denitrification (the conversion of organic nitrogen to molecular nitrogen), and through export of inorganic nitrogen in streams draining cutover areas.

The problems associated with carbon-nitrogen interaction may be important over long time scales. It has been estimated that nitrogen is lost from the ocean by denitrification at a rate of approximately 10^{14} g/yr, enough to deplete the oceanic nitrogen reservoir $(8 \times 10^{17}$ g) within 10^4 years. Nitrogen is added to the ocean through a combination of runoff from land, input from rain, and in situ biological fixation. It is of interest to document whether the imbalance is real, and if so, to explain how the nitrogen content of the ocean is replenished. One hypothesis is that erosion during glaciation periodically might add significant nitrogen to the ocean through transport of soil and runoff.

Phosphorus is essential for growth, but is often unavailable to the biota, and therefore can affect the carbon and nitrogen cycle. Phosphorus is nonvolatile, and only minor amounts are transported—as dust—through the atmosphere. Phosphorus occurs in relatively insoluble forms that limit its availability to organisms in soils, rivers, and oceans.

Human activity has altered the availability of phosphorus. The application of phosphorus fertilizer has increased its availability in some regions. Fire, either natural or as a management technique,may increase the availability of phosphorus, since oxidation of plant litter transforms organically bound phosphorus into more available forms. Increased phosphorus can, in turn, increase nitrogen availability in soils.

Sulfur is an essential nutrient for all organisms, and the study of the sulfur cycle should be part of the first decade of research.

Emissions of gaseous sulfur to the atmosphere from fossil fuel combustion may be equal to releases from natural systems.

The study of biogeochemical cycles raises a number of questions:

- What is the present state of the major biogeochemical cycles?
- What was their state prior to anthropogenic perturbations?
- What are the perturbations (anthropogenic and natural)?
- What may be the future state?
- What are the likely results of these future states?
- What must be known to permit us to reverse or stabilize trends if and when this becomes desirable?

The History of Ecosystem and Biosphere Research

To date, only a small portion of the scientific community has engaged in ecosystem or biosphere research. The recognition that life greatly influences the atmosphere, oceans, and solid surfaces developed during the twentieth century. In the 1950s, the importance of the biota in maintaining the atmosphere far from a thermodynamic steady state with the oceans and solid surfaces was identified. Much of the motivation to study the biosphere has come from a concern with the impact of industrial civilization on the biosphere, especially with the effects of atomic bomb testing, burning fossil fuels, and the worldwide spread of pollutants, including acid rain. In 1936, the first suggestion was made that the difference between nineteenth- and twentieth-century measurements of the carbon dioxide content of the atmosphere could be accounted for by the burning of fossil fuel, thus stimulating a debate that is still continuing over the fate of anthropogenically produced carbon dioxide. Theoretical models of the carbon dioxide cycle have always been central to this debate. Until recently, however, models of the biogeochemistry of carbon ignored the possibility of variations in atmospheric and ocean circulation, so that the biogeochemical models were uncoupled from models of atmospheric circulation and ocean circulation, and models of temporal changes were uncoupled from models of spatial variation.

In the last two decades, the global impact of many activities of technological civilization have stimulated interest in the biosphere, including the acid rain issue, the potential depletion of

atmospheric ozone by various processes, and the worldwide spread of chemical and radioactive toxins, such as DDT and fallout from nuclear explosions. Since the mid-1970s, there have been numerous reports on the major biogeochemical cycles. Although valuable, these analyses have been limited by the lack of a sufficient fundamental understanding of the interactions among the elements of the biosphere.

RESEARCH NEEDS

The Role of Remote Sensing

Ecological theory is today in its youth. Although progress has been made, ecosystem models have been severely limited. Data generally have been obtained sporadically and over heterogeneous and often barely accessible areas. Thus, the data on which models have been based are at best rudimentary, especially in regard to large spatial scales and spatial variation. Although much information on local settings is often available, the data have rarely been integrated into global models that achieve description accuracy or predictive reliability.

Remote sensing permits data to be obtained from locations that cannot be studied in any other way for reasons of inaccessibility, distance, prohibitive expense, and social unrest. Remote sensing allows data to be obtained from points too numerous to be studied by any existing ground methods. For example, inferences concerning soil moisture, acidity, salinity, and other conditions can be made from the nature of remotely sensed ground cover of forests. Remote sensing also allows one to obtain measurements of important transitory events, such as floods, fires, and flowering and fruiting times. Such measurements often cannot be obtained at all by ground-based methods.

A most impressive and extensive study undertaken applying remote sensing to land vegetation in the grasslands of the midregion of the United States and several other selected sites was the Large Area Crop Inventory Experiment (LACIE). Only a single major species (wheat, *Triticum aestivum*) was censused and monitored through the season by Landsat, and other attempts were made to predict the amount of edible products of its photosynthesis. Both the powers and the limitations of the Landsat satellite methods were revealed. The ability to obtain, relay, and process

data about a dominant species quickly in a grassland ecosystem of large area and great economic importance was demonstrated without doubt. If the powerful tools, techniques, and expert personnel of the LACIE program were applied to basic scientific problems of ecosystem description, our understanding of the role of natural terrestrial ecosystems in the biosphere would advance rapidly.

Present studies of marine ecosystems rely primarily on fixed buoys or shipboard sampling to support the counting of organisms, measurement of chlorophyll, nutrients, temperatures, and other factors, such as effects of water density gradients, eddies, and storms of importance to oceanic productivity. Oceanographic vessels are enormously costly in time and money and slow in sampling rate. Furthermore, they provide limited samples, and sampling schemes are determined by the ship's course. It often is impossible to sample at the time of most interest, for example, to study storm-related events of significance to plankton distribution and fisheries research. Often, the distribution of organisms changes at a rate that is similar to or even faster than that of the sampling period. Coverage by remote sensing can help to solve some of these problems. Continuous coverage over time even for a restricted range of factors, such as chlorophyll water temperature, and turbulence, will allow examination of poorly understood phenomena.

The phytoplankton populations in large patches in the southern oceans provide an example of the potential for remote sensing to obtain data otherwise unobtainable. Measurements of the distribution, abundance, and temporal changes of the phytoplankton patches by ships or fixed. stations have been expensive and inadequate. Estimates of the annual production of krill presumed to relate directly to the quantity of phytoplankton suggest that the krill populations contain more edible protein than the total catch of the world's commercial fisheries. However, little is known about their numbers, patch size, or how rapidly they change in abundance.

The Need for Coordination of Data Sets

The scientific information already obtained, for example by LACIE and by conventional ecosystem projects, is in need of coordination, interpretation, and standardization of units of measurement. For example, understanding water and organism transport is critical

to the recognition of aquatic ecosystems and description of their productivity.

The detailed applications of remote sensing to ecosystem analysis will require further study and the development of a set of priorities. These priorities must take into account the capabilities of remote sensing in terms of the extent, depth, and timing of the sampling and the acquisition of an amount of data that can be processed effectively.

Satellite remote sensing permits for the first time the generation of globally consistent data sets from which spatial and temporal ecological information can be derived. In this form, these data can be utilized for ecological modeling.

3.
PERSPECTIVES ON
THE BIOSPHERE

HISTORICAL PERSPECTIVES

Introduction

How the Earth has developed and maintained the biospheric system that differentiates it from all other bodies in the solar system is one of the most intellectually exciting questions imaginable. The biosphere and evolution influence each other. The study of the biosphere offers a new perspective on evolution. For example, the fossil record indicates that the biosphere has been subject to major occasional pertubations, some of which were the result of biological evolution.

Table 3.1 lists a number of sources of biospheric perturbation. Many of the events noted, especially the biological ones, are historically unique, changing the biosphere in a unidirectional way that must have required adjustments in many components of the system.

Processes controlling biogeochemical cycles have changed through time. The history of these cycles must be taken into account in explaining the global distributions of elements. An obvious example is the stores of fossil fuel, most of which accumulated during the Paleozoic. A less obvious example is the pool of nutrients in living biomass and its depletion through the conversion of forest to cropland.

TABLE 3.1 Causes of Biospheric Perturbations in Earth History

A. Biological innovations perturbing the biosphere
1. Origin of life
2. Origin of photosynthesis
3. Origin of aerobic photosynthesis
4. Origin of aerobic respiration
5. Origins of other biogeochemically important metabolisms
6. Origin of eukaryotic organisms
7. Orgin of calcium-containing skeletons
8. Origin and expansion of bioturbating organisms
9. The colonization of land by plants and animals
10. The evolution of angiosperms
11. The evolution of humans

B. Abiotic perturbations
1. Extraterrestrial perturbations
   a. Changes in solar luminosity
   b. Impact on the Earth of such bodies as asteroids and comets
2. Crustal changes
   a. Major tectonic change at the Archean/Proterozoic transition (the growth of large continents)
   b. Variation through time in volcanism
   c. Plate tectonic changes altering continental geographies, topography, and ocean circulation
3. Climatic change, principally glaciations
4. Sea level changes (related to 2 and 3)

All of the biogeochemical cycles were affected by the massive changes in vegetation and climate that occurred repeatedly during the Quaternary period (the last 2 million years). It is now believed that there were 18 glacial-interglacial cycles during the Pleistocene. During each of the glacial phases, major changes took place in the pattern of ocean circulation, affecting the generation of deep ocean water at high latitudes, the transfer of heat from the equator to the poles, and the exchange rate of water between the Pacific and Atlantic basins. New data indicate the carbon dioxide concentration in the atmosphere declined, perhaps by as much as 50 percent, perhaps because of increased ocean mixing rates, although other explanations involving the biosphere have not been ruled out. Calculation of an overall carbon budget, especially one that includes the lag in equilibration of ocean and atmosphere, must include glacial as well as interglacial phases.

A justification for the study of the past is the prediction of the future. The climate is changing now, and it may be possible to predict the trajectory of climatic changes in centuries to come. The

reactions of physical and biotic processes to these future climatic changes can be guessed at from biotic responses to climatic events in the past.

Biological Innovations

Biological evolution has changed the Earth: radically new forms of life and new sets of organisms that are capable of new chemical reactions, inhabiting new regions, or feeding in new ways are innovations that have altered the biosphere. Thus, natural selection must be considered within the context of global ecology.

Biological innovations that have affected biogeochemical cycles include the origin of life; the origin of photosynthesis and respiration; the origin of certain metabolisms, such as sulfate reduction, nitrogen fixation, and denitrification; the origin of calcium-containing skeletons; the origin and expansion of bioturbating organisms; the colonization of land by plants and animals; the origin of angiosperms and of humans. The evolutionary events may have had effects on the biosphere similar in magnitude to abiotic perturbations, such as changes in solar luminosity or collisions with asteroids or comets, crustal changes, such as the growth of large continents, plate tectonic changes, variations in volcanism, orbital changes that affected solar inputs to different parts of the globe, and associated changes in climate and sea level. Many of these perturbations are historically unique, and changed the biosphere in a unidirectional way.

What was the biosphere like prior to each event, and how (if at all) was it different afterward? Beginning with a model for the present biosphere, one can subtract components to arrive at a retrospective prediction of biospheric dynamics prior to a given event. In this way, it may be possible to strip away components of the model until one arrives at a conceptualization of the biosphere of the primitive Earth. Such modeling can be constrained by the geological record. More rigorously quantitative models of the biosphere will enable geologists and geochemists to ask better questions about the earlier Earth.

Early in our planet's history, the foundations of the modern biosphere were established through an intimately interrelated series of changes in the physical and biological Earth.

A few examples illustrate the historical interrelationship of the crust, atmosphere, hydrosphere, and biota. The first concerns the influence of tectonics on the biota. Tectonic changes across the Archean/Proterozoic transition involving the growth of large continents resulted in major changes in the biosphere. Late Paleozoic changes in continental configurations, oceanic circulation, and glaciations caused the burial of organic carbon as coal. The second concerns the influence of the biota on the atmosphere. The biological production of oxygen led to an increase in atmospheric oxygen concentration, and made aerobic respiration possible. This changed the rates and efficiency of organic production and decomposition, and set the stage both physiologically and environmentally for the evolution of the eukaryotic cell.

These examples bring us to another justification for the study of the past: historical perturbations often can be used as major biospheric experiments, in which one factor influencing biogeochemical cycles is changed, thereby altering the system. These changes provide us with information that can be obtained in no other way, either because the experiment is too massive, too expensive, or too dangerous to perform in the modern world, or because the time scale of the experiment exceeds the time scale of human observation.

As a brief example, one can cite the evolution of oxygenic photosynthesis. The biological production of oxygen altered geochemical cycles by changing the rates and sites of mineral weathering and organic decomposition. Interestingly, there is little evidence for a significant increase in the partial pressure of oxygen in the Earth's atmosphere until several hundred million years after the first evidence of photosynthesis. It may well be that global biological productivity was limited at that time to rates equal to or below those of oxygen consumption for tectonic reasons. The rapid growth and stabilization of continental crust at the close of the Archean eon promoted increased primary production. This appears to be, at least in part, a result of an increase in the area available for colonization by benthic blue-green bacteria (*Cyanobacteria*), a concomitant increase in the rate of nutrient influx from continental weathering into the oceans, and a significant increase in surface ocean nutrients supplied to the photic zone (the upper zone of the oceans where light is bright enough for photosynthesis) by upwelling. This example suggests that continental

changes caused biological changes that in turn altered the composition of the atmosphere. The earliest records of an oxygen-rich atmosphere coincide with the first sedimentary rocks deposited on the margins of large continents.

Historical Reconstruction

The Pleistocene

Studies of global biogeochemical cycles raise two important questions: are these cycles at steady state at present? Were they at steady state prior to major anthropogenic perturbations? Currently, the Earth is experiencing an interglacial climate, typical of short (10,000 to 15,000 years) intervals that have returned at approximately 100,000 year intervals throughout the last 2 million years. The remaining 90 percent of the time, the Earth was generally colder than today. The typical condition in the recent geological past was thus very different from the global condition now available for study. There are lags in the equilibration of major sinks and sources for the major elements. This means that some major components of the biosphere may not yet have reached equilibrium since the most recent glacial perturbation.

It has been suggested that fluxes of phosphorous and fixed nitrogen to the oceans were appreciably higher during the glacial maximum when sea level was lower and land materials were eroding more rapidly. Increased nutrient supplies to the ocean may have supported higher levels of marine biological productivity. Net losses of nitrogen from the ocean through denitrification that are postulated from recent measurements may represent a disequilibrium condition as the nitrogen pool in the ocean oscillates between glacial and interglacial levels.

On the land, lags in the response of vegetation to climate change resulted in almost continuous flux in the species composition of vegetation communities throughout the Holocene. Even major biomes, such as temperate zone deciduous forests, may have lagged behind climatic change, advancing slowly onto deglaciated territory limited to a smaller area by the slow speed at which trees can disperse seed and become established in new habitats. For example, American Chestnut trees did not reach their present northern extent until about 2000 years ago, although the appropriate climate for them had existed for at least 5000 years. This

raises the possibility that the productivity of terrestrial vegetation during the first few millennia of the Holocene was lower than the maximum. Even longer lags might occur in the accumulation of organic matter in soils. These should also be taken into account in considering the rate with which a steady state can be achieved within the biosphere following a major environment perturbation.

More accurate information on the relationship of terrestrial vegetation and terrestrial productivity and biomass to climate will have particular application to studies of the distribution of vegetation during the glacial intervals. Estimates of biomass and productivity when vegetation was differently distributed from the present are needed to understand the distribution of carbon reservoirs during the glacial ages and to explain the change in carbon dioxide concentrations in the atmosphere during the last glacial period.

We need more information on historical changes in the carbon, nitrogen, phosphorus, and sulfur cycles. For this purpose, additional attention should be given to chemical studies of ice cores, particularly to detailed studies that provide information on fluxes of materials to the ice surface and that date precisely the speed with which changes in fluxes occurred.

Additional studies of marine cores should be undertaken to study the transfer of materials from the continents to the ocean, especially the transfer to the shelf and from the shelf to the continental slope. A concentrated effort should be made to reconstruct the environment on the exposed shelves during the glacial maximum. Estimates of productivity in the oceans during the glacial periods are essential. These should be compared with estimates of land productivity, based on improved maps of land vegetation during the glacial period. The latter should be based on increased numbers of studies of plant fossils, especially pollen, in sediments. An effort should be made to obtain greater numbers of long sedimentary sequences that extend through the last glacial period to the preceding interglacial. Exploration for glacial-age sediments should be expanded, with particular attention to the tropics and to continental areas that are largely unexplored, such as South America and Asia.

Research to date has focused on the Holocene (last 10,000 years) and on the last glacial maximum (18,000 to 20,000 years). These time intervals represent extreme conditions of minimum and maximum ice volume, but together they make up only 12

percent of the last glacial-interglacial cycle. During a much longer interval in the early Wisconsin, glaciation was intermediate, with oscillating sea level and glacier volume. Although the evidence is fragmentary, long cores from continental areas suggest very rapid changes in vegetation distribution, and studies of marine cores and raised coral terraces have similarly suggested rapid changes in ice volume. A high priority should be given to increased understanding of biogeochemical fluxes, climatic changes, and the interrelated changes in land and marine biota during the early Wisconsin.

For much of the time during the Quaternary period, conditions were outside our range of experience, based as it is on the Holocene. To understand climatic conditions, glaciation, ocean circulation patterns, and biogeochemical events, models may be the only practical approach. Improved mathematical models of the atmosphere and ocean, which take biogeochemical fluxes and feedback effects into account, are needed to reconstruct the changes that occurred during the Pleistocene and to relate them to present biogeochemical conditions.

The Cretaceous

On a longer time scale, the Cretaceous period (about 100 million years ago—Table 3.2) has been an interval of great interest to geologists and paleontologists because of its warm climate (characterized by unusually low latitudinal temperature gradients), periodically anoxic ocean bottoms (the source of much of the world's petroleum), orogenic activity, and distinctive biota. The Cretaceous is a period for which much paleogeographic, paleoecological, and paleoclimatological information exists. It is also a period whose known history poses numerous biological and ecological problems and whose solutions may best be approached by modeling aspects of the Cretaceous biosphere. An interdisciplinary working group (perhaps modeled on the Precambrian Paleobiological Research Group) should be formed to synthesize relevant, geological, ecological, and climatic information into a coherent picture of a past biosphere. Another time interval of interest is the late Eocene epoch (approximately 50 million years ago), which might be an easier biosphere to reconstruct. Its climate was as warm as the Cretaceous, but its biota appear more similar to those of the present than to those of the Cretaceous.

TABLE 3.2 Geologic Time Scale

Era	Approximate Age in Millions of Years (Radioactivity)	Period (System)
		Recent (Holocene)
	2	Pleistocene
	6	
	25	
Cenozoic	36	Tertiary
	58	
	65	
		Cretaceous
	135	
Mesozoic		Jurassic
	181	Triassic
	220–230	Permian
Paleozoic	280	Pennsylvanian
	345	Mississippian
	405	Devonian
	425	Silurian
	500	Ordovician
Proterozoic	570–600	Cambrian
	680	Vendian
	900	Riphean
	1300	
Early Proterozoic	2000	OXYGENIC CRISES
	2800	Stramatolites
Archean	3500	Earliest autotrophs
	3800	Oldest terrestrial
Hadean	4000	rocks

If we could generate models for both the Eocene and the Cretaceous biospheres, we could attempt to make the system evolve from one to the other, and thereby examine the long-term biogeochemical consequences of the Cretaceous-Tertiary boundary extinctions.

