THE SCIENCE OF THE BIOSPHERE

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(Received 21 March, 1985)

Abstract. This paper considers the needs and potentials for the development of the biosphere. An emphasis is placed on the unusual qualities of the biosphere, such as important time lags, interactions between life and its environment at large scales, and biological evolution, which has led to large scale changes in the environment during the Earth's history. These qualities require a different approach to the development of a theory for this large scale system than has been used in the past, when the biosphere was treated as a steady-state, quasi-linear system. Other aspects of the development of the science of the biosphere, including the use of remote sensing, are reviewed, and the application of these techniques to the estimation of certain biological variables is discussed.

1. Introduction

The study of the biosphere – the large-scale planetary system that sustains and includes life – is developing into an exciting area of research. The recent excitement in this subject has to do with two factors: the re-emergence of a synoptic view of life, in a planetary perspective, and the development of new technologies that seem to offer the possibility to make this study quantitative. It is my purpose today to introduce the study of the biosphere to those interested in chemical evolution and the origin of life.

To accomplish this, in this talk I would like to try to do two things: first to discuss some general aspects of the study of the biosphere and second to discuss some of our research which derives from these general issues.

The study of the biosphere is important for the understanding of chemical evolution and the origin of life, two investigations that are intimately linked. Scratch the surface of most biologists' heads and you will discover each is asking the same question, albeit at different levels: why do I find this form of life (individual, ecosystem, biosphere) *here* and not *there*. But to ask this is to ask two questions: "How did life get here?" and "What allows it to persist?" At the planetary level, the first question is, "How did life originate?"; the second is a question about how the biosphere operates-that is, "What are the qualities of a planetary system that sustains life over long periods?" To go one step further, one can argue that progress in unraveling the origin of life will be greatly enhanced by an understanding of what is required to sustain life over long periods, and by elucidating the constraints forced on all life by the necessary characteristics of a large life-support system. Thus the study of the biosphere should become more important to those interested in chemical evolution and the origin of life.

Life interacts with the environment in complex ways at a global scale: the biota affect the Earth's energy budget and its climate and the global chemical cycles; climate and biota interact. Not only does the climate affect life locally, regionally, and globally, but evidence is accumulating that life affects climate, at least on regional scales, and thus *probably* on a global scale. Life depends on the cycling of many chemical elements; the biota also greatly influence and alter these cycles. Life influences the Earth's energy budget directly by changing the reflective characteristics of surface (green vegetation reflects differently from bare soil), the biota influences the energy budget indirectly, by emitting greenhouse gases to and removing them from the atmosphere.

2. Some Qualities of the Biosphere

Accepting the importance of the biosphere, we must then ask how can we approach the study of it? In the past, the biosphere has been viewed simply, as if it were a steady state-system. In regard to biogeochemical cycles, it has usually been assumed that this steady-state system could be viewed as a set of storage compartments each linked to others by simple, linear flows. The number of compartments was usually very few. For example, some of the models of the global carbon cycle divided the Earth into land, oceans, atmosphere, and life. Much of the reason for this simplicity was the lack of data and the lack of understanding of the dynamics of the biosphere. We are now at a stage where the questions we are asking – and we are being forced to ask by global environmental issues – require better answers than can be provided by these very simplified views.

To emphasize this, I would like to describe a few of the aspects of the biosphere that make it complex. First of all, any large scale system containing, sustaining, and affected by life has features which are quite different from standard systems that have been subject to a long history of analysis – systems such as mechanical ones, cars and aircraft – using engineering system theory.

For one, the biosphere is characterized by time lags at many different time-scales. For example, the return of forests to the north following the end of the last ice age took thousands of years, even though the climate returned much faster to conditions that would have allowed tree growth.

The biosphere is also characterized by a 'mutual causality' between the biota and aspects of the environment. The interaction between climate and biota illustrates this interaction.

Biological evolution is itself a biospheric complication; it is a kind of 'trick' that the biota play on this system, since evolution of new characteristics is as if the parts of the system change while the system continues to operate.

Another complex quality of the biosphere is that the biota undergo and respond to episodic events which are extremely important. Many biologists believe that the importance of an event to the biota in inversely related to its frequency; the less common the more important it will be.

These and other qualities lead to a peculiar system, about which we know very little. All of this is well illustrated by the now famous series of measurements of carbon dioxide made since 1957 at Mauna Loa observatory in Hawaii. The NOAA laboratory is sited there at 11 500 feet, which places it generally above the local affects of human activities and vegetation. Since Hawaii is several thousand miles downwind from the nearest major landmass, observations taken at Mauna Loa should represent a good background measure of the gaseous constitution of the atmosphere. However, the CO_2 concentration in the atmosphere measured at Mauna Loa shows two very interesting and now well-known patterns: a continuous upward trend, and an annual oscillation. The upward trend has been generally attributed to the addition of carbon dioxide from the burning of fossil fuels. The annual oscillation is due to the storage and release of carbon by land vegetation, corresponding to the annual cycle of summer growth and winter respiration.

