CHANGING THE GLOBAL ENVIRONMENT Perspectives on Human Involvement

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18 LINKING ECOLOGICAL NETWORKS AND MODELS TO REMOTE SENSING PROGRAMS

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INTRODUCTION

Engineers and scientists working with high-altitude and space-oriented hardware and software have surpassed the abilities of environmental scientists and ecologists to utilize remote sensing information, while at the same time not really understanding fundamental problems on the ground. Developments in technology of remote sensing are now at a stage where these methods can be applied to large-scale environmental issues, but the ability to attribute the images to specific features on the Earth's surface and, even more importantly, to general conditions at other locations, had lagged behind.¹

Ecological dynamics and global-to-local-scale variables associated with environmental change must be identified if goals of the newly formed International Geosphere-Biosphere Programme (IGBP) are to be met.² A focus must be placed on identification and analysis of processes, rather than a continued reliance on monitoring of state variables, one of the primary goals of many large-scale programs studying global, regional, or even local environmental dynamics. New technologies hold some prom-

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ise for increasing our abilities to acquire information about vegetation dynamics,³ detection of a variety of stresses in plant communities,⁴ the identification of physical features on the Earth's surface that can be mapped to specific locations,⁵ and the carbon and nutrient state o plants and inferred soil responses.⁶ However, in addition to this techno logical development, we also need to develop a protocol that car integrate information about terrestrial and aquatic communities, geol ogy, and soils in order to predict with reasonable accuracy changes in space and time. Thus, for studies of ecological phenomena with complex spatial patterns and changes across large areas, we need accurate determination of variables in space and the definition of processes by which change on the landscape is induced in time. In order to use remote sensing for developing this information, new process and modeling studies will be necessary to complement studies that can be carried out now.

THE BASIC PROBLEM

In developing ecological theory for landscapes and the technology of remote sensing, unwittingly a situation has been created where scientiste find it difficult to couple the two subjects. On one hand, we have the extraordinary ability to engineer extremely capable satellite and remote sensing systems, while on the other we have gained enormous insighinto how ecological associations come together and function. Olson⁷ compare the situation to digging from opposite sides of a mountair to construct a tunnel. This task is possible, but only when the two teams have received and understood the same set of instructions. For the design of the study of large-scale environmental problems where both remote sensing and ecological theory play a role, seldom have the experts in each field gotten together to plan for common goals.

The need for this synthesis may seem strange at this stage of development of remote sensing of the environment, but it is still no apparent that scientists and engineers with the ideas and capabilities of accomplishing useful monitoring of global environmental change have developed a rational program. There is considerable progress in some areas,⁸ but it is not sufficiently broad in scope. The extent of the problem is perhaps best understood by contrasting two well-knowr systems that have received wide attention in the past few years, coverage of the Earth's surface by Landsat and NOAA satellites and their on-board instruments.⁹ In one [Landsat with Thematic Mapper (TM) there is high spatial resolution (30 m), which allows for detailed examination of surface features, but the temporal resolution is very low (at best a 16-day repeat potential). In the other [NOAA series with Advanced Very High Resolution Radiometer (AVHRR) capabilities], there is excellent temporal resolution for a large portion of the Earth because images can be collected daily, but the spatial resolution is very low (1 km). To describe ecological systems, which of these two remote sensing systems is best? The question can be answered only when the objective is clearly defined. In actual practice the two systems approaches are complementary and should not be regarded as alternatives in the study of ecological problems, particularly when examining problems with several levels of spatial and temporal scale. But, because the two systems were designed without thought being given to the ecological scale of the problems, their combined use can be achieved only with a great degree of effort after costly research and development.¹⁰

For the future, programs designed around the strongest attributes of remote sensing and ecosystem analysis are needed. In such a program, scientists from a variety of disciplines should be invited to assemble a proposal for coupling these two different approaches. Experts on both Landsat TM (along with France's SPOT technology) and AVHRR should meet with experts on physical and biotic function of specific ecosystems. The ecological focus should be in ecosystems where there already is a great deal of available information about structure and function, especially where ecosystems have been set aside as research reserves. The best candidates for such new research and development are the Man and the Biosphere Reserves¹¹ and the United States National Science Foundation's Long-term Ecological Research Sites (LTER).¹² (There is considerable overlap in the United States; eight of fifteen LTER sites are Biosphere Reserves.)