The Late Proterozoic

It is important to examine the early developmental history of the biosphere, one order of magnitude further back in time. The late Proterozoic era (specifically the so-called Sturtian or late Riphean period, approximately 700 to 800 million years ago) constitutes an excellent focus for biospheric research because it represents the Earth just prior to the development of multicellular plants

and animals. It is a period for which a great deal of geological, geophysical, and geochemical data exist. Phosphorites have an unusually wide distribution in sedimentary rocks of this age, and planktonic microfossils record a dramatic radiation among the eukaryotic phytoplankton. We have extensive knowledge of both planktonic and benthic microbial communities from this period, and these biotas have good analogs in restricted areas of the present Earth. In short, the Late Proterozoic record offers us our best opportunity to understand a Precambrian biosphere. Again, a working group of geologists, paleontologists, geochemists, phytoplankton and microbial ecologists, and theorists should be constituted to examine this most interesting and evolutionarily significant period.

The Archean Eon

The earliest available record of biosphere development is contained in rocks of the Archean eon (3800 to 2500 million years ago (Ma)). It was during this period that the anaerobic metabolism fundamental to modern geochemical cycles evolved. Much of the available data on the Archean Earth have recently been synthesized by the Precambrian Paleobiological Working Group, but it is clear that this preliminary understanding could be tremendously augmented and refined by increased ecological research on modern anaerobic environments coupled with a theoretical, modeling approach to present and past biospheres advocated in this document. Inquiries into the natures of Archean and late Proterozoic biospheres provide a direct connection to NASA's existing program in exobiology.

In summary, the view of Earth history as a series of global experiments run through time has the potential to contribute significantly to our understanding of both the present biosphere and the paths by which it came to its present state. Consideration of the Earth's past should be incorporated as an integral part of any research effort in global ecology.

THEORY AND GLOBAL BIOLOGY

Global biogeochemistry cycles involve systems of enormous complexity. Given only chemical and physical constraints, one can imagine life persisting on rather small and simple scales. One can imagine a living system containing only two species in which

individuals of one convert radiant energy to chemical energy and small compounds to macromolecules required for growth, while individuals of the other would transform these large molecules to small recyclable compounds. However, the biosphere includes between 3 and 10 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, ecological communities show temporal heterogeneities involving changes at time intervals that range from minutes to thousands of years. A system of such complexity can only be studied through the intermediary of mathematical models.

Thus far, the most advanced work in modeling biogeochemical cycles has dealt with the carbon cycle. These models have tended to be aggregated into comparatively small numbers of global-scale, well-mixed reservoirs with first-order kinetics and no interaction among chemical elements.

The immediate need is for conceptually clear models of the global cycles that include an initial state, perturbations, and the effects of elemental interactions on the cycles. This should be followed by the development of a collection of models that range from one based on mechanisms of elemental interaction to large-scale spatial distribution and temporal dynamics of biomes. These models should be used to test our understanding of the sensitivity of the biosphere to various alterations and to explore theories of how the biosphere functions on both a large and a small scale.

Thus, an adequate approach to a theory of a global cycle will require globally aggregated models, globally disaggregated models, and mechanistic models.

Development of globally disaggregated models, even with only simple causalities, will be paced by the continued development of new data. More aggregated models could begin immediately, though the inclusion of complex causality will be paced by expanding understanding of the processes involved.

Simple Causalities

The simplest class of models involves element abundances (budgets) that are static (i.e., in a steady state). Such models are useful in developing the magnitude of biogeochemical cycles of components and the pathways connecting them. Not even those simple models can be made accurate and realistic at present since there are numerous major uncertainties in the budgets of all elements. Such static budgets cannot describe transient responses to perturbations. Thus, more complex models will be required, probably involving nonlinear processes.

Models that incorporate spatial patterns should be used to capture differences in rates and effects of perturbations on different parts of the biosphere. For instance, different systems have had different histories and the response of land ecosystems to disturbances, such as forest clearing or acid rain, will vary significantly among different types of ecosystems.

Initially, the program should focus upon change rather than an inventory. It should be easier to measure areas undergoing change than to inventory the entire stock of the Earth's vegetation. Such global inventories will be necessary, however, for later models that will consider disequilibrium dynamics and deal with total (not simple net) fluxes.

Linked Causalities

Theoretical advances in planetary biology require the modeling of linked global cycles. Global biogeochemistry involves a large number of interrelated processes. Such highly interconnected networks exhibit system properties that cannot be predicted from a knowledge of subsystem dynamics. Therefore, global studies will require system models to integrate the findings of more specific investigations.

The present state of our understanding delineates the major spatial compartments that must be considered and some information on the flux pathways and rates. We can also divide biophysical processes into oxidation-reduction reactions within the compartments and transport between compartments. Some processes, such as photosynthesis, are not possible without the direct participation of living organisms. Other are kinetically limited unless catalyzed by organisms.

Positive Feedback in
Global Biogeochemistry

Unlike the perspective we gain when we view life as a collection of organisms, the global perspective reveals the biosphere as a complex, hierarchical system composed of many positive feedback loops with constraints formed by interrelated biogeochemical cycles. This perspective introduces new and exciting theoretical problems that must be solved before we will understand life on this planet.

At the global scale, the "environment" is constantly changing on long time scales, and biotic systems are continuously moving away from previous states and toward new states appropriate to the changing conditions. Once initiated, these processes tend to move the biosphere unidirectionally toward new states. Since, over geological time, the constraints change and the ecological system moves to new states, the biosphere seems to be less a stable, negative feedback system and more a positive feedback system.

In contrast to this perspective forced on us by a global point of view, ecological theory has assumed that the biotic systems at local scales are stable entities that resist or react to changes in a relatively constant environment. Thus, attention has focused on controls that permitted the system to return to its initial state following perturbation.

Current concepts of the origin of life are consistent with this perception of the biosphere. Early living forms produced oxygen, changing the atmosphere from reducing to oxidating, and preventing the de novo production of further living forms. A constraint on the system was changed, and it moved to a new set of operating states.

There are numerous examples of positive feedback loops at the global level. As a glacier advances, the snow and ice surface changes the albedo, further cooling the atmosphere and encouraging advance of the ice. The same is true of erosion cycles in which removal of vegetation facilitates removal of soil and encourages the further loss of vegetation.

The importance of positive feedbacks to an ecological system is also seen in the process of desertification. Removal of vegetation through human activities, such as overgrazing, reduces the amount of moisture returned to the air through evapotranspiration. Decreased moisture in the air reduces local rainfall, resulting

in further removal of vegetation. Once the positive feedback cycle is begun, the area is turned into desert.

It is customary in ecology to view population growth as a positive process (reproduction) balanced against a negative feedback (carrying capacity). In fact, the negative feedback is an artifact of the scale on which we viewed the process. Population growth is a positive feedback system (reproduction) that proceeds until a constraint is met, such as limited food resources. It may be that the concept of positive feedbacks with constraints is a better paradigm for examining ecological processes at all levels of resolution. It may be that viewing ecological processes at the global scale is the most reliable guide for developing paradigms applicable to ecological processes at all levels of resolution.

Systems composed largely, though not exclusively, of positive feedback loops are inherently unstable. They have not been well studied. The dynamics and general properties of such systems are not well understood, and considerable theoretical development is called for.

The unique properties of such a system can be seen by considering how it responds to a change in the concentration of a pool or compartment. In most cases, the system would respond by returning the pool to its previous level. But if the pool serves as a constraint on other processes (e.g., nitrogen limiting carbon fixation), then the system may respond unstably, moving the entire system into a new operating state. The new state could not be predicted if the system is conceptualized as a negative feedback system.

A positive feedback system responds quite differently to different perturbations. It responds differently to a change in a pool size, a change in a rate process, and a change in a constraint. Particularly important might be the sensitivity of such a system to certain alterations. Since each component in the system constrains other processes, small changes can be rapidly amplified.

4.
TERRESTRIAL BIOSPHERE STUDIES

INTRODUCTION

It is not possible to understand the response of the biosphere to any major change without taking into account the effects of the land and the interactions between life on the land and the atmosphere. Terrestrial vegetation has a rapid interchange of carbon dioxide, oxygen, and water with the atmosphere. On a seasonal and annual basis, carbon dioxide exchange by terrestrial vegetation measurably affects the concentration of carbon dioxide in the atmosphere. The great importance of terrestrial vegetation to atmospheric gases is illustrated in Figures 4.1 and 4.2. Figure 4.1 shows the atmospheric concentration of carbon dioxide at Mauna Loa, Hawaii; Figure 4.2 shows this concentration measured at Antarctica. Both measures were made far from the predominant influences of the major land masses—the first in the central Pacific, the other in the only continent devoid of higher plant life. Both curves show an annual cycle that reflects the summer growth of green plants, the uptake of carbon dioxide by those plants, and the decrease in total atmospheric carbon dioxide as a result. However, the amplitude of the Antarctic variations is much smaller than that at Mauna Loa. This is a direct consequence of the considerable difference between the southern hemisphere and the northern hemisphere in land mass area and therefore vegetation. These figures illustrate that land vegetation can greatly affect short-term variations in the concentration of carbon dioxide in the atmosphere.
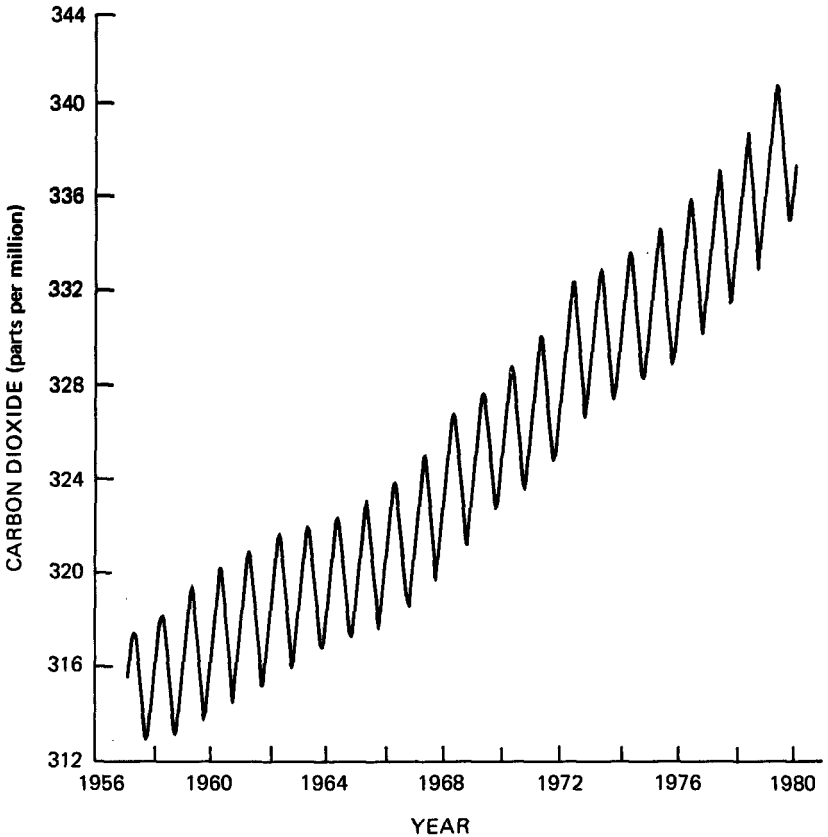
FIGURE 4.1 Changes in carbon dioxide concentration in the atmosphere at Mauna Loa, Hawaii.

Any major change in the abundance and kind of land vegetation could be expected to have effects on the atmosphere. Because atmospheric trace gases, such as carbon dioxide and others, produced and taken up by land vegetation, have important effects on climate, certain major changes in land vegetation can be expected to have a climatic impact.

For instance, roughly 70×10^{15} g C are fixed through terrestrial primary production and then respired each year by a complex pattern of vegetation and soils. The world-wide release of carbon from fossil fuel burning is approximately 5 to 8×10^{15} g C. Further human disturbance over the last 100 years of natural ecosystems, conversion of forest and grasslands to agriculture, and the harvest
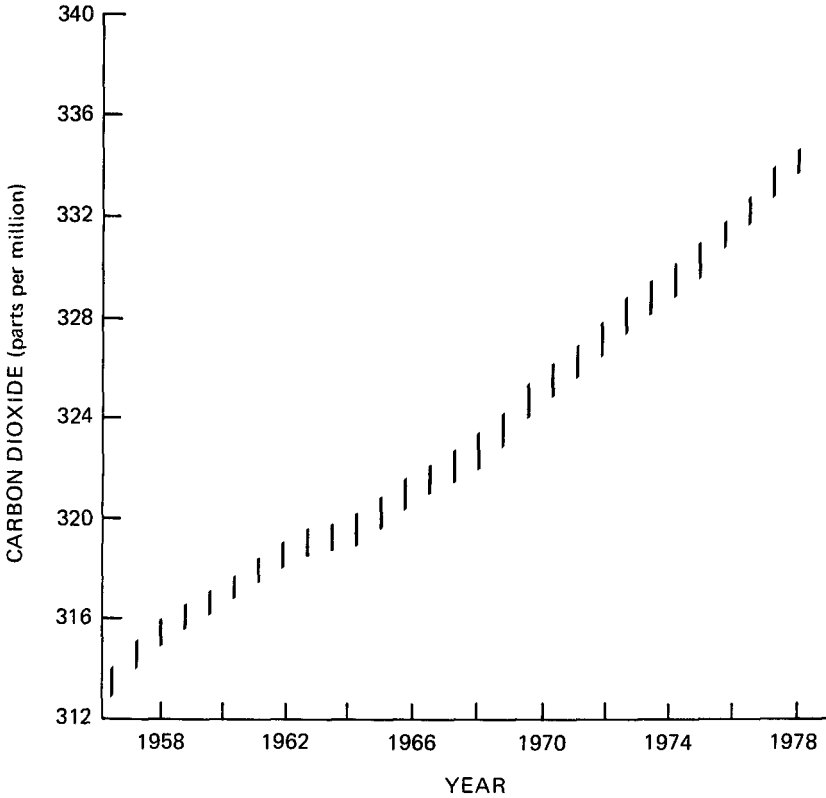
FIGURE 4.2 Changes in carbon dioxide concentration in the atmosphere in Antarctica.

of forests, may have reduced the vegetation and soil reservoirs by 150×10^{15} g C. This estimate is, itself, an important issue since a release of 150×10^{15} g C as carbon dioxide would constitute a contribution to the atmosphere that is 20 to 30 times greater than that due to fossil fuels. The principal uncertainty arises from the large disparity concerning rates of deforestation and recovery.

Changes in terrestrial vegetation can have long-term effects on the atmosphere. Terrestrial vegetation contains about as much carbon as the atmosphere; terrestrial soils contain about twice as much. Because trees are long-lived, and soils have the potential to store carbon for years, land is a major storage site for carbon in the biosphere. Forests, grasslands, savannahs, and other vegetation types respond to climatic change at different rates. Major

changes in climate will have complex, little understood effects on the distribution and abundance of land vegetation and its storage of carbon and other elements necessary for life.

Land vegetation also affects the global hydrological cycle. Terrestrial vegetation evaporates, on the average, two-thirds of the rainfall received. Removal of this vegetation from a single large region (e.g., tropical rain forests in the Americas) would greatly change regional atmospheric moisture. Models of global atmospheric circulation suggest that such regional changes can have complex effects on climate, such as increasing rainfall in some areas and decreasing it in others. In general, a major regional removal of vegetation could be expected to lead to a global increase in the Earth's surface temperature because of the loss in cooling effects of the evaporation of water from land vegetation.

Although it is obvious that terrestrial vegetation and the atmosphere are coupled, we do not yet have sufficient quantitative understanding to predict the effects that a specific change in one sphere (such as the harvest of tropical rain forest) will have on the other. Each affects the other on local, regional, and global scales. A global change in climate will affect vegetation, and a regional or global change in vegetation can have global effects on climate.

ENERGY BUDGET AND VEGETATION

Vegetation can affect the Earth's albedo and micrometeorology. Most of the understanding of these effects is based on small-scale studies, where radiometers are used to measure the ratio of incident to reflected light. We do not have good quantitative knowledge on a global scale. 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 need to refine the estimate of the Earth's reflectance. There is virtually no information on the change of reflectance due to changes in vegetation in the recent past, or during the entire Pleistocene. It must be emphasized that remote sensing from a space platform can improve the current areal estimate of vegetation types and hence serve to monitor possible changes of reflectance. Once the reflectance of particular vegetation types has been established, such measures are crucial to an understanding of the Earth's energy budget.

The effect of vegetation on regional climate has not been extensively studied. The only notable example is the recent study of the Sahel desert in Africa that 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 reflectance. This leads to a decrease in the radiative heating of the surface, and thus a cooler surface. Since cooler air tends to sink, this could suppress cumulus convection and its associated rainfall. Hence, the decrease of vegetation could result in a decrease in rainfall, setting up a positive feedback that would create more arid land unsuitable for vegetation. It has been suggested 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 contribute substantially to the "greenhouse effect." These, in order of importance, are carbon dioxide, ozone, methane, and nitrous oxide. The net effect of all these gases is to keep the atmosphere warmer than it otherwise would be. One primary practical concern in global ecology is the design of a strategy to counter the increase of atmospheric carbon dioxide 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. Increases of methane are much more efficient in absorbing solar radiation than is carbon dioxide. A large portion of methane is produced in marshes and swamps, which occupy only 2 percent 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.

REMOTE SENSING OF
AREAL EXTENT OF BIOMES

Vegetation Mapping

Ecologists have approached the study of land surface by classifying areas into broad categories, often defined by the dominant shapes (called "physiognomy") of major higher plants. Inasmuch as the dominant vegetation is an expression of environmental conditions, these vegetation maps are maps of biomes, including and reflecting variation in soils. An estimate of the world-wide land area covered by each biome is fundamental to our understanding of the effect of the biota in the surface chemistry of the Earth. The areal extent of each biome multiplied by the mass of vegetation and soil carbon (measured in carefully selected sample plots chosen as representative of these categories) yields an estimate of the size of the biotic pool of living and dead material in each category and ultimately the world. Using similar methods, the sizes of the pools of nitrogen, phosphorus, and so on, can be calculated for the above- and below-ground portions of land ecosystems.

Our current precision in making areal estimates is limited by inaccuracies in mapping (typically ± 100 percent) rather than by errors in measurements in the sample plots in the field (typically ± 20 percent). For example, one study found variations in the chemical content of sites in the temperate deciduous forest of 50 percent. Another study found variation in the soil carbon pool of temperate forests of 33 percent. There is effectively no strategy developed to extrapolate these data beyond the confines of the study plot. 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 x 10^8 ha), but variations in the areas of vegetation categories are much greater. Even within North America, our estimates of cultivated farmland vary widely.

Some of the variation in area is the result of different classification schemes used by different workers. Presumably, consistent definition of biomes would improve our estimates of their areal extent. Meaningful ecological regions are those that differ in the magnitude of their carbon and nutrient reservoirs, that differ in rates of net primary productivity, and that differ in probability of change. Stratification must be developed because the scale of the

planet makes impractical and unnecessary sampling at the same level of resolution over the entire surface of the Earth. Accurate assessment of areal extent of vegetation units is necessary to assess the sizes of reservoirs, while accurate mapping is necessary to assess rates of change in particular categories of ecological region. Sampling must be designed not only according to the probability of change but also according to the size of the change, and the length of time of the change that is detectable by instruments. There is little point in expending a larger amount of effort in appraising change in an area where there is no change or where a large change in the vegetation or soils could not affect carbon and nutrient storage appreciably.

While the initial definition of the different biome borders will be somewhat arbitrary due to a lack of detailed understanding of the variability of net primary production (NPP), the locations of the boundaries can be refined as the real variability becomes better known through a succession of joint satellite and ground observations. A preliminary activity will be the verification of the approach for delineating borders of different biomes, and, estimating the areal extent of landscape units from satellite remote sensing with minimal ground observations. The verification step will make use of land test sites selected in the various biomes. The initial work could make use of U.S. sites where detailed ground data are already available and where needed additional data can be readily collected.

It is expected that multispectral scanner (MSS) data already collected by Landsat and other sensors, such as the NOAA AVHRR, augmented by additional data collected in the future from the Thematic Mapper and AVHRR, will be the primary information for these estimates.