The Mauna Loa data pose a puzzle. They indicate that the atmospheric concentration of carbon dioxide is increasing at approximately a rate of 2.3 billion metric tons per year. However, calculations of the rate of burning of fossil fuels suggest that approximately 5 billion metric tons are added to the atmosphere from that source alone. A large fraction of this carbon is transferred directly to the ocean, but calculations based on the chemistry and physics of atmospheric-ocean interchange suggest that some 0.5 billion metric tons of carbon are still unaccounted for. The puzzle is: what has happened to the missing carbon?

Several 'hiding places' have been suggested. Broeker (1979) suggested that the remaining carbon could be taken up by land vegetation. For this to happen, however, two assumptions must be met: the rate of regrowth of land vegetation is greater than the rate of land clearing; and the carbon dioxide increase in the atmosphere has acted to fertilize the rate of photosynthesis. The increase in photosynthesis accompanying an increase in carbon dioxide concentration is a well-known phenomenon from laboratory experiments. However, the complex interactions among all the biogeochemical cycles, as well as the influence of climate on biological production, make it unclear whether such a fertilization effect has actually taken place. (A contrary argument has also been proposed: that land vegetation, rather than acting as a sink for the missing carbon, is actually a net source. This assumes that the rate of land clearing exceeds the rate of vegetation regrowth. There is some, but very sketchy, evidence that can be used to support this hypothesis.)

Another possible fate for the missing carbon has been suggested by Walsh (1981). He proposed that there could be an increase in the photosynthesis among the planktonic algae in the ocean waters along the continental shelves. While this would not lead to an increase in the algal biomass, since the algae have a very short generation time, it could increase the production of all organisms in the food chain that depends on that algae. This in turn could increase the production of dead organic matter, which would lead to an increase in the deposition of carbon on the floor of the continental shelves.

Which of these hypotheses is correct? How can we resolve the missing carbon problem? It is necessary that we obtain accurate measurements of the amount of biomass on the land and the rate of change in this biomass, to determine whether the land biota are source or sink for carbon at the present time. This leads to the second part of my talk, which concerns our research on developing methods to make such measurements.

There is a century of history of estimates about the total organic matter on the Earth. Liebig (1862) in the nineteenth century was among the earliest to make an estimate and took an approach still used today: he used measurements of biomass density from a few local sites, and multiplied these by estimates of the total land mass in vegetation. The problem then, and today, is that the estimates of both biomass density and areal extent are too inaccurate to provide acceptable measures. In fact, it is not possible to obtain any meaningful measure of statistical error from the existing estimates.

In the past, there have been two approaches to estimating global biomass and net primary production. The first approach is, following Liebig's method, to take direct measurements, made *in situ*, from a few locations, and then multiple these estimate by estimates of the area covered by vegetation. Usually this is done for each major biome, and all estimates summed. The problem with this approach is the lack of data.

The second approach is to correlate biomass and biological production with environmental conditions, and then use maps of environmental conditions to predict the potential vegetation biomass and production. Usually the environmental conditions are temperature and some index of soil water, or an index that is a combination of these, such as actual or potential evapotranspiration. For example, Lieth (1975a) made a global map of net primary production based on evapotranspiration. This was a valuable first step, but it too was limited by the paucity of data. Lieth used 52 measurements of evapotranspiration and net primary production in one vegetation type, and from these extrapolated to global land vegetation production.

Neither of these techniques have been done with adequate data to lead to sufficiently accurate measurements to help resolve the missing carbon issue. Measures of both the biomass density and the areal extent of biomes remain inaccurate.

How can we obtain the necessary accuracy? The prospects for doing this solely by ground measurements are dim. A very large number of measurements would be required at many remote locations. The difficulties increase rapidly for a program that plans to monitor these factors at periodic intervals. Remote sensing seems to be a necessary tool, but considerable research is needed to develop and test techniques that could be used to measure biomass and net primary production by remote sensing.

3. Remote Sensing of Biomass and Biological Production

As a first step, we are attempting to develop methods to estimate biomass and biological production for one major biome, the boreal forest. We have chosen this biome because it seems to offer the simplest case for measurement, yet it is a major biome of the world. In North America, it is estimated that the boreal forests occupy more than one-half of the total forested area. The advantages of beginning this work with the boreal forested are many. Boreal forests have relatively few species, some of which occur over wide ranges; large areas exit on terrain of low topographic relief, and, compared to other areas such as tropical rainforests, boreal forests exist in areas with a relatively large number of cloud-free days. All of these reduce the difficulty of using remote sensing.

One key to the remote sensing approach we are using is the leaf area index (LAI), which is the areas of leaves above an area of the ground. Waring (1983) has shown that biomass and forest production are linearly correlated with LAI, at least for mature stands under a variety of climatic regimes. Moreover, other work has indicated that the leaf area index can be detected by remote sensing (MacDonald and Hall, 1981). Leaf area index, for example, was the central measure in the LACIE project that used remote sensing to estimate world wheat production (MacDonald and Hall, 1978).