As a measure of concern about how people contribute to change in global environment, it is noteworthy that 30 years ago none of the major facilities we now have to measure and describe the degree of global environmental change existed. Since then, the International Geophysical Year, the International Biological Program, and the International Hydrological Decade, to name only a few prominent programs, have come and gone. Now we have the Man and the Biosphere Program with its Biosphere Reserves, many national projects, such as the National Science Foundation Long-term Ecological Research project, and recently the advent of the International Geosphere-Biosphere Programme. All these programs have required research sites and have sought to link their findings through a network. With the growing desire to develop more robust links between remote sensing and ecological principles, it is logical to turn to the sites that have accumulated the most information over the past several decades. To start discussion on this design, experts from four U.S. Biosphere Reserves (three of them now LTER sites) and researchers and agency staff from NASA attended a workshop in Athens, Georgia, in May 1985. Some of what we report here emerged from that workshop.¹³

BACKGROUND AND APPROACH

The four research sites discussed here, particularly the three U.S.D.A. Forest Service research watersheds, are widely scattered, but they all collect the same types of ecological information. Because of this spatial displacement, there are certain similarities and differences that must be considered, both for ecological and remote sensing problems. All are forested systems, even though the community type and species composition vary greatly among sites. All have steep elevation gradients and highly variable aspects, with streams both controlling and integrating several landscape and ecological features. Nurients are highly variable, both from site to site and on yearly and seasonal bases within sites. Green-leaf surface area is high because of dense, thick forest canopies and is also highly variable. None of these four systems is homogeneous. Accordingly, they display a large site-specific variability in their ecological parameters. Indeed, there is likely as much variation within each of the sites as there is among them. Thus, the overall problem reduces to asking questions about what dominant land and ecological features exist at each site, how these vary spatially and temporally within a site, and, lastly, how they vary from site to site. Even though the task for defining this variance is not easy, it is one that is amenable to hierarchical ordering, a subject examined later in the chapter.

SETTING

To assess the problem, four sites were chosen from forested U.S. Biosphere Reserves: Coweeta Hydrological Laboratory, North Carolina; Great Smokey Mountains National Park, Tennessee; H.J. Andrews Experimental Forest, Oregon; and Hubbard Brook Experimental Forest, New Hampshire. Great Smokey Mountains National Park is administered by the U.S. Department of Interior, National Park Service; the other three are administered by the U.S. Department of Agriculture, Forest Service. The three U.S. Forest Service sites are widely known for their long-term research base on mountain watersheds; a great amount of work, funded by the National Science Foundation, has been conducted on basic ecosystem research projects at each site. The Great Smokey Mountains National Park is known for its diverse biotic communities and, even though there are no experimental watersheds, it has a long research tradition. Short synopses are presented to acquaint readers with the characteristics of the four chosen sites.

COWEETA HYDROLOGIC LABORATORY

This 2185-hectare site is located in a basin of the Nantahala Mountain Range of western North Carolina within the Blue Ridge Mountain chain, a part of the Eastern Deciduous Forest ecoregion.¹⁴ The area has a moderate climate with cool summers and mild winters, and abundant rainfall is present in all seasons, averaging 1,780 mm at lower elevations and 2,500 mm at higher elevations. Its terrain is steep, highly dissected with elevations ranging from 686 to 1,600 m. There are 69 km of first- to third-order streams in the basin, many with active gauged weirs operating full time. Soils are deep and occur in two orders, fully developed Ultisols and young Inceptisols. Vegetation belongs to the Eastern Deciduous Forest province and is Appalachian oak forest¹⁵ with abundant oak and hickory. The forests are diverse, with their distributions highly associated with moisture gradients, elevation, and aspect.¹⁶

GREAT SMOKEY MOUNTAINS NATIONAL PARK

The Great Smokey Mountains National Park is a 208,000-hectare preserve in the southern Blue Ridge Mountain chain, just slightly north of Coweeta Hydrologic Laboratory. Elevations range from 260 to 2,021 m. Climate varies from mesothermal-humid at low elevations to microthermal-perhumid at high elevations.¹⁷ The terrain is steep and highly dissected with many streams throughout the preserve, ranging from first to approximately fifth or sixth order. Vegetation is complex. The reserve lies in the Appalachian oak forest section of the Eastern Deciduous Forest¹⁸ but contains mixtures of evergreen; needle-leaved forests; and deciduous, broad-leaved forests. Two nonforest types, heath and grassy balds, are also present. Its complexity is further increased by the fact that much of the lower elevations of the preserve has been highly disturbed in the past, being either burned over, logged, grazed, or cleared for small-scale agriculture and subsequently allowed to revegetate. As was the case in the southeastern United States, the once dominant chestnut (*Castanea dentata*) was all but extirpated by a blight 50

to 60 years ago and has been replaced by other broad-leaved species. Elevation and site moisture class dominate the environmental gradients, as noted for Coweeta. As a result, biotic communities in the preserve are quite patchy.¹⁹