A sampling strategy should be developed initially on the basis of currently available knowledge together with satellite-acquired imagery. An initial stratification of the biomes can be made on a basis of the variability of the parameters that constitute NPP. Estimates of the variability of these parameters can to be derived from existing ground-based data, and from satellite remote sensing. As improved estimates of NPP become available, the biomes can be restratified; such an iterative process will lead to improved estimates on a planetary scale.

Estimating Disturbance Rates

Disturbance rates and rates of change in land use are even less well known than the areal extent of vegetation types. Agricultural land area data collected by national governments and international organizations represent the primary sources of synoptic data on land use and land clearing rates.

Controversy centers on rates of tropical deforestation. The difficulties in studying regional assessment are due in part to the methods of data acquisition. For example, the Food and Agricultural Organization (FAO) of the United Nations relies heavily on data reported by national governments. In many tropical countries, cutting and clearing data may be no more than informal estimates. Indonesia continues to report that its forest cover is estimated at 1,200,000 km², a figure that is 20 years old. The widespread logging, clearing for agriculture, and intensified shifting agriculture of the last 30 years is not represented.

However, a valuable new data set is slowly being formed. Within the past 5 years, a number of countries have published their own comprehensive and accurate surveys, mostly by using remotely sensed imagery. The results have been important: in the Philippines, these new estimates show only 38 percent forest cover as opposed to former estimates of 57 percent; Thailand now possesses 25 percent as compared to the 48 percent figure of earlier reports; forest in the Ivory Coast has diminished by more than one-third in 10 years. Many countries, such as Brazil and Indonesia, have also apparently instituted comprehensive remote sensing programs. These data are not generally available to outside investigators, and they have not been critically summarized. A final note: New estimates by FAO will be available soon for land use patterns that are based on remote sensing data and may be a considerable improvement on previous data sets.

MEASUREMENT OF NET PRIMARY PRODUCTION (NPP)

Natural Vegetation

Through the action of photosynthesis, the atmosphere of the Earth has become enriched in oxygen and impoverished in carbon dioxide. The excess of photosynthesis over respiration has led to a vast

store of carbon compounds in the sedimentary rocks on the Earth, including the fossil fuels that supply the needs of modern industrial society. The burning of fossil fuel is now returning carbon dioxide to the atmosphere at a faster rate than photosynthesis or mixing with the ocean can remove it, leading to a carbon dioxide buildup that may have serious and permanent consequences affecting the survival of life on the planet.

The carbon budget of the Earth must be understood in order to predict the future course of the carbon dioxide flux to the atmosphere, and if necessary (or possible), to take steps to reverse the trend.

Measurement of primary productivity is a first and fundamental step for calculating fluxes of oxygen and carbon dioxide. The estimate must be made on a world-wide basis to have any meaning.

In the oceans, estimates of productivity are made difficult by spatial and temporal variability. Technological innovations are permitting the calibration of spectral observations by satellites in terms of primary production, resulting in fine-scale observations of productivity in the variable near-shore environments where productivity is highest.

Net primary production will equal the rate of photosynthesis less respiration by all the plants in the system. The rate of photosynthesis depends mainly on the total abundance of leaves (leaf area index) and their utilization of available light, temperature, moisture, and nutrients. Respiration will be affected primarily by temperature and soil moisture, but will also differ markedly in stands of different ages and in different locations. Thus, for a given abundance of leaves, young vegetation colonizing a newly disturbed site will have lower respiration and greater net productivity than older vegetation that is no longer accumulating biomass.

Previous attempts to assess net production on a global basis have extrapolated measurements of production of local vegetation to the area of the globe occupied by similar vegetation. These attempts yielded widely varying results because of inaccuracies in mapping and because regional variations in the variables were not taken into account. The areal extent of major biomes, including cropland, is not known accurately.

A parallel program must be established for the terrestrial environment. Though the land biota are responsible for a much greater share of carbon fixation, estimates of productivity on a

global scale are still in a primitive state, preventing agreement on a world-wide carbon budget. The gross and net productivity of different ecosystems must be measured and their areal extent mapped, in order to evaluate the impact of widespread changes in land use currently in progress throughout the Earth, especially in the tropics, where human populations are expanding rapidly. For example, will the harvest of tropical rain forest now taking place result in a significant reduction in the pool of fixed carbon and thus to increased carbon dioxide in the atmosphere?

The improved remote sensing capabilities that are now available make accurate, more direct measurement of net primary production feasible for the first time. A combination of remote sensing and ground-based information, combined with computer modeling, can yield a relatively accurate measurement of net carbon dioxide uptake, a functional understanding of new productivity as related to climate, and improved areal mapping of vegetation that can be used for more accurate estimates of biomass.

Many of the variables that affect photosynthesis can be measured with existing technology. For example, existing geologic maps give a rough idea of nutrient availability. Temperature and precipitation are currently measured at a network of stations and could be measured more precisely in remote or mountainous regions by remote sensing. When coupled with satellite cloud cover measurements, accurate assessments of available light are attainable.

Leaf area index (LAI) is a measure of the ratio of leaf area (in square meters) per unit land area (in square meters). Several fundamental processes for land vegetation, such as evapotranspiration, photosynthesis, and energy
exchange, are directly proportional to LAI, at least within a single biome type and within a range of 2 to 7. Remote sensing experiments suggest that leaf area indices within this range can be measured from aircraft and orbiting satellites (Figure 4.3). Because LAI can be measured by remote sensing, it provides, for the first time, a means for assessing the photosynthetic potential of vegetation on a continental scale.

Examples of different vegetation zones that could test the capability to measure LAI on vegetation of different color, canopy geometry, and seasonal display include the following:

1. Boreal forests where LAI from 1 to 8 is reported.
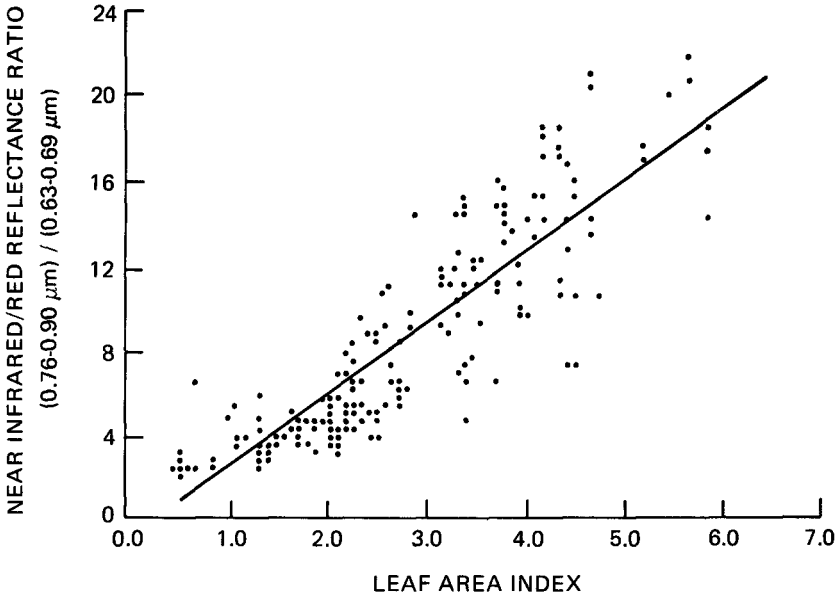
FIGURE 4.3 A plot of near-infrared/red reflectance ratio against leaf area index for corn plots of varying planting dates and population density.

2. Climatically steep gradients in the Pacific Northwest where LAIs of 1 to 15 are documented with similar ranges in net primary production.

3. Pure forests of Monterey pines planted extensively in differing age-classes and varying soils in New Zealand.

4. Deciduous forests of the eastern United States along a north-south gradient where canopies with similar leaf areas are active from 3 to more than 6 months.

5. Transition zones between short and tall grass prairies, as in the North American Konaz prairies.

6. Savannahs where there is a north-south gradient in the density of trees (e.g., the Serengeti).

7. Agricultural areas where a definite gradient in leaf area index is known.

8. Single-species forests, such as those that occur in Hawaii.

Analysis of these regional data should provide a test of the general approach. In some cases, ground verification measurements may be already available or could be obtained for canopy leaf area, net primary production,

and stand age and height. Standard methods for estimating forest leaf area can be accurate to within 10 percent.

It is critical to test this capability on areas of diverse vegetation, and demonstrate what accuracy is attainable. Given adequate accuracy, ecosystems within biomes could then be defined quantitatively by LAI, rather than by species type, and provide a more meaningful variable for study of material and energy exchange.

However, even present LAI is not a sufficient measure in itself of plant ecosystem dynamics. The LAI of a western coniferous forest may peak at a stand age of 30 years, while biomass will continue to accumulate for 200 years. Consequently, any measure of LAI alone will not necessarily provide a measure of NPP, standing or maximum biomass. In addition, any recently disturbed site may be carrying LAI much below potential maximum. Necessary data include the present LAI; the maximum LAI a site will support based on limitations of light, temperature, water, and nutrients; and the temporal trajectory between present and maximum LAI.

On moderate sites, maximum LAI may be reattained with 5 years of disturbance. Over this short time frame, maximum LAI could be attained merely by annual measurement until equilibrium is reached. On sites with a longer recovery time, maximum LAI may best be predicted from climatological analysis of the area. However, this may be difficult in that a global basis, maximum LAI may be limited by light, water, temperature, nutrients, or some combination of any or all four basic driving variables on any given site.

In the arid western United States, a site water balance can be used to predict maximum LAI of forests. In the moist, warm tropics, light penetration through multiple layers of canopy may ultimately limit LAI. Particularly in cold boreal climates, temperature limits vegetative development and LAI.

Relating LAI to Net Primary Productivity

Because LAI is a measure of the quantity of photosynthetic machinery available on a site, a close correlation between LAI and NPP would be predicted. For specific conditions, this correlation has been found (Figure 4.4). NPP has been found to increase linearly with LAI over a range from 0 to 7 in both corn and young Douglas fir. Above LAI = 7, as found in many coniferous
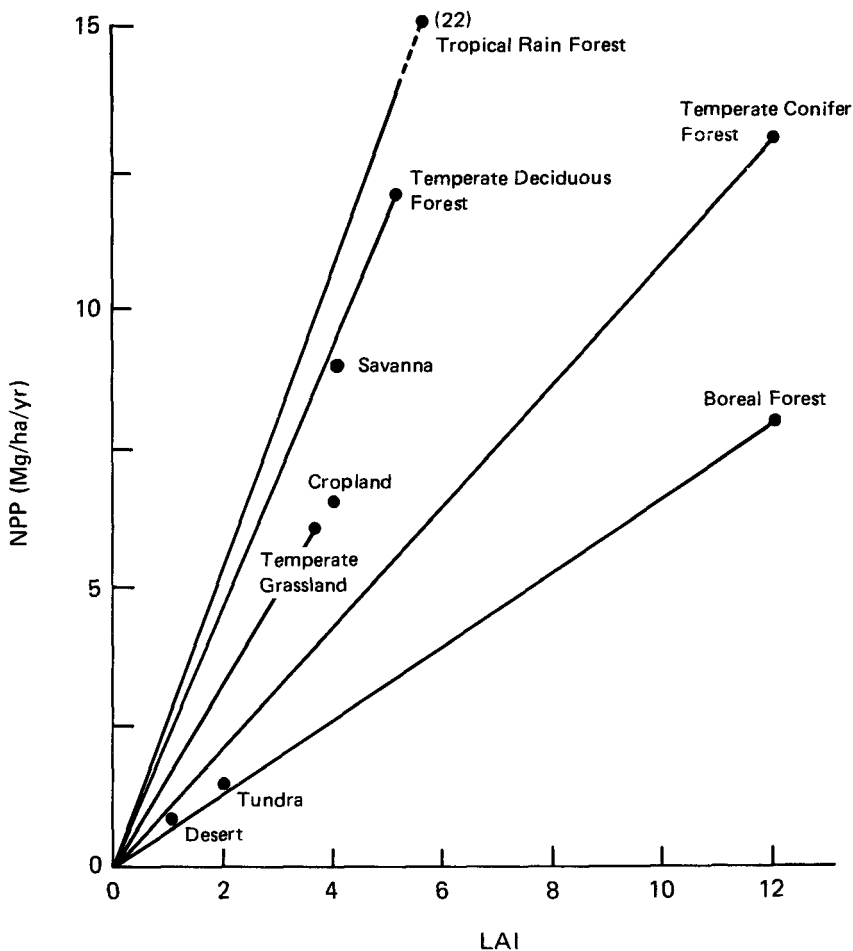
FIGURE 4.4   The average leaf area index (LAI) and net primary production (NPP) observed for different biome types worldwide. Differences in slope of the lines illustrate differing carbon uptake efficiencies of the vegetation types.

stands, NPP plateaus despite increasing LAI. Environmental controls may allow the site to carry higher LAI, but light limitations cause photosynthetic efficiency of the additional LAI to be low.

Because LAI is insufficient in itself to predict NPP over a wide variety of stand conditions and ages, additional information is required. Some empirical relationships have been developed from

field studies as previously cited. Additional field studies in different biomes over a range of environmental and stand developmental conditions could be done.

Of longer range value would be the construction of more mechanistic models relating NPP and LAI, possibly using process relationships developed during field studies. Specifically, photosynthesis-respiration (PSN-R) balances could be calculated on the basis of the climatic driving variables (carbon dioxide, light, temperature, water, and nutrients) known physiologically to control PSN and R. For a global analysis, PSN and R rates and controls could be generally represented at a subbiome level, ignoring species differences within the designated subbiome. Correlation estimates of NPP from global climatological analysis have been sufficiently successful to warrant continued pursuit, particularly when combined with advanced satellite measures of global meteorology and global distribution of LAI.

Predicted environmental driving variables would be necessary at a number of points in a global NPP estimate. First, as suggested above, calculation of the "carrying capacity" of LAI for a site would require environmental data. Second, adjustment of the empirical NPP/LAI ratio across different biomes would best be done from environmental correlations. Finally, a mechanistic approach involving modeling of the PSN-R balance and LAI development would require driving variables.

PSN-R has been modeled from the cellular to the ecosystem level, with most models working at a leaf to single-plant resolution. Modeling PSN-R at a subbiome resolution would call for significant extrapolation of current PSN models. However, the committee sees no more realistic basis to predict NPP on a global level.

In addition, this mechanistic approach to NPP prediction would allow us to attack questions such as: What global effects might volcanic activity or other major particulate input to the atmosphere have on NPP through decreasing incoming shortwave radiation? How would increasing global temperatures change NPP rates? How do changes in regional precipitation change NPP, desertification rates, and so on?

Cropland

Traditionally, crops are thought of as those plants we eat, but food, fiber, fuel, grazing, and building materials are, in the most general

sense, the uses to which we put terrestrial primary production. Barring some catastrophe, the current world human population of 4 billion may increase to 10 billion or more in the next 50 to 100 years. Such a population increase will force us to use our renewable resources efficiently and increase world food production. It will be necessary to improve food quality (the nutritional value) for this future population as well as to increase food quantities.

To feed the world's growing human population, it is necessary to maintain the continued fertility of existing soils and to decrease soil erosion rates. On a global basis, 10 to 20 percent of the total land surface (approximately 1.4 billion hectares) is currently cultivated for food crops. Estimates of additional land that can be brought into food crop production vary from 1 to 2 billion hectares.

With some 10 to 20 percent of the total land surface in agriculture and critically dependent on climate changes, it is important to better understand the interactions between the agricultural biomes and the other biomes of the biosphere. It is especially important to understand how future agricultural development will change the biogeochemical characteristics of these regions. As new land is brought into cultivation, there are significant alterations in such factors as average albedo and net primary productivity, which, in turn, will influence the energy balance, and biogeochemical cycles. The best agricultural soils exist at this time under good climates for agriculture. It is readily conceivable that a subtle change in the Earth's energy budget could shift the distribution of rainfall and temperature so that this would no longer be true.

Agricultural lands may have important effects on global elemental cycling, erosion, hydrology, and the atmosphere. These raise several questions:

- What are the effects of fertilization of large areas employing nutrients transported from outside a given region?
- What are the impacts on erosion of clearing large areas in the tropics for agricultural production?
- What are the cumulative implications on the hydrologic cycle of the mining groundwater for large-scale irrigation agriculture?
- What are the effects on albedo from the conversion of arid areas to irrigation agriculture?

In the long term (forecasting 10 years and longer), forecasts of crop production require the ability to project major climatic changes. In the short term (forecasting for a current year), we also need to know present and changing patterns of land use and vegetation growth.

Growth of land vegetation is most strongly correlated with sunlight, temperature, and rainfall regimes, and secondarily with soil and topography. In the oceans, economically important production of fish and shellfish correlates with areas of abundant nutrients. These areas change over time in response to climate, and with clearing of land and associated increases in transport of chemical elements from the land to the ocean (e.g., by glaciers, deforestation, and overgrazing).

Agricultural lands offer special opportunities to evaluate processes that operate slowly in other systems. On a global basis, most crops are planted, harvested, and consumed within a period of a few months. Crops also offer special opportunities to evaluate the effect of spatial scale on biospheric phenomena and on remote sensing imagery. There is a wide range in the size of agricultural fields. The same crop in the same physical condition, but produced under different cultural practices, can produce substantially different satellite image responses. Wide variations in response may also occur because of many variables found in crops within any one growing season, or even between or during sequential passes of the satellite. These variations can cause wide aberrations in the responses recorded in satellite imagery. Thus, effort should be directed toward calibration of remote sensing responses in relation to crop condition and yields.

Recent evidence suggests that we can no longer be certain of further dramatic increases in biological productivity in the near future. Present evidence suggests that the total area of good farmland is decreasing, soils continue to be degraded even on the best lands, prime farmlands are being converted to urban and other uses, acid rain and other pollutants are decreasing production, energy-intensive farming methods are becoming more expensive, and many soils or areas of production are near satuation from fertilization so that future production increases are unlikely. Of more significance perhaps is that global changes in climate can be expected to change temperature and, more ominously, to shift regions that have the best combinations of temperature and rainfall for crop production to those with poorer and even untillable

soils. With such concerns, it becomes increasingly important for a highly technical society to be able to forecast actual and potential crop production. Experience with the LACIE and AGRISTARS program suggests that this can be done.

An example of a current yield estimation method is the following:

• First, historical estimates of yield are examined from records. The five highest yields are averaged and taken as maximum potential production for that area.

• Imagery for the area under investigation is then acquired prior to traditional planting dates. Here, meteorological satellite data and weather status data are employed to estimate starting soil moisture conditions. Starting soil moisture is estimated from precipitation data derived from ground station reports, arcillary observations, and, to a lesser extent, satellite cloud cover data. Planting dates are obtained from either local reporting or other data sources.

• Once starting conditions have been estimated and planting has occurred, an agrometeorological model is used. Ground data, augmented by satellite data on temperature and cloud cover, are followed daily. These are used to either increase or decrease the estimated yield. Landsat data are employed during the growing season to modify the condition of the vegetation. The total area of a crop is obtained from published data and direct measurement from Landsat-type data.

Estimates of food production within a given season depend on the areal extent and geographic location of crop type, estimating its current condition, and forecasts of the remaining weather.

Landsat data, together with proper sampling procedures (2 percent of production region by area), can be used to reduce the uncertainty in acreage for harvest to a minimum. Landsat data, together with ground weather station data augmented by meteorological satellite data, gathered over time (three or four Landsat passes in the right time periods together with time averages of moisture and temperature) can be used in the monitoring process. Temporal profiles (time trajectories) derived from Landsat are important in the determination of the date of emergence and for estimating the times when a crop is at different states of development. Weather data, together with LAI derived from Landsat data, can then be used to estimate biological yield more accurately.

To be of optimal utility to global biology studies, crop yield information may need to be translated to a biogeochemical cycling perspective.

CLIMATIC INFLUENCES ON
NET PRIMARY PRODUCTION

Net primary production varies with climate, soil, and the state of the biota. NPP can be predicted from these. This approach requires the use of models of photosynthesis and respiration for the different vegetative types of biomes.

