

Reprinted from

Tenth International Symposium

Machine Processing of

Remotely Sensed Data

with special emphasis on

Thematic Mapper Data and

Geographic Information Systems

June 12 - 14, 1984

Proceedings

Purdue University
The Laboratory for Applications of Remote Sensing
West Lafayette, Indiana 47907 USA

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ROLE OF VEGETATION IN THE BIOSPHERE

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ABSTRACT

Land vegetation plays a major role in the biosphere. Understanding this role requires remote sensing. A program in biospheric research would include remote sensing to classify major vegetation landscape units and to measure leaf area index. These measurements would be combined with remote sensing and in situ measurements of climate and soil conditions. This paper reviews the role of vegetation in the biosphere and discusses an approach to the required remote sensing research.

1. INTRODUCTION

The "biosphere" is the planetary scale system that sustains and includes life. It includes all of the biota, as well as those parts of the atmosphere, the oceans, and the sediments which are in active exchange with the biota. In the biosphere, terrestrial vegetation plays an important role, greatly affecting the energy budget and biogeochemistry of the Earth. These effects are so great that it is not possible to understand the response of the biosphere to any major change without taking into account the effects of the land surface and its vegetation.

Some effects are due simply to the presence of vegetation, as in the effects of vegetation cover on reflection of sunlight by the surface. It is well known that vegetated surfaces have a much different albedo than a bare soil or exposed rock surface. There are also important differences in albedo among major classes of vegetation. For example, a northern coniferous forest has a considerably different albedo than tundra. A global change in climate that changed the relative area covered by tundra and conifer forest might change the Earth's

total albedo and lead to a further climatic change.

Other biospheric effects of vegetation occur indirectly, as when vegetation affects the gaseous concentration of the atmosphere. Terrestrial vegetation has a rapid interchange of carbon dioxide, oxygen, and water with the atmosphere, and these interchanges affect the atmospheric concentration on daily, seasonal, annual and longer time scales.

The effects of terrestrial vegetation are illustrated by the hydrologic cycle. Recent analyses suggest that as much as two-thirds of the precipitation in tropical rain forests is returned to the atmosphere by evapotranspiration. For a given soil and vegetation type, evapotranspiration is directly proportional to the number of layers of leaves above a given area of ground, known as the leaf area index (LAI). The conversion of tropical rainforests to cropland greatly decreases leaf area index, reducing evapotranspiration and increasing runoff.

In general, a major regional removal of vegetation could increase the surface temperature because of the change in the surface albedo and the loss in cooling effects from the evaporation of water. Such a change over a large region such as the Amazon Basin could greatly decrease the regional transfer of water from the land to the atmosphere, decrease the amount of energy lost from the land to the atmosphere by the latent heat of evaporation, increase the surface temperature, and increase runoff, soil erosion, and sediment transport to the ocean. The change in runoff would in turn affect the transfer of chemical elements from the land to the ocean, which could affect coastal marine biological productivity. Models of global

atmospheric circulation also suggest that such regional change could have complex global effects on climate, because it could alter the general atmospheric circulation.

The indirect effect of terrestrial vegetation on the biosphere are clearly illustrated by comparing the well known series of measurements of atmospheric carbon dioxide concentration acquired at the Mauna Loa Observatory, Hawaii (Coulson, per. comm), and in Antarctica (Ekdahl and Keeling 1972). Both series of measurements show an annual cycle, decreasing in the summer and increasing in the winter, caused by the summer uptake of carbon dioxide by land vegetation, but the amplitude of the Antarctic variations is much smaller than that at Mauna Loa. This is a consequence of the smaller amount of vegetated land mass in the southern hemisphere compared to the northern hemisphere. These measurements illustrate the impact of land vegetation on short-term variations in the concentration of atmospheric carbon dioxide. The potential climatic implications of such changes because of the "greenhouse effect" are well known.

Terrestrial vegetation and soils also have longer-term effects on the biosphere. Current estimates of global productivity and biomass (Olson, et al., 1984; Aitay et al., 1977; Rodin et al. 1975; Baes et al., 1976) suggest that terrestrial vegetation contains 500 to 700 x 10¹⁵ g carbon, about as much carbon as is in the atmosphere (700 x 10¹⁵ g carbon), while terrestrial soils contain perhaps twice as much. Soils and perennial land vegetation are a major reservoir over periods of years, decades, and centuries for carbon and other elements essential for life.