H.J. ANDREWS EXPERIMENTAL FOREST

This experimental forest is a 6,050-hectare watershed located in the central-western Cascade Mountains of Oregon. The climate is maritime. Winters are mild and wet, with warm, dry summers. Precipitation is high, on the order of 2,300 mm at lower elevations to over 2,500 mm on higher ridges. Its terrain is also steep and highly dissected with elevations ranging from 500 to 1,600 m. Several first- to third-order streams, many fitted with gauging stations to measure stream flow, are being studied intensively. Bedrock and soils are complex throughout the area, owing to a large number of volcanic flows in the Pliocene and Pleistocene. The vegetation is in the silver fir/Douglas fir section of the Pacific Forest,²⁰ and the H.J. Andrews site is dominated by Douglas fir (*Pseudotsuga menziesii*) in old-growth forest areas. Second growth, following fire or logging, is dominated by Douglas fir or noble fir (*Abies procera*).²¹

HUBBARD BROOK EXPERIMENTAL FOREST

This experimental forest is an approximately 3,000-hectare preserve situated in the White Mountains of New Hampshire. Its climate is continental, with an average rainfall of 1,300 mm per year, one-quarter to one-third of which is snowfall. Its terrain is also steep, dissected by first- to third-order streams, several of which have gauged weirs. Bedrock for the site is coarse-grained gneiss covered by a shallow layer of glacial till. Soils are relatively thin and well-drained, of a type called "Spodosols," with a sandy loam texture. The forest floor is also thin, and surface topography is rough because of pits and mounds caused by tree falls and surface boulders. Vegetation is complex, belonging to the Northern Hardwoods and the Spruce-Fir Forests.²² The forest composition is correlated with elevational gradients, ranging from deciduous northern hardwoods at lower elevations to spruce and fir typical of the boreal forest at higher elevations.²³

The three U.S. Forest Service sites have emphasized watershed research programs for decades; thus, an unequaled data base of terrestrial, aquatic, and geochemical processes exists for them. One of the main approaches in the three research programs has been to study effects of perturbations to entire watersheds. The most prominent perturbation has been removal of the forest trees. Clear-cuts and a variety of partial tree cuts have been employed over several decades. Each site, thus, has a strong published history of effects of forest community perturbations on successional patterns, ecosystem productivity, hydrology, water chemistry, and general models of the biogeochemistry of the area. This information is available for synthesis and new study efforts, which are needed to extrapolate the site-specific findings to other regions.

STUDY COMPONENTS

As we develop programs to examine ecosystem function through remote sensing technologies, it is apparent that we need to know a great deal about both topics. Not only that, we have to know what surrogates of ecosystem function we can measure from a remote sensing standpoint, since ecosystems have no metric per se. Measurement of green-leaf biomass has been one of the most useful methods developed to date.²⁴ Also, soil spectra have been measured to help resolve green-leaf biomass²⁵ but might be useful for other ecosystem parameters as well.²⁶ More recently, methods utilizing imaging spectrometer have been developed that can identify a wide variety of surface materials, including vegetation, soils, and minerals,²⁷ and perhaps total nitrogen and how it is partitioned in living plants.²⁸ However, to date, other than green-leaf biomass changes over time in an area, no ecosystem function properties have been examined in depth.

From changes in green-leaf biomass, it is possible to construct a view of ecosystem functioning using various ratios of spectral bands currently contained by Landsat satellite data. Botkin et al.²⁹ expanded this potential into a spatially hierarchical problem by calibrating green-leaf reflectance at a single site so that an area with low vegetation heterogeneity could be examined from a variety of heights with remote sensing equipment. Tucker and his coworkers³⁰ have followed seasonal changes of green-leaf biomass on the entire continent of Africa for a 19-month period. They have also viewed changes in large portions of the rest of the globe³¹ using NOAA AVHRR satellite information. Also, crop coverage of the wheat and corn belt of the United States and other areas of the world has been reported for several years.³² With the exception of inferences derived from some of the AVHRR work conducted by Tucker and his coworkers,³³ few of these reports really address the problems of ecosystem function that is needed for future monitoring and predictive purposes when we turn our attention to global change programs.