Existing data suggests, therefore, that remote sensing of leaf area index could provide estimates of biomass and vegetation production. We have taken this as a hypothesis which we are testing under the simplest conditions we could find for a boreal forest.

We have begun this work in the Superior National Forest, Minnesota. This site was chosen because it provide excellent logistics, has a long history of ecological research, has low topographic relief, and is one of the major areas in the lower 48 states where the boreal forest occurs.

We are attempting to test techniques in a way that allows us to evaluate precisely what the remote sensing instruments are responding to. The approach involves a series of stages, beginning with measurements on the ground, proceeding to measurements made from a Barnes 8 band radiometer mounted in a helicopter which hovers at 130 m above forest plots. We are also using measurements made at three other scales: measurements made from a C-100 aircraft carrying the Thematic Mapper Simulator and also making high altitude photographs; LANDSAT satellite imagery with a resolution of either 80 or 30 meters, and advanced very high resolution radiometer (AVHRR) imagery, with a resolution of 1 km. In this talk I will focus on the helicopter work.

The procedure we have used is to establish a series of plots ranging from low to high LAI for two representative species: black spruce (*Picea mariana*) and trembling aspen (*Populus tremuloides*). These are the two tree species with the broadest geographic ranges in North America, both being found from Alaska to eastern Canada. We chose to begin our research with these species not only because of their major geographic range, but also because they represent biological and ecological extremes. The spruce is a conifer, dark in color, evergreen, found in bogs and wetlands, and characteristic of old forests (forests undisturbed for comparatively long periods). Aspen is an angiosperm, deciduous, with light colored leaves, found on upland areas and poor soils, and characteristic of recently disturbed areas.

Approximate 30 plots of each species, each at least 60 m in diameter, were established. From 130 m altitude, the Barnes radiometer views a circle of diameter 30 m, the same as one pixel of the Thematic Mapper in the LANDSAT satellite. We set out plots with twice this diameter to avoid boundary problems. Within this 60 m we have laid out five field plots, with the centers along a cross, one plot at the intersection of the cross and one plot at each end of the cross.

4. Field Measurements

Because repeated measurements were required, we could not use destructive techniques to measure biomass and production *in situ*. Moreover, such destructive measures are extremely labor-intensive and could not be used for a broad survey of vegetation, and therefore would not have been desirable as part of the test of our techniques. Instead, we used a two stage sampling method, with non-destructive measurements made on the remote sensing plots, and destructive measures made elsewhere following a well-known ecological technique called dimension analysis.

Dimension analysis is a procedure that relates simple dimensions of trees, such as tree diameter and height, to biomass, leaf area, and production. The procedure involves cutting down trees representing the entire range of sizes of a species, measuring the dimensions, and measuring, through subsampling procedures, the biomass, leaf area, and production. Once this is done, regression equations are developed, relating these factors to tree diameter, height, etc. These then allow one to measure the dimensions non-destructively on the experimental plots and calculate area, and production.

The helicopter was flown repeatedly through the 1983 growing season, beginning in spring and continuing into the late fall. We are still in the process of analyzing the data, but have some preliminary results (Table I). These show that one remote sensing index, the ratio of infrared to red reflectance, appears to distinguish (1) aspen from spruce both before and after leaf emergence of the aspen in the spring; (2) the increase in leaf area index of the aspen as the leaves emerge and expand during the spring; and (3) low and high leaf area indices. While preliminary, these results are encouraging.

We are continuing to analyze these data, and to analyze the other information obtained from high altitude aircraft, LANDSAT, and AVHRR satellites.

TABLE I

Ratio of infrared (.76-.90nm) to red (.63-.69nm) reflectance

	n	May 15	June 9
Black spruce – dense	3	5.9	5.2
Black spruce – sparse	3	3.3	3.6
Aspen – intermediate	2	2.5	9.7
Aspen – mature	2	2.2	7.0

Ratio of light infrared (.76 - .90 nm) to red (.63 - .69nm) reflectance for spurce and dense spurce and aspen stands in the Superior National Forest, Ely, Minnesota.

5. Summary

The biosphere represents a new, exciting area of research. The biosphere is a complex system, with many features that we are not accustomed to finding in systems that scientists have analyzed in the past. This makes the study of the biosphere fascinating, but difficult. The state of the study of the biosphere is primitive, and we lack even the most basic measurements of the current state of this large scale system. Of great importance, we lack accurate and reliable measurements of the biomass and production of the Earth's land vegetation. We have begun a research program to attempt to develop and test techniques to obtain these measurements by remote sensing. Although just in its early stages, the results from this research are encouraging.

Acknowledgements

This research is part of a cooperative agreement between the University of California, Santa Barbara, and NASA's Johnson Space Center. The principal investigators under this agreement are myself, J. E. Estes, and R. M. MacDonald. Many people have contributed to this research including F. Hall, K. Woods, D. Pitts, A. Feiveson, G. Badhwar, G. Houston. T. Reynales. C. Sladek contributed to the preparation of this manuscript.

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