Some classes of terrestrial vegetation may have greater biospheric effects than others. For example, the importance of salt marsh vegetation may be much greater than one would believe simply from the land area they cover, in part because salt marshes are a major source of methane, an important greenhouse gas. Methane represents only 0.00015% of the atmosphere, but this concentration increases the Earth's temperature by 10 C (Walker, 1977). Marshes are also major sources and sinks for sulfur compounds, and must be considered important chemical refractors for the entire biosphere. Marsh vegetation provide habitats for, and may act as symbionts for, prokaryotic organisms which carry out these chemical reactions. A major climatic change could change sea level, which would markedly change the distribution and abundance of

marshes. A rapid, catastrophic change in sea level could temporarily eliminate many of the active marshes and lead to a temporary major change in the production of absorption of trace gases.

II. AN OPERATIONAL APPROACH TO THE STUDY OF VEGETATION IN THE BIOSPHERE

We have established the role of terrestrial vegetation in influencing energy, water and biogeochemical cycles. The operational question is how to best describe vegetation to allow measurement and analysis of energy and mass exchange. Two kinds of measurements are required: (1) the areal extent of "biomes" (which are major classes of biota); and (2) the organic matter and biological activity density (the amount of organic matter per unit land area and the rate of energy and mass exchange per unit land area within each biome). Remote sensing offers a great potential for these measurements. Indeed, it is only with remote sensing that measurements at a sufficiently large scale--regional and global--can be made. Without remote sensing, the study of terrestrial vegetation's effect on the biosphere would not be possible. This potential, however, has barely been tapped.

Remote sensing has been used to provide a basic delineation of vegetation into forest, chaparral, grassland, farmland, desert, etc. This "biome level" classification has been accomplished from LANDSAT digital imagery by a number of investigators, and there are some recent attempts to accomplish similar classifications using the Advanced Very High Resolution Radiometer (AVHRR). The classification of terrestrial vegetation by remote sensing, however, has been done predominantly on the basis of "physiognomic" types--on the gross shape and form of vegetation. (Shrubs are a physiognomic type; a shrubland is a vegetation classification based on physiognomy.) It is not at all clear that this basis is the best in terms of biospheric influences. Physiognomy may not be closely related to biomass density or the rate of energy and mass exchange.

Furthermore, the level of classification needs to be extended. It is recognized by ecologists that within each biome type there is potential for a wide range of energy and mass exchange. Within the coniferous forest biome, for example, annual carbon fixation of mature stands can easily vary by a factor of 20 (Kira 1975). Evapotranspiration by

temperate forests can range from 40cm to 75cm annually, while tropical forests may contribute over 130cm to atmospheric water (Rozenzweig 1968). Long term accumulations of carbon, nitrogen, phosphorus, and other important elements can also vary by a factor of 10 or more (O'Neill and DeAngelis 1981). Clearly, biome type classification is insufficient to describe the magnitudes of energy and mass exchange even within a single class of vegetation. Remote sensing techniques and classification schemes must be developed that distinguish vegetation on the basis of biomass density and the rates of energy and mass exchange.

Leaf area index (LAI) is the single most useful structural characteristic of vegetation for the quantitative analyses of interest in global ecology (Botkin 1980, 1982a, 1982b). LAI provides a means of estimating carbon fixation, evapotranspiration, and elemental accumulations of the vegetation directly (Webb et. al. 1983). Therefore the first priority of a global vegetation study must be to accurately measure LAI from a satellite data base. The remaining papers in this symposium will present the current capabilities of satellite estimation of LAI in forests, grasslands and croplands. In this introductory paper we will discuss the temporal dynamics of LAI development in a plant community and the global range of LAI observed in different biomes. Additionally, we will attempt to illustrate how knowledge of LAI can be used to estimate net production of organic matter by vegetation (known as net primary production or NPP) and total biomass. Comprehensive analysis of biogeochemical cycling in vegetated land surfaces will require explicit definition of near-surface climatic patterns and the development of more mechanistic ecosystem models of carbon, nitrogen, phosphorus, and sulfur cycling than exist at present.

A. FACTORS CONTROLLING LAI

Three primary factors determine the LAI displayed by a land surface at any given time. These are (1) the vegetation type, whether forest, grassland, cropland etc.; (2) the stage of development in the life cycle of the vegetation; and (3) the climate. The capability for routine satellite discrimination of vegetation type already exists, and with this alone some information on the range of LAI is possible (Table 1). This approach provides an estimate of the maximum LAI that could exist in each measured area.

However, these maxima LAI presuppose mature vegetation communities. Plant communities in other stages of development will display LAI ranging from 0 in an area just cleared of vegetation to a maximum value that occurs at maturity. Ultimately we must be able to distinguish mature from immature vegetation, particularly for long-lived perennial plant communities.