There are two approaches to obtaining spatially distributed measurements of the environmental variables. The first relies on a network of ground measurements; the second uses remote sensing. Remote sensing has the capability to provide significantly improved estimates of such critical variables as canopy temperature and soil moisture.

Canopy Temperatures

To use remote sensing to provide improved estimates of canopy temperatures, we need a better understanding of the effective emissivities for different vegetative types at their distinctly different stages of development. This requires a combined empirical measurement-modeling approach. A deduction of the "effective emissivities" for different units requires knowing or measuring their physical temperature and the output radiance to, say, 10.6 microns. This involves additional work at different test sites where temperatures are measured in the canopies and estimates of radiance are collected with remote sensors.

This initial research can make use of sensors on helicoptors or fixed-wing aircraft as well as from satellite sensors. As the technique is developed, it should be incorporated into a test program to verify the degree of improvement for parameter estimation. It is thought that such an approach utilizing ground calibration points could well provide significant improvements through an ability to have many more measurements over space and time and for required areas. Current ground meteorological data are often collected in towns, cities, airports, and so on, as opposed to rural regions of central interest. Also, these data are usually for valley

bottom or flat terrain and are not representative of the conditions in complex topography.

Soil Moisture

Conventional methods for obtaining surface moisture measurements tend to be expensive and/or time consuming to a degree that severely limits the quantities of the measurements. This, together with an understanding of the considerable variability that exists for surface and subsurface moisture over space and time, leads to a conclusion that this is a critical area of concern. Two approaches need to be explored. One involves the use of satellite remote sensing together with ground station reports to derive improved estimates of the amount and areal distribution of water precipitation. A second involves the use of satellite-acquired spectral data at optical and microwave wavebands. Both approaches tend to be limited to providing data about moisture on, at, or near the surface and require a modeling approach incorporating important physical properties of the surface and below-surface materials to derive estimates of moisture below the surface, i.e., down to vegetation root zone levels. Research conducted to date tends to show that in the absence of vegetative cover remotely sensed measurements (at 20-cm wavelengths) provide "reasonable" estimates of moisture in the first 5 cm of soil. Research is currently being directed at using remotely sensed optical measurements to account for the effects of vegetative cover. This approach needs to be critically analyzed for its capability for the different biomes with their distinctly different types of soils and vegetative covers. Again, if this technique is to be useful, it too will probably make use of ground calibration sites distributed at appropriate locations.

A third approach that is deserving of consideration involves the use of soil penetrator devices that can be deployed and can directly measure soil moisture, carbon dioxide flux, and temperature. This approach could provide an important source of data in conjunction with the other techniques.

Research Goals

One long-term (10-year) goal is the measurement for all major terrestrial biomes of biomass and net primary production with a

statistical error of less than 20 percent. To accomplish this, several stages in research are required.

First, we need to determine the extent to which techniques using LAI are accurate for a wide range of vegetation types, and the extent to which specific parameters from one site can be extrapolated to other sites. The first steps in this process involve transects across biomes and studies of variation within biomes. A transect of sites across the biomes in the United States (coniferous forest, deciduous forest, grassland, and cropland) could be established. A range of species compositions, environmental conditions, and stand ages would be desirable. Other studies should address the variation in LAI within a biome, examining variation in relationships at geographic extremes and determining the extent of within-site variation. Remotely sensed LAI could be validated on the ground with measured LAI on these diverse stands. Second, environmental conditions could be measured directly and prediction capability by satellite and permanent weather station extrapolation tested. Third, NPP could be measured and correlations between NPP, LAI, and environment developed. Fourth, predictions of NPP from mechanistic PSN-R models could be validated against these measured data. With the completion of these studies, methodology would be established, and extrapolation to globally similar biomes would be possible.

SPECIAL ROLES OF MICROBES IN TERRESTRIAL BIOGEOCHEMICAL CYCLING

There are two critical microbial activities that have a major effect on the biosphere: (1) gas production largely by anaerobic metabolism, which has profound effects on the atmosphere and (2) the conversion of large biopolymers to smaller, soluble ones.

Microbial Role in the Atmosphere

Most of the gases in the present atmosphere except those of the noble elements (neon, argon, helium, and krypton) are biological products under biological control. The exceptions are gases from volcanic outgassing, together with cosmic, photochemical, and electrical discharge inputs that represent a small percent of the total. Human activities have added new sources of inputs and

altered natural sources and sinks of the atmospheric gases. To understand the microbial contributions to the composition of the atmosphere, the factors that regulate the biological transformations of nitrogen and sulfur must be examined. Their contributions through the biodegradative activities are essential to the carbon cycle. Microbes provide unexpected inputs to the atmosphere; their metabolism is the source of some of the volatile halogenated hydrocarbons that affect the ozone concentration of the atmosphere.

Nitrogen is an element present in all proteins and nucleic acids and hence a nutrient on which life absolutely depends. Molecular nitrogen cannot be used by most organisms and must be converted to ammonia or nitrate. Only lightning, prokaryotic enzymatic activity, and sometimes human interruption carry out this conversion.

The ammonia release from microbial metabolism that accompanies the decay of organic matter is an important component of atmospheric aerosols. It is also the end product of protein metabolism in many microbes and animals. Ammonia is removed from the atmosphere photochemically and by rain where it modifies the activity of rainwater and hence affects organisms on the land.

Methane is almost entirely a product of microbial decomposition of organic matter by fermentation in anaerobic zones. Photochemical products in the methane oxidation chain include formaldehyde, carbon monoxide, hydrogen, and ozone. These gases also result from oxidation of the higher molecular weight hydrocarbons released into the atmosphere by higher plants and bacteria.

Carbon monoxide is released in significant quantities from internal combustion engines as well as from animals, plants, and bacteria. Carbon monoxide is utilized by specific aerobic bacteria—one of the few known terrestrial sinks for carbon monoxide.

Both hydrogen sulfide and sulfur dioxide are toxic to people. Hydrogen sulfide is produced by anaerobic bacteria from sulfate. It can be produced even from evaporite minerals, such as gypsum (calcium sulfate). Sulfur dioxide is produced from combustion of fossil fuels, such as coal, and is involved in the problem of acid rain.

Major sources of several other atmospheric gases, such as carbon disulfide, carbonyl sulfide, and dimethyl sulfide, are not

established. The relative importance of photochemistry, lightning, combustion, fossil fuel burning, and microbial metabolism in the production and removal of these gases has not been precisely determined.

Decomposition of Biopolymers and Carbon Storage

Through decomposition of polymers, microbes regulate the amount of stored organic carbon in soils and sediments. The rates of this decomposition are functions of biological and physicochemical conditions. Physicochemical conditions, such as the availability of trace nutrients, buffering against extremes of pH, water activity, temperature, and oxygen content, also regulate rates of biopolymer degradation and organic carbon accumulation. Thus, the rate of decomposition is a complex function of many variables, the primary ones (temperature, soil moisture, and so on) of which can be estimated by remote sensing. It is of crucial importance to know what will happen to the rate of microbial biodegradation if, for example, the mean temperature of the Earth's surface changes by a degree.

On the land surface, there is a general pattern from equator to pole and from low elevations to high in terms of the amount of stored organic matter in soils. Closed canopy forests in cold climates and cold region grasslands with moderate to high rainfall exhibit a slight positive accumulation of dead organic matter. Accumulation is greatest at mid-latitude and mid-elevation. Accumulation is close to zero at the lowest and highest latitudes, at highest elevations, and in areas of lowest rainfall. The storage is thus closely related with climate and will change with climatic changes.

As organic matter accumulates in soils, compounds of carbon, nitrogen, hydrogen, and oxygen may build up, but phosphorous and sulfur are mobilized by microbial decomposition. They are transformed into soluble or volatile forms. This facilitates return of the two elements to the biota, or to transport via streams and rivers to the oceans. Thus, over time a depletion of phosphorus and sulfur relative to carbon, nitrogen, hydrogen, and oxygen occurs. The rate at which this occurs is currently poorly known. An important scientific issue is to determine the rates of mobilization of phosphorus and sulfur. It is also important to understand what

factors determine these rates and to ascertain how these factors can be measured by remote sensing.

Microbial biodegradation, particularly in flooded soils or sediments, is largely anaerobic. For its first 2 billion years, the biosphere was anaerobic and the biota were exclusively anaerobic prokaryotes. Today, crucial biospheric chemical reactions take place only in anaerobic environments. Anaerobic processes are carried out by microbes in oxygenless water, in wet soils, in wet muds, and in sedimentary deposits of bays, lakes, estuaries, ponds, and rivers as well as in the intestines of animals, particularly the ruminant mammals and insects. We know little about these processes. Most studies of these microbes have been carried out in laboratories on populations of single species. However, in the biosphere microbes exist in complex communities and their activities and rates of transformation of chemical compounds depend on many factors, including the abundance and activities of other species. For example, recent studies in anaerobic sediments show that physiologically different microbes in colonies make more efficient use of energy than do populations of single species. It appears that certain bacteria, which require anaerobic conditions, live in tiny habitats protected from oxygen by the activity of oxygen-using bacteria. The presence of these interactions means that classical methods of isolating specific microbes, examining the biochemistry of each species, and then synthesizing a model of anaerobic processes are not realistic. For example, the amount of methane that enters the atmosphere from anaerobic environments is a small fraction of that generated. Most of the methane is oxidized by aerobic microorganisms in a sedimentary-soil methane cycle. The methane-oxidizing bacteria are important nitrogen fixers and are becoming increasingly important because they can degrade chlorinated hydrocarbons. A major decrease in the global abundance or activity of these microorganisms could increase the atmospheric concentration of methane and have a major climatic effect.

On a global scale, the reduced gases in the atmosphere, including methane, methyl chloride, hydrogen sulfide, carbon disulfide, carbon monoxide, and sulfur dioxide, are derived from these anaerobic processes. In addition, pathways of carbon fixation and oxidation hidden within anaerobic environments may contribute significantly to net carbon dioxide production and consumption on the Earth's surface.

Where the physicochemical conditions become extreme, biopolymers can accumulate. Peats under proper conditions become coal fields attesting to periods of the planet's past when anaerobic bogs covered extensive areas of the Earth. Highly saline surface waters in the past and present lead to blooms of hydrocarbon accumulating cyanophytes and algae. The salt prevents eukaryotic grazing and the efficient function of the degrading bacteria, and thus accumulations develop that may represent the source of petroleum deposits.

Assaying a Microbial Assembly

There are two methods for assaying a microbial assembly: the first involves in situ measurements of the relative abundance of certain molecules that are indicative of activities of microbial communities. The second depends on co-occurence of higher plants and microbes: because of the many symbiotic relationships between higher plants and soil microbes, the occurrence of certain sets of vegetation species implies the occurrence of certain sets of microbial species—thus, the state of the vegetation can also indicate the state of the microbes.

We need to pursue both of these methods: (1) to develop in situ measures of the molecules that indicate the state of microbial activity, and (2) to develop correlations between (1) and remotely sensed measures of vegetation.

Current information suggests that this two-stage approach holds considerably more promise for monitoring microbial activity than standard techniques.

Standard public health assays that involve growth of the organisms in the laboratory have not proved adequate in ecology. These methods greatly underestimate the microbial abundance in soils, sediments, and the water column.

Methods that require the removal of the microorganisms from surfaces also have proved irreproducible and nonquantitative. Furthermore, methods using staining procedures have proved inadequate.

The proper approach to this complex microbiota is to utilize certain biochemical measures of components that are ubiquitous in all cells as measures of biomass. Components that are restricted to a subset of the total community can be utilized as "signatures"

of that subset in the analysis of the community structure. Microbes in nature, much as the enzymes of a higher vertebrate, spend most of the time in an inactive status. Consequently, the metabolic activity of the microbiota must be measured. Although the compounds that are utilized in these measures have a rapid turnover upon cell death, they are measures that clearly relate to the cellular or "viable" biomass. If these compounds can be extracted, isolated, purified, and analyzed, it is then possible to use a quantitative analysis to estimate biomass with the community structure determined from the "signature" compounds. If rates of incorporation or turnover of these components can be included in the measures, then estimates of growth are possible.

"Signature" lipids can be utilized to define important groups of bacterial anaerobes, such as the phytanyl glycerol ethers of the methane-forming bacteria, the plasmalogen phospholipids of the anaerobic fermenters, and certain specific branched unsaturated or hydroxy fatty acids localized in the phospholipids of the sulfate-reducing anaerobes. Long-chain polyenoic fatty acids are concentrated in more-or-less specific subsets of the microeukaryotic algae, fungi, protozoa, and micrometazoa. Phosphonates, certain specific lipids of the photosynthetic apparatus, and specific carotenoid pigments, are distributed among various subsets of the microalgae.

We need to develop these quantitative methods to describe the biomass, community, structure, metabolic activity, and nutritional status of the microbial community and to automate these methods for remote sensing. These methods can be correlated with the production of specific metabolites, such as the disappearance or turnover of gases such as hydrogen, methane, carbon monoxide, nitrous oxide, and hydrogen sulfide in soils and sediments.

5.
AQUATIC ECOSYSTEMS AND THE BIOSPHERE

INTRODUCTION

The roles of oceans and rivers as a physical and chemical component of the biosphere are discussed in the other NRC reports. Here, the committee focuses on the role of aquatic biota and aquatic ecosystems in the biosphere.

The study of the major role played by aquatic ecosystems in the biosphere should focus first on aquatic productivity, because it is through biological productivity that aquatic biota affect biogeochemistry and the energy budget.

OCEANS

Large areas of the ocean, such as the central gyres, have relatively low rates of production per unit surface area, but account for a major fraction of total carbon fixation because of their large area (Table 5.1). In contrast, highly productive coastal and upwelling regions account for only 10 percent of the ocean by area, but probably 25 percent of the ocean primary productivity. They provide more than 95 percent of the estimated fishery yield. Some have suggested that the coastal zones are the sites of most of the organic carbon sink of atmospheric carbon dioxide. These various ocean provinces exhibit pronounced differences in their phytoplankton species assemblages. As a consequence, they have significant differences in spatial and temporal variability of algal biomass as a function of nutrient input and grazing losses, they

TABLE 5.1 Biogeochemical Importance and Associated Carbon
Fixation of Aquatic Ecosystems

Region	Area, km^2	Net Primary Production $(x10^9$ tons C $yr^{-1})$	Biogeochemical Importance
Open ocean	$3.1x10^8$	18.60	Sulfur emission (SO_4 aerosols); inorganic carbon storage; nitrogen fixation
Shelves	$2.7x10^7$	5.40	Denitrification, phosphate sinks
Slopes	$3.2x10^7$	2.24	Organic carbon storage ($1.6x10^9$ ton)
Estuaries	$1.4x10^6$	0.92	Nitrogen sources, organic ($0.2x10^9$ tons)
Salt and fresh marshes	$2.0x10^6$	2.00	Sources of CH_4, N_2, and organic carbon storage
Rivers and lakes	$2.0x10^6$	0.40	Freshwater source
Coral reefs	$1.1x10^5$	0.30	Inorganic carbon storage
Seaweed beds	$2.0x10^4$	0.03	Source of CH_3Cl for interaction with atmospheric ozone
TOTAL		29.89	

have different fates of the fixed carbon, and their contribution to
global carbon fixation (Table 5.1) may be underestimated from
twofold to tenfold.

There are two basic reasons for the large uncertainty in the
estimates of marine carbon fixation: (1) the methodology used to
estimate the rate of primary productivity (the ^{14}C method) may
be in serious error; (2) the highly productive shelf regions exhibit
a much wider range of spatial and temporal variability of biomass
than the open ocean. It is in the oligotrophic (gyre) regions, where
the biomass variability is not pronounced, that the methodology

errors are greatest. The long food chains and 90 percent recycling of the offshore regime provide little net biotic storage of carbon dioxide, and, in addition, provide little fish harvest.

In the coastal regions, where productivity is much higher and the results of the ^{14}C methodology are probably more representative of the actual rate, the spatial extent and temporal variation are poorly known. For example, within 30 km of the Peru coast, the surface chlorophyll ranges from 0.4 to 40.0 g chlorophyll m^{-2} and the integrated primary production from about 1 to 10 g C m^{-2} day^{-1}.

Approximately 20 percent of continental shelf production (1.0 x 10^9 tons C yr^{-1}) is thought to be sequestered as organic carbon deposits on adjacent continental slopes. Although the anthropogenic input of nitrogen to the shelves may have increased tenfold over the last 50 to 100 years, a sufficient time series of phytoplankton data is not available to specify accurately changes in primary productivity or shelf export to continental slopes. This lack of a proper spatial and temporal perspective of the planktonic algae has hindered our understanding and, therefore, our ability to make accurate estimates of coastal productivity and subsequent carbon and nitrogen fluxes to the rest of the food web.

The fate of carbon and nitrogen fixed in the highly productive shelf regions is quite different from that in the open oceanic areas. In the open ocean, a large fraction of carbon and nitrogen enters biological food webs and is decomposed to inorganic forms and recycled in the upper waters. Because the effects of human activity are greater in the coastal region, understanding the coastal processes has far greater significance than their areal extent or contribution to total marine carbon fixation would suggest.

In order to make progress in understanding the primary productivity of the oceans, we need a program of research to obtain synoptic data on biomass and productivity for the highly dynamic oceanographic regions. Measurements are needed both over long periods (decadal time scales), and at much higher frequencies for resolution of biological processes. Satellite and aircraft remote sensing techniques, as well as moored biological buoys, have matured rapidly in the last 3 to 5 years to now make such sampling feasible. As a consequence, multiplatform (ship, buoy, aircraft, and satellite) sampling strategies offer an opportunity to reduce

significantly the variance in estimates of shelf phytoplankton abundance, carbon fixation, deposition, and their concomitant nitrogen and phosphorus fluxes.

Uptake of carbon dioxide during marine primary production is 10 to 20 times that of the fossil fuel carbon dioxide released from anthropogenic sources each year. Major unknowns are what areal and temporal changes of shelf production have occurred over the last 100 years and how much of the "missing" carbon of global carbon dioxide budgets is stored in ungrazed, slowly decomposing organic matter. As a result of human activities including use of agricultural fertilizers, production of urban sewage, and deforestation, the nutrient content of major rivers (e.g., Mississippi, Rhine, and Yangtze) is estimated to be 10 times that of both the preindustrial river condition and even the presumed unmodified nutrient content found in continental slope waters.

With respect to the global impact of the changing nutrient input from the two boundaries of the shelf (land, shelf-break) and subsequent carbon fixation, future biosphere programs should address the following questions:

1. What is the relationship between estuarine outwelling and shelf-break upwelling of dissolved nutrients on the development, distribution, and magnitude of the spring bloom of phytoplankton, both off an individual estuary and along an entire coastline?

2. How far seaward and over what area does estuarine influence extend both in regard to dissolved pollutants and in regard to the transport of phytoplankton? In particular, are phytoplankton transported across an entire shelf to the slope boundary?

3. Can the land source of nutrients be distinguished from one estuary to the next?

4. What is the relative influence of shelf edge upwelling compared to current intrusions, such as warm core eddies, on phytoplankton abundance, distribution, and metabolic activity?

5. Annual cycles of phytoplankton composition, distribution, abundance, and production are generally repeated from year to year over a shelf area, e.g., from Cape Hatteras to Nova Scotia, within the southeast Bering Sea, or off Peru. As an example, can chlorophyll accumulation at shelf fronts, e.g., the Irish and Bering Seas, be detected within CZCS overflights on a routine basis?

The ocean is characterized by considered annual and seasonal variations in phytoplankton, but there is little known about the

repetition of these patterns. The biosphere program should include satellite remote sensing systems that can determine these.

6. In the ocean, there are episodic events, such as algae blooms, that extend over large areas. The causes of these blooms are unresolved, but ocean temperature is believed to be important. Satellite remote sensing is important in monitoring the origin, distribution, and fate of these events. The biosphere program should include satellite remote sensing of these factors.