In order to build a program where ecosystem function can be monitored by remote sensing, it is necessary to consider the fundamental requirements. One of the first is recognition of the fact the problem is hierarchical.³⁴ Without the definition of the problem components, it is not possible to address proper ecological questions. This approach has been described in some detail for forested systems, such as represented at the four Biosphere Reserves discussed here. As Olson³⁵ indicated, we must work at more than one level in such a problem, but the question is how to integrate these levels. Highly detailed information being collected at the ground level for "bottom-up" research purposes must be linked to lower resolution information from Landsat or AVHRR satellite images for "top-down" assessment. Both approaches must deal with patchiness of information. The main problem is to be able to assign the linkages to either of the two approaches.³⁶

In order to create the linkages, models must couple the two information sources.³⁷ To design this approach, it is necessary to define the state variables of the system being studied and then to structure the flows (processes) so they can be linked. If there is a hierarchical structure, then each of the levels in the hierarchy must in turn be linked. In practice for remote sensing purposes, it will be necessary to design and carry out ground-level research to make certain that either the changing state of key state variables can be measured or that some measure of the key processes themselves can be measured. Only in this way will it become possible to ascribe any degree of dynamics to a living system.

Once we can measure these systems adequately and learn to link them together with simulation models, we must consider whether the phenomena being measured can be made to represent similar conditions elsewhere. Perhaps one of the biggest problems to be encountered in this entire array of programmatic developments is the ability to extrapolate point-source information to larger areas. This step must be guided by model representation as well because there simply are not enough resources to repeat these intensive site examinations over and over to fill in gaps with statistical interpolations. Several approaches make this important step possible, although all are in early development. One is the use of fractal geometry to investigate whether patterns of state variables or processes are repeated in nature.³⁸ Building new regional models from those model systems developed at point locations will be daunting, but it is still possible.

PROGRAM DESIGN

In this chapter, we have promoted codevelopment of technological, environmental, and ecological projects. We urge new work at sites where ecosystem-oriented research is being conducted or at other sites with key system-level experiments called for by Waring et al.³⁹ At least two biome types should be considered, grasslands and temperate forests. They contain the best and longest-term data sets available, and there is in place a network from which such new work can be structured. Since we deal with temperate forests in this chapter, we will concentrate on them. However, programs exist for other areas. For example, in 1987, NASA, in association with the International Satellite Land Surface Climatology Project (ISLSCP), launched a three-year program in grasslands at the Konza Prairie Conservation Area and Biosphere Reserve in Kansas.

The foregoing sections concerning the three U.S. Forest Service and Great Smokey Mountains National Park give a synoptic review of their strengths for developing whole-system projects to be coupled with remote sensing. The work of Botkin et al.40 suggests that correlations of state variable information with ground-level to high-altitude sensors should be an early part of this work, although it should not necessarily be the prime goal, since such correlations are lacking in predictive capabilities, one of the main aims of such work. Early in any new projects, it will be necessary to formulate conceptual models that can represent the essential hierarchical aspects of the entire problem. A simulation model structure should then be sought to represent the conceptualizations. One of the best potentials for this simulation approach is the development of what is currently being considered as the "telescoping model," one that can describe a series of hierarchical levels in an ecosystem, ranging from individual tree and small-plot performance to entire watersheds, all without having to change the model structure.⁴¹ There currently is sufficient information about the state variables and processes at the U.S. Forest Service sites to commence this model development.

Remote sensing coverage for each site should progress at the same time. Thematic Mapper (TM) data exist for the H.J. Andrews Experimental Forest and should be developed more broadly in the other sites. Aircraft flights equipped to provide Multispectral Scanner (MSS) information exist for Great Smokey Mountains National Park.⁴² There is a large library of information for AVHRR coverage for all sites. Along with this satellite coverage must be considered other types of remote sensing work, but with specific experiments at ecosystem-level research projects in mind. Finally, investigations into new modes of sensing ecosystem parameters remotely must be considered. A large variety of potentials exists, and each will have to be evaluated in the context of the whole-system properties and the ability to develop the technology to measure them.

Once these site-specific and cross-site programs have been initiated, it will be necessary to develop methods for broadening the scale and extrapolating the findings outward to surrounding areas to use this information for regional models.⁴³ It is also necessary to expand the measurements into other Biosphere Reserves so that a network of information can be built up. This expansion will constitute the Geosphere-Biosphere Observatory network being considered for the International Geosphere-Biosphere Programme (IGBP). These will be crucial steps, because it is only at this point that we can begin to utilize the full potential of satellite-based remote sensing of long-term change in the biosphere and geosphere.

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