The general LAI dynamics of vegetation are surprisingly similar across biomes if plotted as a function of life cycle, not time (figure 1). In figure 1 the time scale (X axis) may vary from 1 year in an annual crop or grassland to over 1,000 years for the longest-lived coniferous forests. In like manner, figure 1 can describe the relationship among other important ecosystem variables, changing only scale. Maximum LAI can range between 0 and 23. NPP can vary by at least a factor of 100 from desert to tropical rain forest. Total Basal Area (TBA) varies by three orders of magnitude from arctic tundra to the redwood forests. In each case the general relationship in figure 1 remains the same, only the scale of the Y-axis changes. As a plant community reaches maturity, NPP slows, total biomass approaches a steady-state, and biogeochemical activity becomes one more of internal cycling than accumulation.

Environmental Control of LAI

Climate exerts a strong control over LAI, even within a single biome. Grier and Running (1977) were able to predict the LAI of mature coniferous forests across Oregon ($R^2=0.99$) by computing a simple site water balance in this water limited region. LAI ranged from 21 in the dense stands along the Pacific coast to 2 in the semi-arid savannah-like stands of central Oregon, all within one biome--the coniferous forest. Similar gradients of LAI controlled by water availability are found in grasslands and chaparral.

In other environments, different climatic factors may control LAI. The extreme temperatures of the arctic tundra limit the growing season so severely that LAI of only 0-2 can develop, regardless of biome type (Van Cleve et al 1983). Tropical rain forests are not temperature or water limited. There, light penetration through multiple layers of canopy becomes so dim that lower leaves can no longer maintain positive net photosynthesis rates. Deciduous forests of the eastern United States appear to develop LAI as a function of site fertility and

nutrient cycling efficiency. The complex interaction among biome type, climate, soil and LAI make prediction of LAI rather difficult. Direct, regular measurement from satellite sensors could solve this problem and lead to the next stage of land surface research.

B. ANALYSIS OF NPP FROM LAI

LAI is important as an intermediate variable to allow estimation of NPP, total biomass, and the status of associated elemental cycles. A first look at these variables for biomes worldwide can be derived from a well-known data set compiled by Whittaker and Likens (1975) shown in abbreviated form in Table 1. These average values illustrate that forests have much higher LAI than other vegetation types. However forests do not necessarily generate correspondingly higher NPP than savannahs, grasslands or croplands. Climate exerts a major influence on the NPP realized for a given LAI regardless of biome type.

A first approximation of the relationship of LAI with NPP combining deserts, grasslands, deciduous and coniferous forests has been completed by Webb et al (1983). They correlated LAI with NPP ($R^2=0.79$) for these biome types across the United States. The success of this correlation lay primarily in the tremendous range of LAI and NPP covered. Although this equation could be used to generate a rough estimate of large scale NPP once LAI was known, insensitivity to climate and vegetation stage severely limits accuracy within a biome. For example, the correlation of LAI versus NPP within the coniferous forest biome was only $R^2=0.21$. However Gholz (1982) found a very high correlation between LAI and NPP ($R^2=0.96$) when only mature forests were considered within a small area, in this case Oregon. A more careful analysis of differing efficiencies of NPP:LAI for different biome types is shown in figure 2, using the data from Table 1. Clearly, estimates of NPP can be markedly improved by using biome specific ratios of NPP:LAI which reflect the varying efficiencies of different vegetation in converting solar energy to plant biomass.

Further improvements in the prediction of NPP could be made by including remote sensing of climatic conditions. To illustrate, when NPP:LAI is compared for coniferous stands in Florida, Oregon, and Washington, the range of production efficiencies differed noticeably (Fig. 3) (Grier et al 1981, Gholz 1982, Gholz and Fisher 1982). Slash

pine stands in Florida exhibit much more growth per unit leaf area than either the Oregon or Washington stands. The warm, wet year-round climate of Florida allows much greater photosynthesis than the Pacific Northwest. However, while the Oregon and Washington stands had lower growth efficiency per unit LAI, they had much higher total LAI, so that the NPP of the stands in Oregon was actually higher compared to stands of similar ages in Florida. Consequently, a combination of measured LAI and climate is necessary to optimize the estimation of NPP (Waring 1982).

Finally, as illustrated in figure 1, maturity of the vegetation markedly changes production efficiency. Young stands are more efficient than older stands (Fig. 3). The climate of the two age classes of stands in Washington was identical. Yet the 23 year old stand had higher NPP than the older stand despite carrying less LAI. It will not be easy to discriminate age status of vegetation by remote sensing directly.