7. How can the distribution of hydrographic and nutrient properties be related to phytoplankton abundance, distribution, and type as indicated by winds, ice, and temperature data also derived from concurrent satellite observations?

8. What is the behavior of fish (avoidance or attraction) with respect to natural and eutrophic features? How much of the primary production is passed up the food web in a local area?

ESTUARIES AND MARSHES

Estuaries and marshes are usually so heavily covered by plants, suspended sediment, or both as to make them inaccessible to CZCS-type scanners. In addition, they are too monotonously colored for Landsat-type scanners. Therefore, they are, at present, less well known as objects of remote sensing than either open oceans or dry land. Since special equipment and effort will be required and since these wetlands are geographically minute compared to land masses and open ocean, it must be asked if they are likely to be of sufficient geochemical or theoretical importance to merit the effort.

The greatest significance of estuaries seems to be (1) as a nursery for important animal species; (2) as a locus for anaerobic events that may be important in the nitrogen and sulfur cycles; and (3) as a filter through which most of the freshwater runoff from the continents must pass before it can enter the sea. All three roles relate intimately to the high primary productivity of estuaries and marshes.

Estuarine productivity per unit area is comparable to, or higher than, that of land systems, and much higher than all but a few marine regions. Runoff water, high in most soluble minerals, traveling either as river water or groundwater, pauses in estuaries. Rooted vegetation, floating mats, or plankton blooms occur in

most estuaries. Rich bases are thereby provided for animal food chains.

The same abundance of plant productivity often provides so much decomposable organic matter as to produce, at least temporarily and locally, highly anoxic regions, in which anaerobes are active, releasing nitrogen to the atmosphere and consuming oxides of sulfur. Muds of many kinds are produced, containing much of the mineral sediment that came from the land; little particulate matter escapes the estuaries to the sea. The extent of anoxic environments: (1) strongly influences the flux of gases, such as methane, hydrogen sulfide, nitrogen, ammonia, and carbon dioxide derived from anaerobic, microbial metabolism; (2) are important locations for long-term storage of organic carbon; and (3) are possibly significant sites for bacterial fixation of atmospheric nitrogen.

Both marine and freshwater anoxic environments occur where degradation of organic inputs exceeds the influx of oxygen. The source of the organic inputs is NPP within the same ecosystem or from neighboring ecosystems. Thus, a direct linkage exists between the extent of anoxic environments and NPP.

The following questions are in regard to estuaries for a biosphere program:

1. What determines whether an estuary will produce rooted vegetation rather than floating mats or phytoplankton?

2. Are different types of estuaries and marshes comparable in their production rates? In a model of any estuary, there will be terms for water inflow and departure, nutrient levels, plant productivity, and so on. Given such models for any two estuaries, can the models be transformed into each other by constant multipliers related to water flow rates, nutrient concentrations, or some simple function of the two? If so, then the number of ground measurements that needs to be made to assess the global role of marshes and estuaries is accordingly reduced. If not, an ecological taxonomy of estuaries and marshes becomes necessary.

3. Are there global controls of coastal wetlands, or is each ecosystem dependent on only its local environment?

4. Are marshes and estuaries in general and in total sources or sinks for carbon?

5. With proper calibrating, can data from a well-monitored small estuary be combined with remote sensing techniques to develop a carbon budget for large, difficult-to-measure marshes or an estuary like the Mississippi?

6. What are the relative effects of "greenhouse" gases, e.g., methane and carbon dioxide, released from marshes during periods of changing sea level?

LAKES

Because of their well-defined limits, universal geographical distribution, and the proven accuracy with which primary production can be measured in them, lakes are useful natural laboratories for determining the factors that control global primary production and the fate of the fixed carbon. Besides being convenient ecosystems for study, there are practical reasons for studying lakes and other inland waters. Without adequate supplies of unpolluted fresh water, society as we know it would not exist. Indeed, fresh water could well become a primary factor limiting the world economic development in the next century. The management of fresh water is now based on empirical relations between forcing functions (input of nutrients, sediments, heat, or toxins) and the observed responses of biological communities (algal biomass, fish yield, and so on). These statistical models are based on short-term studies of a heterogeneous group of lakes and reservoirs in the north temperate zone. Consequently, present management models have wide confidence intervals, and the application to any specific lake involves a great deal of uncertainty. Moreover, extrapolation of these relations to water bodies outside the temperate zone is pure guesswork.

A second major shortcoming of current limnological models is lack of appreciation of spatial variability within lakes. Appreciation of spatial variability can only be gained through techniques that spatially integrate basins. Satellites create the opportunity to look at lakes and their changes through time in a wholly new manner. Chlorophyll, transparency, sediment concentrations, and temperature can be computed for the entire mixed layer of a lake, and the distributions and mean values of these variables can be followed through time with a single, standardized methodology. In particular, the CZCS color scanner tested on Nimbus-7 will allow chlorophyll in the mixed layers of low biomass water bodies to be

mapped anywhere on the globe. These data correlate well with estimates of integral primary production and can be used as input to models to calculate annual production in lakes with an accuracy of ±20 percent.

The accuracy of chlorophyll-based annual productivity models critically depends on annual values of two parameters: alpha, the initial linear slope of the photosynthesis versus light curve per unit of chlorophyll, and Pmax, the light-saturated rate of photosynthesis per unit of chlorophyll. These parameters are apparently stable in the sea, but the only long-term study in small lakes has shown them to be highly variable.

It is important to determine whether there is a relation between the variability of these parameters and the size of the lakes. It is also important to determine whether the parameters alpha and Pmax vary systematically in lakes of a given size from the tropics to the polar zones.

MEASUREMENT REQUIREMENTS

Estuaries and Marshes

Preliminary investigations undertaken in the 1960s provided evidence that the quality of light reflected from an ocean surface and remotely sensed by aircraft instrumentation might be interpreted as phytoplankton biomass, i.e., chlorophyll, in the upper portion of the water column. The work was limited by equipment to an altitude of 3 km; however, even at that altitude, the influence of the atmospheric backscatter was quite obvious as it began to dominate the color signal reflected from the ocean surface. Additional NASA-supported studies in 1971 and 1972, with Lear Jet and U-2 aircraft and a rapid scan spectrometer at altitudes of 14.9 and 19.8 km, demonstrated that this concept could be used to develop spacecraft equipment for the purpose of estimating ocean water column chlorophyll from Earth satellites. This became possible through the realization that problems associated with the scattering properties of the atmosphere, as well as direct reflectance of the Sun from the sea surface, could be either avoided or corrected.

The first satellite-borne ocean color sensor, CZCS, was launched aboard Nimbus-7 in October 1978. It has four visible and two infrared (one thermal) bands, with a sensitivity about 60 times that of the Landsat-1 multispectral scanner. Unlike many

satellite sensors of ocean properties, the CZCS responds to more than the mere surface features of the sea, and is sensitive to algal pigment concentrations in the upper 20 to 30 percent of the euphotic zone. A predictable relationship was established between the CZCS estimates of pigments and plankton chlorophyll measurements made aboard a ship in the Gulf of Mexico. Other shelf studies within the Southern California Bight and coastal waters south of New England have also compared ship track chlorophyll data and CZCS data. In all three coastal regions, there was great spatial variability of in vivo chlorophyll, with a striking agreement between the two methods.

A number of other sensor systems and platforms have also shown a potential for use in the determination of the areal extent of lakes and inland and coastal wetland areas. An early application of the Landsat system was the automated mapping of water bodies within the United States. Personnel of the NASA Johnson Space Flight Center developed automated technologies for mapping water bodies above 10 acres with accuracies well above 90 percent. Similarly, Landsat and combinations of Landsat and Synthetic Aperature Radar (SAR) data have been employed to map the areal extent of wetland areas and to classify the gross species composition of such areas. More recent studies suggest that there is a high prospect for success for a research program designed to accomplish the mapping of biomass and eventually primary production in the coastal ocean, lakes, and inland wetland areas.

Oceans

The first priority for future ocean color measurements is in the productive coastal waters within the 200-mile economic zone surrounding the continental United States, islands, and territories. The second priority is midocean regions. The frequency of required satellite coverage and information will vary depending on location and perhaps to some extent on season. Generally, 2-day coverage will be required in coastal and local waters and 3- to 5-day coverage for most midocean applications. Global coverage may be needed on the order of every 15 to 30 days. In addition to measurements made from satellites, marine research studies will generally require oceanographic data measured from ships, buoys, and aircraft.

Unfortunately, it has not been possible to obtain CZCS-type measurements of the global oceans on anything close to a daily basis. On any given day, the major fraction of our watery planet is obscured by clouds. A qualitative idea of realizable sampling characteristics has been gleaned by screening a few time sequences of CZCS data for which regular sampling was attempted. This experience suggests that in a month of data collection, useful data will be obtained on several days within randomly distributed clear-sky domains that are a few hundred kilometers in extent, and less frequently 1000 km in extent. Of the nominal 2 hours of Nimbus-7 CZCS coverage taken and recorded per day, an average of approximately 30 to 40 percent is rejected and not processed due to total cloud cover.

In summary, our experience to date suggests that global CZCS coverage would yield, on average, between 10 (at the equator) and 20 (at 40°N) usable images per month, i.e., the required sampling interval of every 1.5 days, for a given 1000 km x 1000 km ocean domain, with the majority of usable data in patchy subscenes of typically a few hundred kilometers in extent, and with only an occasional clear view of most of the domain in one image. Coverage frequencies will certainly fluctuate seasonally (and regionally) about these nominal estimates: coverage gaps of 2 to 3 weeks are likely to occur several times per year, with less frequent gaps of longer duration. In winter, low sun elevations will cause sampling voids of several weeks to a few months (increasing with latitude) at latitudes above 40°. These characteristics assume that a single CZCS-type instrument is operated in a Nimbus-7 orbit on a global basis.

Clearly, the present data base collected with the Nimbus-7 CZCS is inadequate to apply to the global mapping of primary productivity, except in a qualitative sense. It is limited both in terms of sampling frequency and in terms of concurrent oceanographic experimental data necessary to bridge the interpretive gap from phytoplankton pigment distributions to net primary production. Adequate data do exist in certain shelf regions, however, to develop a sampling methodology for a global productivity assessment program utilizing a follow-on CZCS-type sensor. The committee advocates deployment of moored in situ fluorometers, and drifting fluorometers, similar to the meteorological sensors of the 1979 Global Weather Experiment, in defined shelf experiments to allow interpretation of time-space composite descriptions of at

TABLE 5.2 Possible Location of Global Marine Biomass/Productivity Experiments

	Ship Measure- ments	Moored Fluorom- eter	Drifting Fluorom- eter	Aircraft Sensor	Ocean Color Imagery
Local Area Shelves					
Mid-Atlantic Bight	x	x	x	x	x
Georgia Bight	x	x	x	x	x
Gulf of Mexico	x	x	x	x	x
California Current	x	x	x	x	x
Bering Sea	x	x	x		x
Local Area Slopes					
Northeast Atlantic	x		x		x
Gulf of Mexico	x		x		x
Northwest Pacific	x		x		x
Global Area Shelves					
North Sea	x				x
Barents Sea					x
S. China/Japan Seas	x				x
Arabian Sea					x
West African Shelf					x
Patagonian Shelf					x
Peru-Chile Shelf	x				x
Timor/Arafura Seas	x				x
Global Area Slopes					
Southern Ocean	x		x		x

least parts of the ocean. This system should be coordinated with a program that would yield global CZCS-type images at a frequency of 15 to 20 days of usable coverage per month. Such global CZCS-type images would instantaneously resolve the shapes of shelf synoptic scale patterns of phytoplankton pigment distribution from any domain. These would allow interpolation from the surface-based data set for representative marine ecosystems (Table 5.2).

Since the chlorophyll distribution in the ocean is patchy on all scales down to the subkilometer level, to adequately map phytoplankton variation in high-concentration shelf areas a satellite must be able to resolve about a kilometer of the ocean. This small spot size also allows measurements closer to the shore, so we can resolve local outwellings and upwelling zones, which tend to be nearshore phenomena in many cases. Such a high data rate may be relaxed somewhat for wide area studies of open ocean phytoplankton. In this case, we can accept a degradation to about

4-km resolution. Therefore, we require a satellite system that can operate in two modes, analogous to the present infrared system: (1) local area coverage of high resolution to about 1 km, and (2) global area coverage of lower resolution to about 4 km.

In order to conduct the in situ field work necessary to exploit the ocean color observations from space, experiments must be staged in a variety of seasons and conditions. Logistically, this implies that the spacecraft mission must cover at least 2 years to specify atypical situations, e.g., the occurrence of El Niño phenomena.

Wetlands and Lakes

Remote sensing of the areal extent and the major species of macrophytes in wetlands and phytoplankton in lakes and open estuaries is currently feasible with Landsat sensors, with SAR sensors, and with CZCS sensors. Sequential imagery at monthly intervals of the same wetland permits calculation of the net changes in plant biomass for those species with a well-defined growing season. In regions where cloud cover precludes repeated coverage with Landsat imagery, a satellite-mounted SAR sensor is required. This is especially important because large areas of tropical wetlands occur where cloud cover is frequent and the option of aircraft with SAR sensors is impractical.

Two levels of sampling are required: (1) a global survey of the areal extent of marine and freshwater wetlands, and (2) an intensive examination of net primary productivity in representative freshwater and wetland ecosystems. The timing of the first survey should coincide with the maximal extent of the vegetation. The spatial resolution of the sensor required is about 50 m. The survey should be repeated every 5 years. For the second purpose, a functional division of these ecosystems based on the major source of nutrients to the plants (water or sediments) and the seasonal range in area inundated (minor or large) could be used. The committee suggests the following:

1. Floating wetlands
   - Annual meadows in Amazon floodplain
   - Perennial *Papyrus* swamps in Sudan
2. Rooted wetlands
   - Annual grasslands inundated in Venezuelan interior savanna

3. Perennial temperate, *Phragmites* marshes
4. Annual tundra wetlands
5. Major estuaries
   - Eutrophic, e.g., Rhine, Mississippi, Yangtze
   - Oligotrophic, e.g., Zaire, Yukon, Amazon
6. Major lakes
   - Tropical, e.g., Lake Tanganyika
   - Temperature, e.g., Lake Superior
   - Arctic, e.g., Great Bear Lake

Detailed examination of the spectral quality of estuarine and lake waters may also permit formulation of a time-dependent model of biological events. For example, the transition from a cyanobacterial (blue-green algae) bloom to its collapse and decay may be discernible. Perhaps quantitative estimation of the dissolved organic compounds that tint water yellow will also allow improved tracing of river inputs to the oceans. A central problem for future sensor design is thus to differentiate the complex colors of estuaries and lakes. Colors other than those of chlorophyll contain information about sedimentation and about the history of the ecosystem. Current sensors are designed for measuring chlorophyll in clear oceanic waters (CZCS) or in terrestrial vegetation (Landsat). Improved algorithms may permit use of these sensors for the application described here. Another possibility within existing technical capability is the launching of a satellite with a tuneable radiometer with greater spectral resolution (e.g., 20 nm). Such an instrument would permit detailed evaluation of the information in water color. The use of remotely sensed parameters in such studies is fundamental to understanding the fluxes of energy and mass in the ocean, wetlands, and lakes. In the next 10 years, remote sensing of entire aquatic ecosystems could change our way of thinking about ecosystems, much as remotely sensing the ocean floor through magnetometry in the early 1960s led to a whole new theory of crustal evolution and geological dynamism.

6.
REMOTE SENSING
REQUIREMENTS

INTRODUCTION

Previous chapters stress the importance of remote sensing in the study of the biosphere. This section briefly enumerates a number of environmental parameters about which information is required in the study of the biosphere. Particular emphasis is given to those developments in the area of vegetation analysis. The range of satellite and aircraft remote sensor systems whose data are available to the researcher interested in the study of the biosphere is presented along with the concepts of multistage data collection. Finally, a brief summary discussion will point out some major issues, problems, and needs in remote sensing for application to the study of the biosphere.

REMOTE SENSING OF ENVIRONMENTAL INFORMATION

There are a number of major environmental parameters about which information is needed and about which remotely sensed data have been and are currently being analyzed. These environmental parameters include those listed in the following sections.

Water

Observation of the hydrologic cycle requires a varied set of meteorological and hydrological information, including data on the location, areal extent, and quality of surface water bodies; the volume of runoff and the variability of stream flows; the geological,

soil, and vegetation characteristics of watersheds, as well as data on the extent and depth of high mountain snow; the area watered by irrigation; and the rate of agricultural use of water. Where floods are common, it is also important to know the areal extent and timing of flooding.

Although considerable work has been accomplished in this area, much work remains. The potential of a variety of sensor systems for input to models of hydrologic parameters must be assessed; this is particularly true with respect to models of hydrologic cycling.

Soils

Small-scale soils maps (1:5,000,000) are now available for all continents, and 1:1,000,000 scale mapping is quite common; but for national and local agricultural purposes, soil association maps of a much larger scale (at least 1:200,000 and even 1:100,000) are essential. For specialized studies of irrigable land, 1:10,000 or 1:25,000 scale may be needed. Soil data have been generated from the analysis of aerial and satellite imagery by agencies of the federal government for many years. Researchers are now examining the potential of Landsat in a geographic information systems approach for the mapping of soil and determining soil erosion potential.

Vegetation

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. Inasmuch as the dominant vegetation is an expression of environmental conditions, these vegetation maps are maps of ecosystems, including the 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 total land area of the world is well known (149 x 10^8 ha), but estimates in the areas of vegetation categories vary considerably. Some of the variation in estimated areas is the result of different classification schemes used by different workers. Remote sensing can play an important role in improving the areal estimation of these vegetation units: the present state-of-the-art for land

use and land cover determination using Landsat imaging provides classification accuracies at approximately the 90 percent level for general vegetation classes, such as conifers and deciduous forests, savanna woodlands, grasslands, and deserts. 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.

In forestry, the needs for information relate to forest inventories, mapping of burned areas, monitoring of logging, and detection of pests and disease. With respect to rangeland, the needs include inventories of range types, estimation of biomass, and monitoring of condition of range forage. Remote sensing with Landsat is being employed to answer the forest inventory needs. Mapping of burned areas with greater accuracy than conventional methods has been accomplished from Landsat data.

Geology

Geologists have for many years recognized the potential of satellite remote sensing. Indeed, it was personnel of the U.S. Geological Survey who very early led to the push for the first Earth Resources satellite. Mineral and fossil fuels—oil, coal, and gas—have been sought and located in many parts of the developing world with the assistance of remotely sensed data. Large areas of the world, however, are still geologically unexplored using advanced technology. Terrain studies, to identify landforms, faults, fractures, folds, major rock types, and geophysical and geobotanical anomalies, are an important element in geological mapping and mineral exploration. There have been initial steps on the construction of a mineral survey and in the identification of potential exploration sites. Geological mapping at reconnaissance scales, which is available for many areas, needs a follow-up by detailed local mapping of selected areas. In some cases, study of groundwater resources also requires special kinds of geological mapping. Expanded research into the uses of the new spectral bands on Landsat 4 and the Shuttle imaging radars should be encouraged. These systems are capable of providing new insights that can influence our understanding of the processes affecting the biosphere.

Oceans

Ocean processes have traditionally been investigated by sampling from instruments in situ, yielding quantitative measurements that are intermittent in both space and time. The past two decades have seen the development of new observing systems, such as the conductivity temperature depth system, current meters, and radio transmitting floats. These devices give a continuous record in one dimension, either instantaneously in the vertical or at a fixed point, or approximately moving with a water parcel. Arrays of these instruments have greatly increased our awareness of the space-time variability in the oceans due to internal waves, mesoscale eddies, or fluctuations in the general circulation itself.