C. ANALYSIS OF TOTAL BIOMASS AND ELEMENTAL POOLS

Without complex models of biogeochemical cycling the best method of estimating pools of carbon, nitrogen, phosphorus, and sulfur in vegetation is to assume proportionality with total biomass. Table 1 illustrates the tremendous range of total biomass observed in biomes worldwide. Although some correlation exists between NPP and total biomass, the life cycle of the vegetation is equally important. In the same climate temperate forest and an annual grassland may have the same NPP. However, the forest will accumulate biomass for 100-500 years while annual plants die back each year producing no annual increase in total biomass.

NPP that is not accumulated in living biomass remains onsite as dead organic matter (called detritus). The dynamics of mass and energy exchange of detritus are sufficiently different from living biomass that their separation is crucial. Consequently, LAI and climate are required to estimate the rate of production, but knowledge of biome type and life cycle of the vegetation is needed to determine the resulting total biomass. Some optimism exists that microwave or radar techniques may ultimately be able to measure aboveground total biomass directly.

11. SUMMARY

Measurements of the net production and total biomass of terrestrial vegetation are essential to the study of the biosphere. Such measurements can only be made over large areas with remote sensing. However, the potential for remote sensing of vegetation has barely been tapped. Two kinds of measurements are required: (1) the areal extent of "biomes" (which are major classes of biota); and (2) the organic matter and biological activity density (the amount of organic matter per unit land area and the rate of energy and mass exchange per unit land area within each biome).

The ability to distinguish and map biomes by remote sensing has been demonstrated for LANDSAT sensors. Biomes appear to have characteristic values of net production and biomass for mature stands. Leaf area index (LAI) is strongly correlated with net production and biomass for mature stands, and thus provides a useful first approximation measurement. Some recent research suggests that LAI can be measured accurately by remote sensing for natural vegetation stands, but the techniques are yet to be proven widely applicable.

Net production and total biomass vary within each biome with the stage in the development of vegetation and with environmental conditions, especially with climate. Thus it is necessary to combine remote sensing measurements of climatic conditions, major vegetation types, and LAI to improve our global understanding of the role of terrestrial vegetation in the biosphere. Measurements of soil conditions, especially soil moisture, also add greatly to the information base. There is great potential in this research, and great need to develop and test techniques using a wide variety of sensors, including visible, infrared, and active microwave.

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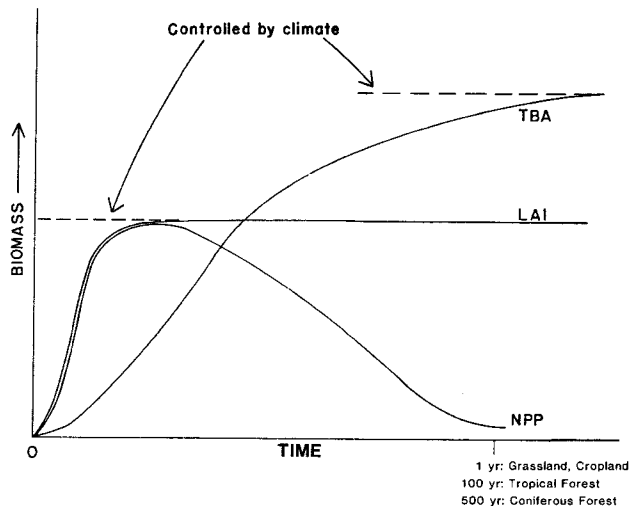


Figure 1: Development of biomass components during the life cycle of a terrestrial plant community. Scales of the X and Y axis change with biome type. Maturity is depicted as NPP approaches 0 causing TBA to plateau. Biome type and time control the trajectory of the variables while climate controls the magnitude of LAI, NPP, and TBA attained. LAI=Leaf area index, NPP=Net Primary Productivity, TBA= Total biomass accumulation.