In principle, space-based techniques can offer substantially improved information important to this four-dimensional jigsaw puzzle. Global coverage of broad-scale surface features (such as wind stress, sea level, and temperature) at time intervals that are short enough to be effectively continuous gives an enormous potential advantage over shipborne techniques. High-resolution images of temperature or color or microwave emissivity allow unique visualization of near-surface processes, such as internal waves or eddy formation; such visualizations can greatly extend the interpretation of conventional measurements, and allow considerable economies and a new kind of strategic planning of ship operations. Communications with sensors on fixed and drifting buoys, and the location of nonfixed systems through satellites, make possible many types of composite subsurface measurement systems that would otherwise be impracticable.

Remote sensors operating from the vantage point of space will never replace direct measurements and acoustic remote sensing because the ocean is effectively opaque to electromagnetic radiation. Seasat and the Coastal Zone color scanner, however, were important satellite systems for the study of the oceans. Continued emphasis needs to be placed on the development of advanced systems of these types.

A BRIEF HISTORY
OF THE REMOTE SENSING
OF LAND VEGETATION

The development of remote sensing can be subdivided into several major periods. The first major period in the history of remote sensing of vegetation extended from the invention of the airplane to the 1950s. Photographs from powered aircraft were first taken by Wilbur Wright on April 24, 1909, over Centocelli, Italy. Applications of aerial photography developed rapidly. By the 1920s, stereoscopic aerial photography in forestry, range, and agricultural studies had been developed. The early 1930s saw the Agricultural Adjustment Administration of the U.S. Department of Agriculture systematically photograph farm and ranch lands throughout the United States. This operation became routine in the 1950s and 1960s as the Agriculture Stabilization and Conservation Service (ASCS) systematically acquired black-and-white aerial photography of agricultural lands for their use in administering USDA's farm programs. In the early 1930s the U.S. Forest Service also began its program to photograph vast areas of the timber reserves of the United States. Since 1948, aerial photography has been employed as a base for the range resource inventories conducted by the U.S. Forest Service.

Early aerial reconnaissance of forests typically employed photographic images acquired from relatively low flying aircraft. Traditionally, manual analyses of stereoscopic aerial photography produced measurements of tree species composition, tree height, crown diameters, crown closure, crown area, and number of trees per unit of surface area. These remotely sensed derived vegetation characteristics were then combined with ground measurements to produce estimates of merchantable timber—a proportion of forest biomass—for large regions.

The second major period in the development and application of remote sensing techniques to the analysis of vegetation was stimulated by the need of resource managers for more accurate and timely information for detection and assessment of loss from crop and forest pests. In 1961 the National Research Council formed the Committee on Remote Sensing for Agricultural Purposes and extended efforts beyond crop and pest detection to information on crop and forest production, management, and marketing from both airborne and space vehicles.

Research, begun in 1964, funded by NASA and USDA, concentrated on problems of data reduction and discriminant analysis for the timely production of crop and forest information. In 1965 NASA began to apply aerospace remote sensing techniques to the study of agricultural crops, forests, and natural grasslands. Research conducted at academic and federal centers through the remainder of the 1960s provided the basic foundations for an Earth-viewing, remote sensing capability utilizing satellites and digital computer processing technologies.

The first digital computer analyses of multispectral data collected from aircraft were made from an agricultural field in Indiana in 1966. Results showed that digital image processing techniques could indeed be employed to distinguish wheat from oats.

A number of key projects in the 1970s led to important advances in the remote sensing of vegetation. These projects included among others the Cornblight Watch Experiment (CBWE); the Crop Identification Technology Assessment for Remote Sensing (CITARS); the Large Area Crop Inventory Experiment (LACIE); the Ten Ecosystem Experiment; and the Forest Classification and Inventory System Project.

In 1970 the Southern Corn Leaf Blight caused extensive damage to the U.S. corn crop. CBWE was initiated in April 1971 to use information derived from multispectral remote sensing by digital pattern recognition techniques and manual interpretation of infrared aerial photographs to detect and control the development and spread of corn blight across the corn belt during the growing season; assess the levels of infection present; estimate the land area affected; generalize information obtained from surface site visits to assess yield impacts; and assess the applicability of techniques developed to similar future situations. Prior to use of remote sensing techniques, information concerning the spread of the corn blight was based often on hearsay.

CBWE utilized high-altitude aircraft taking color infrared photography, a low-altitude aircraft collecting multispectral data, and ground observations, all collected according to a statistical sampling strategy. CBWE demonstrated that large areas, in this case parts of seven states, could be accurately and rapidly assessed. The experiment proved essentially that the location and spread of blight could be accurately monitored.

Landsat-1 was launched in July 1972. The Crop Identification Technology Assessment for Remote Sensing (CITARS) experiment was one of the first major programs that attempted to use data from this satellite for the study of vegetation. CITARS was designed to evaluate existing quantitative measures for the identification of specific crops using satellite remote sensing. Specific CITARS objectives were to (1) determine the ability of Landsat data to identify and distinguish between corn and soybeans during a growing season; (2) assess the effects of different geographic locations with different physical and cultural patterns on crop identification; (3) employ machine data processing and develop quantitative measures of the variation in crop identification accuracy; (4) test the concept of "signature extension"—that classification algorithms developed for one location could be applied to others; and (5) evaluate the benefits of Landsat classification techniques.

CITARS demonstrated that multidate Landsat data improved the potential for accurate classification of agricultural cover types. This program also pointed out two major problems that are still under study: the mixed pixel and signature extension problems. A pixel (picture element) is the area covered by the instantaneous field-of-view of a scanning remote sensor system, thus defining the resolution limit of the system. When two or more types of vegetation cover are present within the area covered by a given picture element (creating a mixed rather than "pure" pixel), the probability of correct classification of those vegetation types can be significantly decreased. When automated techniques are employed to develop correlations for one area that are then used to classify a different area, the probability of correct classification again decreases; this in brief is the signature extension.

Results of the CITARS program affected the design of a new, more focused program with direct applications, the Large Area Crop Inventory Experiment (LACIE) program, which began in 1974. LACIE's purpose was to determine how well one could forecast the harvests of a single and important crop, wheat, on a worldwide basis using satellite remote sensing technology. In LACIE, for the first time, the biological production of a major crop on a global scale was to be estimated. What LACIE found was that techniques developed in this program tended to produce particularly good estimates of wheat acreage in geographic areas having large field sizes (fields having rectilinear dimensions that

were large in relation to Landsat pixel resolution, which is about 80 m). Such areas included the hard red "winter" wheat of the United States, Soviet Union, and Argentina.

In a simulated operational test, the LACIE in-season forecast predicted a 30 percent shortfall in the 1977 Soviet spring wheat crop. This estimate came within 10 percent of the official Soviet figures released months after harvest. In addition, LACIE midseason winter wheat forecasts predicted, within 7 percent, a 23 percent above-normal Soviet winter wheat crop a number of months before harvest with a coefficient of variation for the total wheat harvest of 3.8 percent.

In 1978, the LACIE experiments were extended to more types of crops, as well as to forests and rangelands under the Agricultural Resource Inventory and Survey Technology using Aerospace Remote Sensing (AgRISTARS) program. In AgRISTARS, crop assessment was enhanced in several cases by the construction of agrometeorological models and canopy reflectance models.

Agricultural research employing remotely sensed data in the 1960s and 1970s demonstrated that timely agricultural resource surveys are feasible. Remotely sensed data, however, must be supported by collateral information of specific spatial, spectral and temporal resolution, data processing hardware and software support for both digital and analog imagery, integrated and operated by skilled personnel. The programs discussed above and others also have led to major advances in machine processing of remote sensing imagery of vegetation; major advances in the development of models of canopy structure and of the reflection, absorption, and emission of electromagnetic radiation by vegetation canopies; and a recognition of the importance of models of the energy exchange properties of vegetation.

Remote sensing data from aircraft and satellite platforms has been and is being applied to forest and range inventory and monitoring. The USDA (U.S. Forest Service) NASA Ten Ecosystem Study explored the feasibility of using Landsat multispectral data and automated pattern recognition analysis to inventory forest and grassland resources. By dividing the continental United States into 10 broadly defined ecological classes and examining the similarities and differences among them, this study built on the results of more localized research and could serve as a prelude to larger scale investigations. Ten Ecosystems demonstrated that Landsat data, with appropriate machine-assisted processing techniques,

can distinguish hardwood, softwood, grassland, and water and make inventories of these classes with an accuracy of 70 percent or better at an operational cost of 11 cents per square hectare.

The Forest Classification and Inventory System (FOCIS) employed machine processing techniques to extract and process tonal, textural, and terrain information from registered Landsat multispectral scanner data and digital terrain data. Using these techniques in a portion of the Klamath National Forest (an area of 390,000 hectares), an estimate of softwood timber volume was obtained with a coefficient of variation of 6.3 percent, which was similar to accuracies derived concurrently by Forest Service personnel and yet was produced in considerably less time and at less cost than the data generated by the conventional survey.

In other forestry projects, strong correlations have been found between stand density and Landsat data for single-species plantations, including stands of ponderosa pine, southern pine forests, Douglas fir, and red and white fir. Landsat imagery in digital format are also being used to produce land cover maps for rangeland. When combined with digital terrain information, these data are being used to produce resource maps for habitat assessment and managerial decisions.

A general research advance growing out of remote sensing research on vegetation in the last decade is a better understanding of how different wavelength bands provide different kinds of information, and how the ratio of different bands yields information not obtainable directly. It has been seen that the spectral region between 0.74 and 1.1 μm exhibits some sensitivity to total plant biomass. Healthy green vegetation is typically characterized by both high reflectance (45 to 50 percent), high transmittance (45 to 50 percent), and low absorptance of near-infrared radiation. Analyses of the multispectral remotely sensed data generally involve transforms of the data. Most of these indices or transformations employ ratios of measurements taken from at least one band in the near-infrared region (0.7 to 0.9 μm) and one band in the red (0.6 to 0.7 μm). Research has demonstrated that a linear combination of the ratios is more highly correlated with biomass than either red or near-infrared measurement alone.

Research has also demonstrated that most spectral variability in Landsat data is two-dimensional and has developed a linear orthogonal transformation with one axis representing brightness

and the other representing a measure of the vegetation development. The axis sensitive to vegetation was called "greenness." It has been shown also that this greenness transform is insensitive to shadow effects and atmospheric effects over a reasonable range of atmospheric conditions. The same transformation has also been shown to minimize differences due to soil types and soil moisture conditions. Thus, for a geographic area with a reasonably limited amount of variation in soil type, the numerical value of soil greenness can be assumed to be constant.

Among the accomplishments of the second period in the use of remote sensing for studying vegetation is the development of techniques for (1) monitoring vegetation state and predicting crop yields; (2) inventorying forests as accurately and much more cheaply than before; (3) utilizing repeated measurements from data acquired over time for identifying vegetation type and for monitoring seasonal production; (4) modeling relationships between canopy structure and spectral signatures; and (5) combining information from several wavelength bands to better reveal vegetation characteristics.

Finally, a third period in the use of remote sensing for the study of vegetation is just beginning. Major challanges to be addressed involve devising ways to estimate biomass and net primary production for all major vegetation types. Recent advances in remote sensing and in ecological and forestry research have demonstrated significant potential, and a growing number of researchers believe this challange can be met. Remote sensing offers the potential to measure spatial variation, monitor temporal changes, and estimate the error associated with average values for a variety of biophysical and socioeconomic environmental parameters. Land use and land cover and their changes over time can be monitored for large regions. With the continued development of data processing algorithms for extracting, registering, analyzing, and relating remote sensing imagery to ground measurements, biomass and biological productivity can be estimated with an accuracy never before possible.

At the present time the key to studying vegetation biomass and productivity from space appears to be the vegetative characteristic of leaf area index (LAI). Leaf area index is the ratio of the surface area of all leaves per unit of land surface. Recent ecological research has demonstrated strong functional and statistical relationships among canopy leaf area, stand biomass, and net primary

productivity, and even with evapotranspiration. Research also indicates that LAI can be measured by remote sensing, at least for indices up to approximately 7. Thus, for the first time there is a measure that is available from remote sensing that can serve as a link between a structural characteristic of vegetation and the process of net primary productivity. Yet, problems exist: (1) a major limitation in the use of LAI is how to obtain sufficient ground samples to demonstrate the significance of the relationship between remotely sensed images and canopy leaf area; (2) another problem concerns how to extend the ability of remote sensing techniques to recognize leaf area indices greater than 7.

Indirect methods of measuring LAI are available. Recently, research has shown that tree diameter and height are strongly correlated with LAI for individual species. These correlations may be established by using destructive sampling techniques. Moreover, well-known field and aerial photographic analysis techniques exist for measuring tree diameters and heights rapidly. Yet, considerable work is still required to establish the relationships between destructive sampling, nondestructive ground indices, and satellite remotely sensed data. These relationships must be established for each major vegetation type and their level of accuracy and stability demonstrated. In addition, the potential for extending correlations from one vegetation type to another must be tested.

Other recent research indicates that new sensor systems can provide considerably more biophysical information on vegetation. The lack of advanced sensor data such as the Thematic Mapper and the Shuttle Imaging Radars supported by adequate ground truth data and image processing and analysis capabilities at major research institutions across this country, however, frustrates the study of potential uses. Registered sets of nearly concurrent SEASAT/SAR and Landsat/MSS data exist over a variety of vegetation types. In the few cases in which these data have been analyzed, the inclusion of the SAR data with the MSS data appears to lead to improved discrimination of land cover types.

PERSPECTIVES ON THE FUTURE

Developments in remote sensing and computer science during the past several decades have led to a new potential for research on the biosphere employing remote sensing from aircraft and from satellites. These developments are summarized in Figure 6.1. The

Simple Relationships ·········· ⟩➤ Complex Models

Manual Techniques ·············· ⟩➤ Automated Techniques

Single Data ···················· ⟩➤ Multiple Data

Local Studies ·················· ⟩➤ Global Surveys

Aerial Photographs ············· ⟩➤ Multi-Spectral Images

Balloons ······················ ⟩➤ Satellites
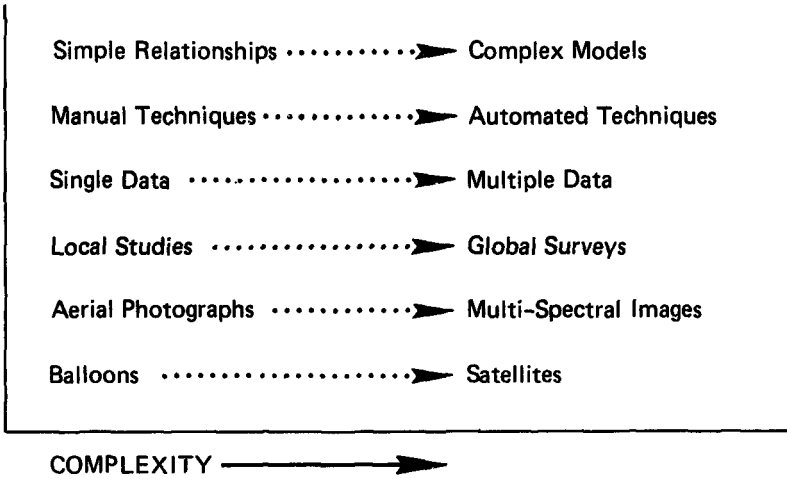
COMPLEXITY ――――――――➤

FIGURE 6.1 The development of remote sensing for earth resources research.

history of remote sensing is a history of increased complexity. This complexity makes it essential that we determine the true capabilities and limitations of remote sensing for the study of the biosphere. Developments to date show considerable promise. The committee believes that these developments make an integrated study of the biosphere truly possible for the first time. The global quantitative data obtained through satellite remote sensing provide the significant key that can unlock new insights into the working of the biosphere and can potentially provide expanded understudies of factors that influence the long-term habitability of the Earth. Remote sensing can significantly aid in studies at scales from sample plots to global estimates. Research on large-scale phenomena, in particular, has always suffered from a lack of sufficient number of samples, and remote sensing has proven to be very valuable in the acquisition of information on large-scale phenomena.

Exploitation of the improved and unique information available to researchers conducting studies of the biosphere from remote sensing has barely begun. Many problems and issues exist. What is required to increase the impact of remote sensing on the study of the biosphere is a concerted effort on the part of both the basic and the applied researcher to learn the capabilities and

limitations clearly. Researchers should be aware that the utility of remote sensing may be greatly increased when the information is combined with other sources of data; time series of remote sensing images are available; and ratios of spectral bands are used. Yet, this awareness is only meaningful if research.there is a commitment on the part of NASA and the federal government to the long-term continuity of remote sensing data. A new start for a major land observing satellite has not been approved since Landsat-4's Thematic Mapper. NASA has conducted studies of both linear and area array multiband, multispectral sensor systems. In addition, NASA is studying the potential for a permanent, highly adaptable civil space facility for scientific studies of the Earth and the development of related technology (the so-called "system-Z"). While such studies are important, it is more important that the next step be taken beyond Thematic Mapper as quickly as possible. A balanced program of instrument development, including high spectral resolution imaging, radar, and thermal sensors, should be pursued. With the current difficulties with the present Thematic Mapper and the existance of only the single backup Landsat-D', a decision must be made. Continuity of advanced satellite sensor data must be made a priority issue by NASA. The current Landsat MSS data have proven extremely valuable; however, the potential new insights from the analysis of the improved spectral information from advanced sensor systems make this an extremely important issue. Almost as important are the major concerns surrounding the planned commercialization of the federal land observing satellite program. Far from saving the government money, every study of this plan has shown it to have the potential for costing the government a considerable amount per year. In addition, many researchers feel that commercialization will kill the land resources remote sensing program. This must not occur. The committee urges that land resources remote sensing satellite systems not be transferred to private industry at this time. That is, it is not yet time for a private, national, or multinational company to have control in any way over a national technology with important national and international implications. Commercialization has the potential for slowing considerably the access to remotely sensed data and consequently the study of the biosphere. While the needs of science for timely, consistent remotely sensed data are not necessarily incompatible with those of operational users in industry

and government, there is a risk that serving the needs of operational users will inhibit the fulfilling of the need for the variety of science data types required in the study of the biosphere.

A final area of major concern is the level of funding in support of land remote sensing research at universities across this country. Funding for basic and applied land-related remote sensing research, which could lead to an improved understanding of the biosphere, has been reduced to a level where the nation stands to lose a major analytical capability. Once lost this capability cannot easily be regained. Today the processing and analysis of advanced remotely sensed data require complex, highly sophisticated hardware systems and software, along with individuals who are familiar with remote sensing and the science of the biosphere. This most often will require interdisciplinary efforts. NASA must find resources to sustain and encourage such efforts. Finally, when thoughtfully analyzed, remote sensing information can provide researchers with significant improvements in the quantity, quality, and timeliness of data. Remote sensing allows us literally to expand our horizons far beyond what was ever thought possible. As more researchers become aware of the significant implications of remote sensing for providing such data, the true impact of the techniques on the study of the biosphere will be felt. When allied with appropriate field studies and modeling, remote sensing can change our perception of the landscape, of land's biota, and of the interrelationships between life on the land and the rest of the biosphere.

7.
DATA MANAGEMENT

INTRODUCTION

Although future scientific data management will be strongly influenced by advances in technology, from both cost and performance viewpoints, most experts believe that the majority of the current data problems are not due to technological barriers. Many believe that current data problems can also be solved by employing projected advances in technology, provided management of data operations is properly organized. There are a number of areas in which technological advancement will not only greatly improve the quality of the data acquired, but also will improve the efficiency with which the data loads required for global monitoring are processed. An example of the type of data load that might be required for ecological modeling is as follows. An area of 600,000 acres (an area covering 42 USGS 7.5-minute Topographic Quadrangle maps) at Landsat resolution of 80 m yields approximately 600,000 grid cells. If we assume that an ecologist might want some 30 separate data plans (e.g., geologic map, soils map, and topographic map), none of which has more than 256 separate categories for the area of interest, the data base is 4.8 million data units. If the resolution of the data base is reduced to 12.5-m resolution cells (a scale possibly more realistic for some more-detailed ecological studies), then using the same 30 categories, the data base would contain some 2×10^8 data units. This size of data base is roughly the equivalent of full-scene Landsat processing today.