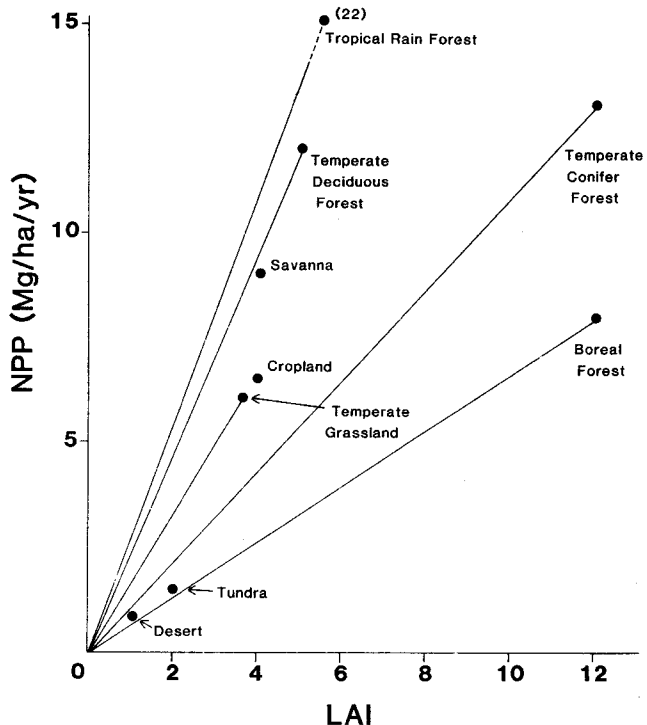


Figure 2: The efficiency with which LAI of different biome types produce NPP. Data are from Table 1 (Whittaker and Likens 1975).

AUTHOR BIOGRAPHICAL DATA

Daniel B. Botkin obtained his Ph.D. at Rutgers University, after which he joined the faculty of Yale University's School of Forestry and Environmental Studies. Prof. Botkin is now chairman of the Environmental Studies Program and Professor of Biology and Environmental Studies at the University of California, Santa Barbara. He specializes in ecological research of wilderness areas. His current research emphasis is the study of the biosphere has been supported by the National Science Foundation, NASA, and the National Oceanographic and Atmospheric Administration. For more than a decade, Prof. Botkin has advised Federal and state governments about the management of our natural resources, scientific research on wilderness, endangered species, and the use of satellite remote sensing for Earth Resources research. He is a member of the National Academy of Science's Space Science Board, which advises NASA about space research.

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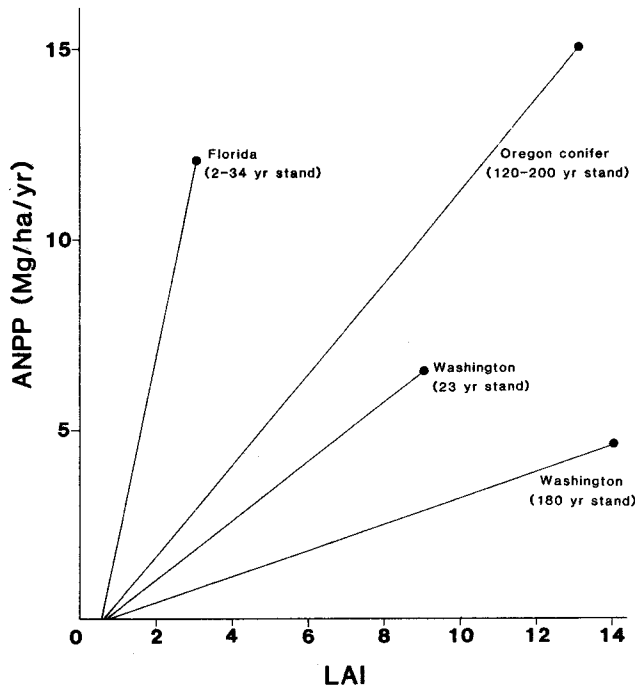


Figure 3: Within the coniferous forest biome, production efficiency (NPP/LAI) changes with climate and age of the forest stand. Data from Florida represents 21 slash pine stands (Gholz and Fisher 1982), from Oregon 7 stands of varying conifer species (Gholz 1982) and from Washington an old and a young stand of Pacific silver fir (Grier et al 1981).

TABLE 1

Leaf Area, productivity and biomass relationships of different vegetation types. (from Whittaker and Likens 1975).

Ecosystems Type	LAI(1)	ANPP(2)	TB(3)	ANPP/LAI
FORESTS				
Tropical Rain	8	22	450	2.8
Temperate Conifer	12	13	350	1.1
Temperate				
Deciduous	5	12	300	2.4
Boreal	12	8	200	0.7
Savanna	4	9	40	2.3
Temperate				
Grassland	3.6	6	16	1.7
Tundra	2	1.4	6	0.7
Desert	1	.9	7	0.9
Cropland	4	6.5	10	1.6

1) LAI = Leaf Area Index (m^2/m^2)

2) NPP = Net Primary Production (Mg/ha/yr)

3) TB = Total Biomass (Mg/ha)