An example of the type of data load that can be produced by remote sensing technology is that generated by the Landsat Multi-Spectral Scanner (MSS) system. The conterminous United States requires approximately 470 Landsat frames. For global coverage of land areas, more than 10,550 frames are needed. This global coverage of land areas amounts to approximately 3.2×10^{11} bytes of data, taking into account that there are four Landsat spectral bands per scene. The newer Thematic Mapper flown on Landsats 4 and 5 expands the problem, because the instrument has 7 bands on a resolution of 30 m. It is little wonder that there is concern in the scientific and applications user communities over problems with the level of planning of systems for scientific data acquisition, reduction, and distribution; the quality, timeliness, and accuracy of sensor data; the allocation of processing functions on the spacecraft and the ground; programmer productivity, software compatibility and portability; and the overall cost to the user of data acquisition. The efficient capture, processing, storage, and transmission to ultimate users of the large number of data that have been acquired in the past, are currently being acquired, and are planned to be acquired in the next decade represent a challenge to NASA, to NOAA, and to the scientific community as a whole.

There are many steps within the flow of remotely sensed data from acquisition through the extraction of information. At each step in the process, the potential exists for the data to be managed in an efficient way. Important elements in the area of data management can be listed as follows: sensor data acquisition, space data processing, space data storage, space data handling, space to ground transmission, computers (ground based), ground data storage and archiving, data base systems, communications networks and distributed processing, interactive processing, and software. Specific issues that are related to data management in several of these areas and are important to the studies of the biosphere are expanded upon in the following discussion.

As can be seen from the discussion of sensor systems and platforms, space data sensor technology has advanced and will continue to advance in the areas of increased spatial, spectral, temporal, and radiometric resolution, along with other acquisition-related capabilities. At present, however, there is a great potential for improvements that can result from advances in processing and data storage. Integration of high-speed signal processors and/or

superminicomputer systems into high-data-rate sensors can provide the capability to acquire, process, and store data selectively as they are collected. Such integration, when combined with techniques being developed in the area of artificial intelligence (AI), can result in "smart" or adaptive sensors with the capability to manage data during the acquisition process.

Specific capabilities that appear possible and feasible include the ability to do the following:

- search out specific types, classes, and/or levels of data and to transmit data to ground stations only when those data have been located;
- modify a sensor program sequence when unable to perform preprogrammed functions because of anomalies, such as cloud cover or the absence of specified events;
- store data/scene from previous observations, perform complex on-board data processing, and transmit to Earth only pertinent and/or new data;
- vary resolution and data rates from area to area;
- preprocess, filter, and perform other complex operations under the preprogrammed and/or interactive control of either on-board or ground-based scientists or users; and
- adapt and/or reconfigure automatically data systems in response to changing data/information requirements and/or environmental conditions.

Considerable work is still required before this potential capability becomes reality. It is important that NASA support expanded research in the area of the links between AI and image-oriented data bases.

SENSOR DATA ACQUISITION

Research has demonstrated that important information on biophysical properties of vegetation, soils, water, and so on, are contained in remotely sensed measurements at distinctly different parts of the electromagnetic spectrum, e.g., visible, near reflectance infrared, middle reflectance infrared, emissive infrared, and X, C, L bands of microwave. Emphasis should be given to the integration of existing sensors and the development of new ones (e.g., linear and/or area array systems and multifrequency

calibrated active microwave systems) that can be flown on suitable aircraft and Earth-orbiting spacecraft.

Effort should also be placed on developing improved technologies that provide an improved capability to bring the data from such different types of sensors in their different orbital configurations into registration or congruency. These data should be registered to each other and to ground geographical coordinate systems in order to support multispectral and multitemporal research investigations. Such a registration capability needs to support high data volumes and be affordable.

In addition to these efforts, research and development efforts also need to be directed toward the development of improved instrumentation and procedures for making in situ biophysical relationships to environmental factors (e.g., water stress to canopy morphology, and spectral measurements within research sites). Conventional capabilities are generally not adequate for collecting enough measurements within a required interval and having sufficient precision to characterize the variance inherent in a test site scene of remotely sensed data. A study needs to be made to identify these deficiencies, and efforts need to be instituted to fill in existing gaps.

Examples of such gaps include in situ determination of such parameters as leaf area index, biomass, net primary productivity, soil moisture as a function of surface distance and depth, and evapotranspiration. NASA should institute a program of field spectral measurements designed to assess the biophysical information inherent in spectral data at various wavelengths throughout the electromagnetic spectrum. This would entail the development of a series of test sites in a variety of environments.

The latest NASA Earth-observing sensor, the Thematic Mapper on Landsat-4, can be a most valuable device for research over at least the next 10 years provided that current data processing and dissemination problems can be resolved and the volume of digital data available to the science community significantly increased. It is extremely important that considerable attention be directed at this effort by NASA and/or NOAA.

SPACE DATA PROCESSING

Traditionally, space data processing has been a highly centralized function with limited resources. Hardware required to accomplish

such processing is complex and expensive. Future availability of more powerful processors and storage capabilities on-board should lessen these burdens. This will not, however, lessen the need for the development of effective and efficient means for storing, distributing, and archiving the data produced by the space systems. The rate at which a science of the biosphere will develop will be strongly dependent upon the ability of scientists working in the field to have access to the data and data bases they require. To date, there has been little success in implementing standards that could lead to the effective and efficient interchange of space data between centers either preprocessing or postprocessing. The NASA Transportable Applications Executive (TAE) program is a step in this direction, and more such steps must be taken.

SPACE DATA HANDLING

Space data handling systems have traditionally been fixed-format systems. Truly adaptive space data handling systems have generally not been feasible because of the complexity and cost of hardware. In additon, features such as data compression have not been effectively applied to Earth-oriented satellite data, in part because of the scientific community's desire for raw data.

Current technology, however, does offer an opportunity to implement adaptive data handling systems for spaceborne instruments and experiments. An ongoing effort in NASA's End-to-End Data Systems (NEEDS) program provides for asychronously multiplexed packets of data, buffered in variable-capacity data buffers. A number of activities are also ongoing to develop data compression algorithms. Current techniques for image data provide a lossless compression ratio of 2.5:1. If some minimal loss in data is acceptable, compression ratios on the order of 10:1 to 20:1 are possible.

COMPUTERS (GROUND-BASED)

In order to meet the requirements for synoptic information on a global scale, a variety of sensor systems on the ground, in aircraft, and on spacecraft have been employed. This has increased the need for faster, more capable computer systems. Fortunately, commercial markets and military and space requirements have driven and continue to drive advances in computer technology at a rapid rate.

Thus, in principle, it is possible to develop computer systems to handle most short-term data processing and storage needs. This situation is not without problems, however; the price of commercial high-speed computers is still high. Some consequences of advances in the microcomputer and semiconductor memory device area that can have an impact on the study of the biosphere include the following:

- Microcomputers and memory chips can be integrated with sensors, instrumentation, and control units in spacecraft to increase the versatility and adaptability of these units to perform data preprocessing on board.
- Large amounts of low-cost computing power and memory can be incorporated into intelligent terminals to enhance interactive computing and display generation and presentation (including sophisticated graphic displays) and provide word processing support.
- Microcomputers can be assembled into large arrays to increase significantly processing power for scientific modeling, and data base query.
- Special-purpose computers can be constructed from microprocessor, memory, and special-function computation chips at relatively low cost for use as data analysis machines, network communication processors, and adjuncts of general-purpose computers (e.g., floating-point processors).

Microcomputers and mainframe computer technologies are also advancing. The cost of computing power is decreasing. Mini and mainframe systems are evolving toward effective use in networks and distributed processing systems. High-speed and super-scale computers, which provide performance at rates up to 100 million operations per second (MOPS) today, can be expected to evolve into computers with performance in excess of 1000 MOPS by 1985. These machines will dramatically reduce the present problems of processing large volumes of space data and will support computations for complex models of biosphere processors. Especially important will be the development of special-purpose architectures for image processing and for management of very large data bases.

DATA STORAGE

Ground data storage requirements fall into two categories: short-term data storage for processing and long-term/archival storage. At present, it appears that short-term needs can be satisfied by a combination of magnetic and optical storage devices, with magnetic devices dominating the field because of their read/write capability and flexibility. Technology for mass storage of data is still evolving for storage in the range of 10^{14} to 10^{15} bits of data, and a clear leader for mass storage media has not surfaced.

With respect to the storage and archiving of space data, it is critical that NASA begin as soon as possible to examine a number of critical issues. Issues here include the following:

- Why and which data sets should be archived and distributed?
- Where are satellite and ancillary data to be archived and how will they be accessed and distributed (this requires that efforts be directed toward the development of standardized catalogs and directories of data and information distributed in many different data bases, which can be interrogated by any researcher and which provide high-level assessments of data holding and capabilities of each participating facility)?
- How should data be archived and distributed?
- Who will archive and distribute these data?

DATA BASE AND
INFORMATION SYSTEMS

Remote sensing is a somewhat unique technology whose transfer to potential users has been greatly aided not only by the U.S. federal role but also by governmental agencies around the world. This has been true both in developing the technology and in making it and its products available to the public at large. Integration of remote sensing—particularly from satellite sensor systems—with data bases has thus consistently been subject to institutional as well as technical limitations. Yet, many recent reports suggest that the full potential of remote sensing cannot and will not be achieved without continued and expanded efforts to adapt the technology to the evolving needs of researchers and resource managers around the world. NASA should focus considerable research here. To the extent that geographic information system (GIS) designs reflect

those needs, GIS design ought to be a relevant concern in development of new satellite systems and in establishment of institutional arrangements for processing, formatting, and disseminating the products of remote sensing. Indeed, to some extent, NASA is beginning to appreciate this, and the Information Science Office in the Office of Space Science and Applications has initiated study of a Pilot Land Data System to examine these needs. The goal of these efforts is not only to improve the ability to handle data and integrate diverse data sets in the modeling of fundamental processes but also to improve our overall understanding of the nature of the processes.

Geographic Information System technology is important to such studies. Yet GIS technology, is itself a developing technology as is remote sensing—neither is yet widely familiar nor well understood within the research and user community at large. Little substantial work has been done on the philosophy and conceptual linkages between information systems and remote sensing. This lack of work on models of the potential interactions between these technologies has, in part, served to isolate design of remote sensing techniques, hardware, and software from concepts of GIS design. As both data base and remote sensing technologies move to new states of maturity, many of the current problems of integrating them can be eliminated. Specifically, integration of remote sensing and geographic information systems is not a matter of fundamental incompatibility or of reluctance on the part of researchers and technologists to collaborate. Integration is dependent on realization that the potential of each cannot be achieved until they are fully integrated. That is, both researchers and resource managers alike must come to understand that data bases are only as good and as current as the data they contain and remote sensing offers the potential to produce high-quality, up-to-date information.

DATA BASE MANAGEMENT

Data base management is crucial to the use of space technology for the study of the biosphere. Fortunately, it is one of the most worked areas in data processing today. The problem is being approached from the standpoints of software, implementations of special processors (back-end processors) that are dedicated to data base management, and the implementation of special computers with internal architectures specifically designed to accommodate

the management of data bases. Such machines may provide advances for a majority of users, but they may not provide all the answers scientists need in this area for two reasons: (1) the software support that will be initially available with these machines will probably be oriented more to commercial applications than to spatially oriented, time series data; and (2) reduced emphasis on numerical computation may have adverse effects on the cost/performance ratio for scientific applications.

COMMUNICATIONS NETWORKS AND DISTRIBUTED PROCESSING

The interdisciplinary nature of ecological investigations increases the importance of communication links between scientists. Communications networks and the potential of distributed data processing are critical elements in advancing a science of the biosphere. Networks and distributed processing technology have evolved at a rapid pace during the 1970s. This evolution has been spurred by the need to link scientists at various institutions and has been facilitated by technological advances in the areas of transmission networks, microelectronics, software, communications protocols, and packet switching.

Here NASA needs to identify effective methods for connecting various classes of participants for the sharing of data, analysis facilities, and results. Studies must also be conducted to determine a best "course of action" to follow in the development of georeferenced data bases and associated management systems to permit the effective storage, retrieval, and distribution of data, preprocessed data, derived data, and information via a network structure. The ultimate intent of such a data base structure would be to provide researchers at many institutions with diverse sets and types of data that are easily accessible and that have been indexed to common spatial reference systems in a logical manner.

In addition, studies should be instituted to identify existing analysis facilities (i.e., NASA and other federal agencies, universities, and private industry) together with the characteristics of additional facilities that would become central nodes in a biospheric research network. It is envisioned that these facilities would fall into different categories or classes based on need, existing capabilities, and other factors. Finally, such an overall distributed system should be phased into existence to factor in the results of ongoing

efforts to determine the nature of and recommend the configuration of a complete distributed data collection, storage, retrieval, and processing system to support regional and global studies of the biosphere.

INTERACTIVE PROCESSING

Interactive processing, though not a technology within itself, is the trend in science data processing today. From the time software and data are entered into a system, throughout the lifetime of a given data base, an interactive approach can permit the scientist to effectively rework, modify, and fine-tune models as the data are being processed. There is considerable potential for improving the capabilities of both basic and applied researchers through the use of AI-assisted interactive image processing and analysis systems. Therefore, NASA should investigate the potential of AI techniques for improving interactive image processing.

SOFTWARE

Data management is almost universally beset with software problems. These problems are manifested in a number of ways, the most prominent of which are the following:

- Software is expensive.
- Software is not generally transportable.
- Software documentation is generally imprecise and inadequate for the requirements of operation, maintenance, sustaining engineering, and transportability.

Data processing professionals have begun to understand the ever-increasing cost of software development, operation, and maintenance. Fear of rising costs of software has led scientists to advocate using engineering discipline in the software development process. Results in software engineering, to date, have seen many new approaches to developing software, many new tools to aid software development, and many new management philosophies for organizing software teams.

Yet, the majority of new discoveries in software engineering have not been widely accepted. Software engineers have yet to provide researchers and scientific users with some type of software metrics or any other alternatives to gauge or demonstrate

the usefulness and effectiveness of the new discoveries in software engineering.

To overcome current problems in software for a study of the biosphere, NASA needs to do the following:

1. Establish disciplined software practices for both individual programmers and group projects.

2. Embark on research to establish software metrics to facilitate software estimation and forecasting.

3. Initiate efforts to set up experimental software engineering frameworks and foundations to validate software methodologies through experimentation.

4. Establish documentation standards and guidelines and strictly enforce their adherence.

5. Establish a unified software library center to make available software products that have already been developed within the software industry.

6. Specify that all software developed by NASA and by NASA-supported researchers should be transportable.

APPENDIX A:
REMOTE SENSING SYSTEMS

The material in this appendix is presented to provide the reader with a background concerning the variety of sensor systems that have been and are being employed to acquire data from satellite, aircraft, and surface platforms.

SATELLITE SYSTEMS

Remote sensing from space represents a major technological step forward over aerial photography in the gathering of data about the Earth's resources. The use of the airplane as a platform is restricted to the area of coverage on any given photographic mission. It is further limited by the costs of the area's coverage and by the degree of uniformity required in repetitive coverage of the same scene in different seasons, or in its coverage of different scenes at the same sun angle. Coverage available from a satellite, however, depends on its orbit (Table A.1). Satellite orbits approximate on an ellipse; the subsatellite track traces out a pattern with north-south limits that are equal to the inclination of the satellite's orbit. Polar-orbiting satellites have inclinations near 90° and observe from the equator to the poles. Satellites in an equatorial orbit (e.g., geosynchronous satellites) always remain over the equator, even though they may carry instruments that can sense as far as 60° latitude.

The altitude of a satellite determines its period. Most satellites have altitudes near 1000 km resulting in a period of about 115 minutes. The Landsats and Seasat experimental satellite are examples. At an altitude of 35,900 km, the satellite would have

TABLE A.1 Satellite Orbit Options

I. Polar

Allows view of polar regions, e.g., ICEX.
Time of satellite overpass changes with season of the year.
This type of orbit is not appropriate for visible imagery.

II. Geostationary

Twenty-four-hour orbit period with 36,000-km altitude.
Keeps spacecraft over fixed equatorial ground point.

III. Sun Synchronous

For a given altitude, inclination can be determined so that
orbit plane precession cancels seasonal variation of sun angle.
Satellite passes over ground point at same local time each day.
The altitude also determines the number of orbits per day.

Considerations for Sun Synchronous Orbit Determination

1. Orbital drag
2. Instrumentation swath and resolution
3. Ground station pass time
4. Desired repeat coverage periodicity
5. Desired sun angle
6. Pattern of orbital coverage desired

IV. Special Orbits

An orbit with an inclination of 108 covers all unfrozen
oceans and provides 40 track crossing angles at equator. This
type of orbit is useful for the study of the marine geoid and
sea surface topography and was adopted for Seasat.

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a period of exactly 24 hours and would remain in a fixed position with respect to the Earth. Examples of this type of satellite are the Geostationary Orbiting Experimental Satellite (GOES), weather satellites, and communications satellites. The combination of height and inclination determines the rate at which the orbital plane rotates with respect to the stars. Satellites with altitudes near 1000 km and inclinations near 100° have a plane that rotates 365° per year and passes overhead at the same local time each day. These orbits are called sun synchronous.

TABLE A.2 NOAA AVHRR Channels

	NOAA-6 AVHRR, μm	NOAA-7 and Subsequent Satellites D Through G, μm
Channel 1	0.55-0.9	0.55-0.9
Channel 2	0.725-1.3	0.725-1.3
Channel 3	10.5-11.5	10.5-11.5
Channel 4	3.55-3.93	3.55-3.93
Channel 5		11.5-12.5

TIROS-N/NOAA Series

The TIROS-N/NOAA series of satellites carry advanced sensing devices. The latest of this series, NOAA-6 and NOAA-7, have identical payloads, fly at an altitude between 817 and 830 km, and are in different orbits so as to provide improved synoptic coverage of global meteorological conditions. These near-polar-orbiting sun synchronous satellites have an expected operational lifetime of 2 to 4 years.

Sensor payloads on these satellites include the following:

1. The advanced very high resolution radiometer (AVHRR), which provides data for real-time transmission and for the storage on the satellite digital tape recorders for later playback, is a 4-channel scanning radiometer capable of providing global daytime and nighttime sea surface temperature, ice, snow, and cloud information. These data are obtained on a daily basis for use in weather analysis and forecasting. The multispectral radiometer operates in the scanning mode and measures emitted and reflected radiation in the visible to thermal infrared spectral regions (see Table A.2). Channels 3 and 4 have a thermal resolution of 0.12°K at 300°K. The data recorded on-board include global area coverage, with a resolution of 4 km, and local area coverage data from selected portions of each orbit at 1.1-km resolution. A third thermal channel is now routinely mapping sea surface temperature with a precision of a fraction of a degree celsius over swaths 27 km wide, with a spatial resolution of 11 km.

2. Operational Vertical Sounder (OVS) consists of three instruments—the basic sounding unit, the stratospheric sounding unit, and the microwave sounding unit—designed to determine radiances needed to calculate temperature and humidity profiles of the atmosphere from the surface to the stratosphere (approximately 1 mbar).

3. The Data Collection and Platform Location System (DCS) provides a means to locate and/or collect data from balloon platforms, fixed platforms, and moving buoys. It includes two services not available in the geostationary (GOES) data collection system: (a) the determination of platform location using an inverse Doppler technique; and (2) the ability to acquire data from any place in the world, but most particularly in the polar regions, that are beyond the receiving and retransmission capabilities of the GOES.

4. The Space Environment Monitor (SEM) measures solar proton flux, alpha particle and electron flux density, energy distribution, and spacecraft altitude. The SEM consists of four detectors and a processing unit. The total energy detector measures the intensity of particles with energies above 0.3 KeV. The low-energy proton alpha telescope measures protons between 150 KeV and 40 MeV and alpha particles between 150 KeV and 25 MeV/n. The high energy proton and alpha detector senses protons and alpha particles from 400 to about 1000 MeV. The proton omnidirectional detector measures protons above 10, 30, and 60 MeV, electrons above 140 KeV, and protons and electrons above 750 KeV.

The last three spacecraft in this series are being modified to further enhance the TIROS mission. Three new payloads are being incorporated into the system package of this advanced TIROS-N mission: (1) The Earth radiation budget experiment designed to measure the energy exchange between the Earth atmosphere systems and space. These measurements are considered important for climate prediction and in developing statistical relationships between regional weather and radiation budget anomalies. (2) The solar backscatter ultraviolet radiometer. (3) An experimental payload for search and rescue of aircraft or ships in distress.

Further design studies are under way to prepare TIROS-N for Space Shuttle launches. This currently scheduled series of TIROS-N missions will provide continuity of data through the late 1980s.

LANDSAT Program

The first satellite in the Earth Resources Technology Satellite (ERTS) program was launched July 1972 and named ERTS-1. It was followed into space by a second satellite in January 1975, at which time the ERTS program was renamed Landsat. In March 1978, a third satellite, Landsat-3, was put into orbit. Table A.3 shows a comparison of the spatial resolution and spectral ranges covered by these three systems and their successor satellites Landsat-4 and Landsat-5.

The Landsat satellites (1-3) flew at altitudes that varied between 897 and 918 km in circular, near-polar orbit and crossed the equator at a 99° angle. Completing 14 sun synchronous orbits a day (103 minutes per orbit), these satellites repeated their coverage of any specific point on the Earth's surface at about 9:30 a.m. local time every 18 days. The 14 strips of the Earth's surface covered each day by Landsats 1-3 are successively 2800 km apart at the equator. On each satellite pass, the strip viewed by the sensors is 185 km wide. A day later the satellite passed over a point at the equator 170 km west of that same strip and sensed a contiguous strip 185 km wide. This provides a 14 percent overlap at the equator so that at least 15 km at the edge of each strip were always viewed twice on consecutive days in each 18-day cycle. The image overlap increases with latitude, giving 19 percent overlap at 20° and 34 percent at 40°. An important advantage to areas enjoying overlap coverage is the double opportunity this provides in a 2-day period to obtain a cloud-free image.

Landsat-4, launched on July 31, 1982, maintained the first four bands of Landsat-3 MSS, but has also added an advanced MSS called the Thematic Mapper (TM). The TM was so named because of its intended use in the production of classified images or thematic maps. The TM has seven spectral bands. Six channels (1, 2, 3, 4, 5, 7) have a resolution field-of-view of about 30 m and image in the visible to middle infrared spectral region has a resolution of 120 m.

The fundamental difference between the four-band MSS and the TM is that the MSS scans in only one direction, while the TM scans and obtains data in both directions. Furthermore, the TM detector arrays are located in the instrument's primary focal plane, thus allowing the incoming radiation to be reflected directly onto the detector, while in the MSS the incoming light is first

TABLE A.3 Comparison of the Spectral Ranges

Landsat Satellite	Spectral Ranges, μm							Resolution, μm
	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6	Channel 7	
Landsat-1 MSS	0.5-0.6	0.6-0.7	0.7-0.8	0.8-1.1				80
Landsat-1 RBV	0.47-0.575	0.58-0.68	0.69-0.83					80
Landsat-2 MSS	0.5-0.6	0.6-0.7	0.7-0.8	0.8-1.1	10.4-12.6			80
Landsat-2 RBV	0.47-0.575	0.85-0.68	0.69-0.83					80
Landsat-3 MSS	0.5-0.6	0.6-0.7	0.7-0.8	0.8-1.1	10.4-12.6			80
Landsat-3 RBV	0.53-0.75							40
Landsat-D and D1 MSS	0.5-0.6	0.6-0.7	0.7-0.8	0.8-1.1				80
Landsat-D	0.45-0.52	0.52-6.0	0.63-0.69	0.76-0.90	1.55-1.75	2.08-2.35	10.4-12.5[a]	30

[a] 120-m resolution.

transmitted through fiber optics before being reflected onto the detector arrays with the possibility of some loss of the radiation intensity.

Major improvements in data acquisition will also be achieved through the use of a series of Tracking and Data Relay System (TDRSS) satellites. These satellites, once operational, should eliminate the need for the on-board tape recorders used by the previous Landsats.

The TDRSS satellites will relay the MSS and TM sensor data through one of two satellites to a single ground receiving station in White Sands, New Mexico. (This station was chosen for its relatively cloud-free location because the TDRSS uses a frequency that is particularly affected by atmospheric conditions.) From the White Sands receiving station, the DOMSAT will be used to transmit the data to Goddard Space Flight Center (GSFC), thus reducing the previous delays due to shipping, and from that location, after some processing, the data will then be shipped to its data distribution center.

GOES Program

First in a series of NOAA's GOES program, NASA launched the first Sun-Synchronous Meteorological Satellite (SMS) in May 1974. Since then, six more geostationary satellites have been put into space.

The sensors of the GOES satellites can acquire data and imagery of a fourth of the Earth's surface every 30 minutes. GOES-4, launched September 1980, was the first of these geostationary satellites to carry an atmospheric sounder. This instrument has three modes of operation:

1. Visible and infrared spin-scan radiometer (VISSR) mode, which images in the visible spectral range (0.5 to 0.7 μm) with a ground resolution of 0.9 km. This visible image is obtained simultaneously with an infrared image (11.2 μm) with a 6.9-km ground resolution every half hour.

2. In the multispectral imaging mode, a filter wheel in the infrared optical path allows selection of 11 other infrared bands for imaging, in addition to the infrared band in the VISSR mode. Earth images can be made to represent temperature or moisture distribution in selectable atmospheric layers.

3. Dwell sounding mode is also included in the payload of this satellite in the Ocean Color Scanner (OCS) and the Space Environment Monitor (SEM).

The expected operational lifetime of these satellites is 2 to 4 years. GOES data have been used in the management of water resources to improve rainfall estimates over large areas of the tropics and subtropics, as well as providing information on ocean dynamics and potential fishing areas.

NIMBUS Program

Nimbus-1 was launched in August 1964, and as of January 1981, the spacecraft in this series have returned more than 60,000 hours of "sounder" data on the temperature and pressure and more than 22,600 hours of data on the Earth's heat balance.

Included in the nine systems on Nimbus-7 (launched October 1978) is the Coastal Zone Color Scanner (CZCS). This instrument was planned primarily for biological investigation, but there is evidence from the data now available that the patterns seen in the images trace dynamic ocean features of interest. The CZCS has several channels in the visible to infrared spectral range that depict the distributions of biological and other scattering agents, such as chlorophyll and organic and inorganic suspended materials. Some early use of these images has shown promising application to the studies of the food web and the illumination of the relationship between planktonic distribution and the development of young fish. However, work remains to be done to discriminate between the various biological and physical processes taking place in the upper ocean layer from the CZCS return signals.

The CZCS on Nimbus-7 takes only 4 minutes to acquire the 182,000,000 bits of raw data needed for imaging a scene 1500 km². This results in an average acquisition rate of 760,000 bits per second.

AIRCRAFT SYSTEMS

It is important to understand that remote sensing from aircraft platforms is not in competition with nor should it be considered an alternative to satellite systems. The role of aircraft is supportive. The focus of NASA's airborne remote sensing activity today is on

developing and testing sensors destined for space and on working with new and experimental remote sensing techniques and methodologies, such as multistage sampling designs and new linear and area array sensors and microwave applications. Airborne and space systems complement each other—not only in developing and testing new instruments, techniques, and methodologies, but also in their unique capabilities. The broad synoptic view offered by space systems cannot effectively be achieved by aircraft. Conversely, aircraft are at present capable of far more detailed ground resolutions for detecting and classifying small features. NASA aircraft support work, now centralized at NASA's Ames Research Center (ARC), can provide data that can be correlated with space images and field verification data. These aircraft measurements enhance the potential of both the field and the satellite data by extending detailed surface samples over a wider area with a minimum error on the one hand, and minimizing the variance and ultimately the bias of the satellite data on the other.

NASA's U-2 aircraft have played a key part in the development of sensors for new space systems as well as providing support for various environmental applications. The U-2 is designed for high-altitude (65,000 to 70,000 feet) operations ranging to 2500 nautical miles. The U-2 routinely carries a wide variety of sensors, including aerial mapping cameras, electronic sensors and scanners, and both in situ and remote atmospheric sampling devices. However, the payload for any one flight is limited to approximately 1500 pounds. The U-2 has been used extensively for color infrared photography. An array of camera configurations—featuring a variety of focal lengths, film types, film format sizes, and multispectral capabilities—is available. Uses have varied, depending on the specific remote sensing research and development activity, but include direct evaluation of terrestrial conditions from imagery and the indirect use of imagery for satellite programs.

More than 15 nonphotographic sensors are also flown aboard the U-2; some are part of the NASA inventory but most of them have been built by outside investigators. A palletized system for payload handling makes it easy to switch payloads either in or out of the aircraft or from one aircraft to the other. Table A.4 gives a listing of various sensors that have been flown by the U-2. This list is by no means exhaustive, but is meant to provide a sample.

Similar developments for design of spaceborne sensors occurred using the C-130 aircraft. The C-130 has at times been

TABLE A.4 NASA U-2 Aircraft Remote Sensor Systems

Sensor	Use
Stratospheric and Atmospheric Studies	
Aerosol Particulate Sampler	gathers high-altitude dust particles for laboratory research
Stratospheric Air Sampler	real-time measurements of nitric oxide and ozone concentrations in the lower stratosphere
Water Vapor Radiometer	upward-looking sensor designed to determine total water vapor overburden above aircraft
Condensation Nucleus Counter	measures concentration of particulates having diameters between 0.01 and 1.0 μm
Infrared Radiometer	measures atmospheric non-uniformities in 4- to 5- μm spectral region
Calibrated Air Measurements Program	radiometer that looks downward and measures radiance from the Earth and objects in the atmosphere in six different infrared wavelengths
Quartz Crystal Microbalance Cascade Impactor	senses the mass of suspended particulates as a function of particle size
Daisibi Ozone Monitor	measures low ozone levels
Lyman Hygrometer	measures water vapor
Stratospheric Cryogenic Sampler	samples large volumes of stratospheric air for laboratory analysis of trace gases
Ocean Studies	
Ocean Color Scanner	10-channel multispectral scanner designed for water color measurements

TABLE A.4 (continued)

Sensor	Use
Ocean Temperature Scanner	5-channel scanning radiometer designed to make accurate measurements of sea surface temperature
Heat Capacity Mapping Radiometer	2-channel scanning radiometer that images in visible and thermal infrared bands used to detect thermal pollution

Land Studies

Daedalus Multispectral Scanner	12-channels covering the visible and near-infrared portions of the spectrum with one channel in the thermal infrared
Thematic Mapper Simulator	high-altitude multispectral scanner that simulates spatial and spectral characteristics of the seven Landsat-D Thematic Mapper bands
Heat Capacity Mapping Radiometer	same as listed above, but used to detect wetlands and soil moisture
Airborne Imaging Spectrometer	experimental instrument to acquire data in 2.0- to 2.4- μm region with 10- to 30- μm spectral resolution

Cameras

Research Camera System Vjntent 70-mm framing camera I^{2}S Multispectral 4-bands	high-resolution photographic system consisting of 70-mm panoramic cameras
Wild-Heerbrug RC-10 framing camera Itek Optical Bar	with 24-inch focal length lenses that provide stereo coverage

equipped with both passive and active microwave sensors in addition to a multispectral scanner. These instruments were flown for a variety of investigations, which provided a basis for the Shuttle Imaging Radar (SIR) and for evolving soil moisture studies in support of Earth resources and climate applications.

For several years, NASA's Lewis Research Center has conducted lake ice studies in the Great Lakes region using radar-equipped C-130 aircraft. In 1975, experimental work with aircraft culminated with the establishment of a fully operational system for monitoring winter lake ice as an aid to shipping. This project, known as the Great Lakes Ice Information System, is one of the very few technology transfer efforts employing an airborne platform exclusively for the surveillance task. Developed by NASA, the system is now operated by the U.S. Coast Guard. During the ice season, daily flights over the Great Lakes ice fields are made by a Coast Guard C-130 aircraft equipped with a side-looking radar. Data acquired by the aircraft are relayed via the GOES-1 satellite to the Coast Guard's Ice Navigation Center in Cleveland, where images are annotated and sent on in facsimile to ships on the lakes to guide them through ice fields. As a result of this experiment, a similar system was installed in cooperation with the Coast Guard in Alaska to aid shipping in the Beaufort Sea.

NASA's WB-57F provides a high-altitude (60,000 feet) capability and accommodates large payloads up to about 4000 pounds. The WB-57F is equipped with a modularized pallet system that permits the rapid changeout of sensors without imposing excessive down time on the aircraft. The WB-57F is equippedwith a synthetic aperture radar, multispectral scanners, and a photographic capability for interagency support missions.

Also located at ARC is the Galileo II, a Convair 990. This aircraft is a flying laboratory capable of multiprogram support in applications, aeronautics, and space science. However, it is used primarily for applications research tasks. The CV 990 does not have a sensor complement as does the C-130. It is used mostly as an instrument test platform, but one where the principal investigator works in a hands-on mode with his equipment in a shirtsleeve environment. Numerous investigators and their instruments can be accommodated on a single mission or series of flights. Racks with their instruments are coupled with aircraft power sources, viewports, exterior mounts, and an air data system to superimpose flight parameters with the scientific data, and an on-board

data recording system. ARC assigns a mission manager to each expedition, who acts as the primary contact point for the investigators and is in charge of all planning and on-board experiment operations.

The future of airborne research in NASA must be viewed critically. In the business of rapidly expanding space technology, the aircraft remains a cost-effective bridge from concepts to in-orbit capability. Both high- and medium-altitude platforms will be needed for scientific and applications research programs. The justification for these aircraft will remain strongly tied to the user needs and economics that have driven the effort over the past decade.

Multistage Data Collection

Multistage sampling yields progressively more detailed information for correspondingly smaller units of the area under study. By carefully selecting surface sample sites and choosing appropriate platforms and sensor systems, the more detailed subsamples make it possible to extrapolate findings to an entire Landsat scene and thereby to produce an inventory of chosen features.

The special roles of aircraft sensing and ground observations in a full system of remote sensing may be briefly described as follows:

1. *Aircraft Sensing*: Aerial photography missions can be flown over a specified area to collect data of an intermediate level between satellite sensing and ground observation. If acquired concurrently with a Landsat overpass, or reasonably soon thereafter, the data may be used as "ground truth" with which to calibrate the data of the space sensors.

In addition, for purposes not met by satellite sensing, aerial photography or sensing is frequently the sole alternative. Aircraft provide excellent platforms for photographic cameras, magnetometers, radar, scintillation counters, and infrared instruments, particularly for data collecting missions not requiring repetitive monitoring of wide areas under uniform conditions. New aerial sensors are continually being developed for mineral and petroleum exploration, mapping, geophysical study, and applications relating to forestry, agriculture, ecology, and water resources.

Low-altitude (up to 9 km) aircraft are used currently in range management, fish spotting, water quality studies, and aquisition

of photos for mapping and charting. Medium altitude (9 to 15 km) aircraft, equipped with side-looking radar, radar scatterometers, infrared and multispectral cameras, and various metric and multiband photographic equipment are of special value for photoreconnaissance, urban planning, agricultural monitoring, and environmental quality applications. High-altitude (over 15 km) planes with high-resolution and wide angle cameras, and various infrared cameras and scanners are used in horizon scanning and broad-area, high-resolution mapping. High-altitude, high-resolution photography proved to be extremely valuable in assessing the damage from the Guatemala earthquake in 1976.

Aircraft systems can provide MSS hard copy film and tape for on-ground analysis; some are equipped for on-board analysis or data editing. The aircraft's special advantage lies in the flexibility it offers in the selection of the best line of flight, altitude, and time of day for one-time studies or for observing specific events.

2. *Ground Observation*: Ground observations are essential components of any remote sensing program. Whether an investigation is based on spaceborne or on airborne sensing data, the resulting data may be meaningless without "ground truth"—the examination, sampling, or measurement of features of the Earth's surface to correlate what is seen on the remote sensing data with what actually exists on the ground. The need for such a correlation exists with respect to both static and dynamic elements of the Earth's surface.

Information needs for some broad catagories of information can at times be met by study of satellite data with virtually no ground observation. If hydrologists wish to know the surface area of a country's lakes and reservoirs, spectral analysis of the satellite data alone can yield the answer, often with better than 90 percent absolute accuracy.

In general, however, without ground measurements and observations appropriate to the remote sensing task, the accuracy of information acquired from satellite data may fall below acceptable standards. If the objective, for instance, is to identify, separate, and map categories of green vegetation, along with categories of water, or different soil mapping classification units, the ground observation component becomes exceedingly important.

For some monitoring purposes, in fields such as agriculture and forestry, the need for continued validation of the space data

by ground observations can be progressively reduced with succeed-
ing passes as the data signatures become familiar with experience.
The extent and nature of the ground study in a particular remote
sensing program depend not only on the program's objectives, but
also on the types of sensors used and the methods of data analy-
sis to be employed. To assure efficiency and accuracy in a study,
investigators must carefully select the optimum timing of measure-
ments, sample location, instrumentation, and the properties to be
observed or measured.

APPENDIX B:
GLOSSARY

albedo: The fraction of visible light that is reflected from a surface.

anaerobic: Living or active in the absence of free oxygen.

anoxic: Deprived of oxygen

biome: A biological unit of the biosphere. A biome includes a set of ecosystems that exist under a similar climatic regime and have dominant species with a similar life cycle, climatic adaptations, and physical structure. Tropical savannahs, composed of a mixture of trees and shrubs in a semiarid climate, are an example of a biome.

biosphere: In this report, the biosphere is defined as the entire planetary system that includes and sustains life. Therefore, it includes all of the biota and those portions of the atmosphere, oceans, and sediments in active interchange with the biota.

denitrification: The conversion of nitrate to molecular nitrogen by the action of bacteria. This is an important step in the global nitrogen cycle.

ecology: The science that is the study of the relationships between living things and their environment.

ecosystem: A local set of species and their local nonbiological environment.

ecosystem function: All processes required to sustain life and carried out by ecosystems, including biological productivity, chemical cycling, and energy flow.

eukaryotic cell: A cell that has a nucleus and certain other characteristics that separate it from prokaryotic cells. Eukaryotic cells are those found in higher plants and animals.

leaf area index: The ratio of leaf area (m^2) per unit land area (m^2).

net primary production: Primary production is the production of vegetation and other autotrophic organisms. Net primary production is the net production remaining after utilization. Net primary production is measured typically as grams per unit area or volume.

net primary productivity: The rate of change in organic matter. It is typically measured as grams per unit area or unit volume per unit time. For example, the net primary productivity of a forest is the grams per square meter per year.

oligotrophic: Low in nutrients. Applied to bodies of fresh water. An oligotrophic lake in low in the chemical elements required for life; it is therefore typically clear and low in biomass of algae. photic zone: The upper zone of a lake, sea, or ocean where light is bright enough for photosynthesis to occur and for photosynthetic organisms to grow and reproduce.

prokaryotic cell: A cell lacking a nucleus and other characteristics that distinguish it from eukaryotic cells. Bacteria have prokaryotic cells. Prokaryotic organisms evolved before eukaryotic organisms.

upwelling: In an ocean or sea, (1) a vertical current that brings chemical elements from the bottom waters to the surface; (2) an area, typically on a continental shelf, where vertical currents occur.

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