Remote Sensing and GIS in Ecosystem Management

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Ecological Perspective: Linking Ecology, GIS, and Remote Sensing to Ecosystem Management

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Introduction

Awareness of significant human impacts on the ecology of Earth's landscapes is not new (Thomas 1956). Over the past decade (Forman and Godron 1986, Urban et al. 1987) applications of geographic information systems (GIS) and remote sensing technologies have supported a rapid rise in landscape-scale research. The heightened recognition within the research community of the ecological linkages between local sites and larger spatial scales has spawned increasing calls for more holistic management of landscapes (Noss 1983, Harris 1984, Risser 1985, Norse et al. 1986, Agee and Johnson 1988, Franklin 1989, Brooks and Grant 1992, Endangered Species Update—Special Issue 1993, Crow 1994, Grumbine 1994). As a result agencies such as the U.S. Forest Service, U.S. Fish and Wildlife Service, and National Park Service are now converging on "ecosystem management" as a new paradigm to sustainably manage wildlands and maintain biodiversity. However, as this transition occurs, several impediments to implementation of this new paradigm persist, including (1) significant uncertainty among many land managers about the definition and goals of ecosystem management, (2) inadequate ecological information on the past and present processes and structural conditions of target ecosystems, (3) insufficient experience on the part of land managers with the rapidly diversifying array of GIS and remote sensing tools to effectively use them to support ecology-based land management, and (4) a paucity of intimate, long-term relationships between people (including land managers) and the particular landscape communities to which they belong. This chapter provides an ecological perspective on these issues as applied to ecosystem management in a southwestern U.S. landscape.

An Ecological Perspective on the Conceptual Basis of Ecosystem Management

Ecosystem management is typically presented as an effort toward "sustainable" land management, often defined as the persistence or restoration of diverse, healthy, and productive ecosystems (Salwasser 1991, Robertson 1992, USDI Fish and Wildlife Service 1994, Christensen 1994). While ecosystems may potentially be manipulated into a variety of ecological states, they are not infinitely malleable. So what range of conditions should land managers target in order to achieve sustainability? A reference template to evaluate the ecological status of a site may be derived from the envelope of historic and prehistoric site conditions, as revealed by ecological history and paleoecological research on ecosystem dynamics at multiple spatial scales. This historic range of variability in ecological processes and structures (often called presettlement, "natural," native, or ecological reference conditions) presumably can be used to guide sustainable management action. For certain ecosystems it can be documented that this range of ecological conditions persisted through significant periods of time. Land managers, working through the public participation process, can then develop a "desired future condition" from within the intersection of that ecologically defined template of sustainable conditions and societal aspirations (Figure 8.1).

Many practical applications of wildland ecosystem management seek to manipulate localized, site-scale, ecosystem patches (e.g., a 50-hectare forest stand dominated by relatively uniform vegetation) within the mosaic of patches found in a larger landscape context (e.g., a 5000-hectare watershed, or a 500,000-hectare national forest) to achieve desired future conditions. This typical ecosystem management scenario requires ecological information and operational management attention at two relatively distinct spatial scales: (1) the local site-scale patch, and (2) the landscape mosaic of patches (Figure 8.2).

At both patch and landscape scales, managers require understanding of current and historic ecological processes and structures, as well as their interactions through time, in order to define the envelope of historically sustainable conditions. Managers need information on site-specific ecological processes such as microclimate, water and mass movement, soil development, nutrient cycles, food webs, biotic movements, and disturbance regimes (the frequency, intensity, areal extent, and seasonality of disturbances like fire, windthrow, and insect outbreaks). The ubiquity of disturbances (Sousa 1984) and their significance as formative processes in most terrestrial ecosystems (Pickett and White 1985) lends particular

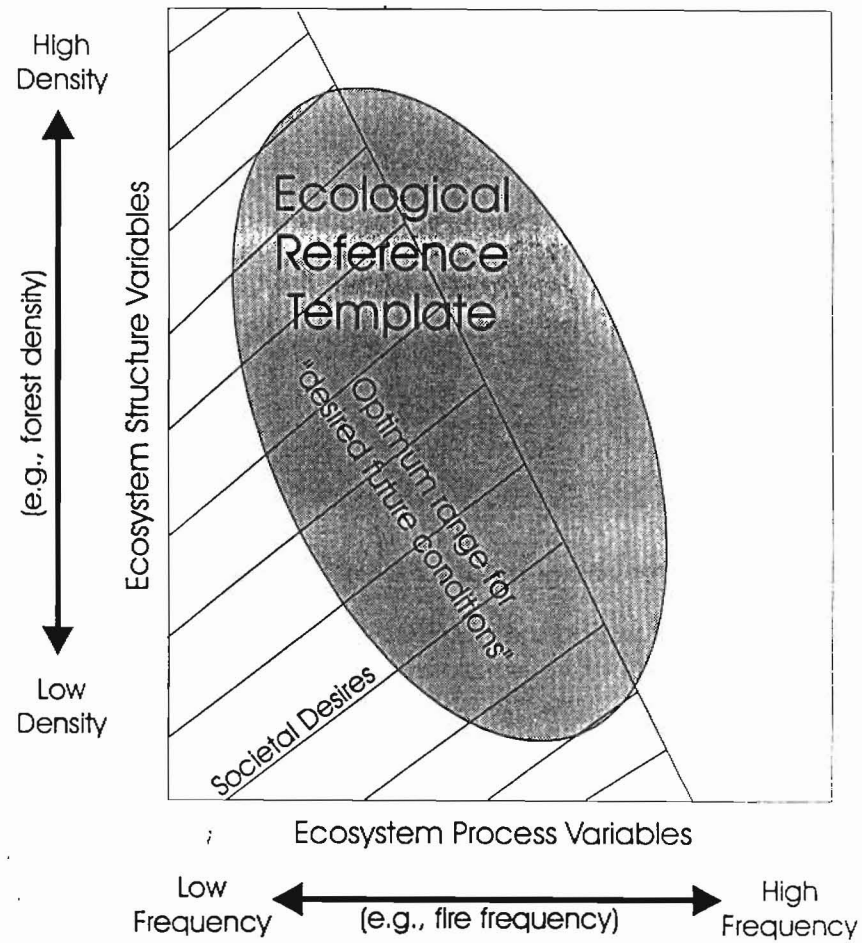

Figure 8.1 Conceptual diagram of an ecological reference template as a limited range of states in ecosystem process and structural variables. The specified ecological reference template is based on historic site conditions and defines an envelope that presumably encloses sustainable ecosytem states. This reference template may be applied in ecosystem management to develop "desired future conditions" by defining ecosystem states within the intersection between the ecological template and societal desires.

importance to collecting information on disturbances so that management may attempt to mimic the role of native disturbance regimes (e.g., Agee 1993). Information on ecosystem structural patterns such as the biotic composition of the site (including sensitive and alien species) and the sizes and three-dimensional spatial arrangement of the live and dead vegetation (e.g., an old-growth pine savanna versus a dense, 20-year-old

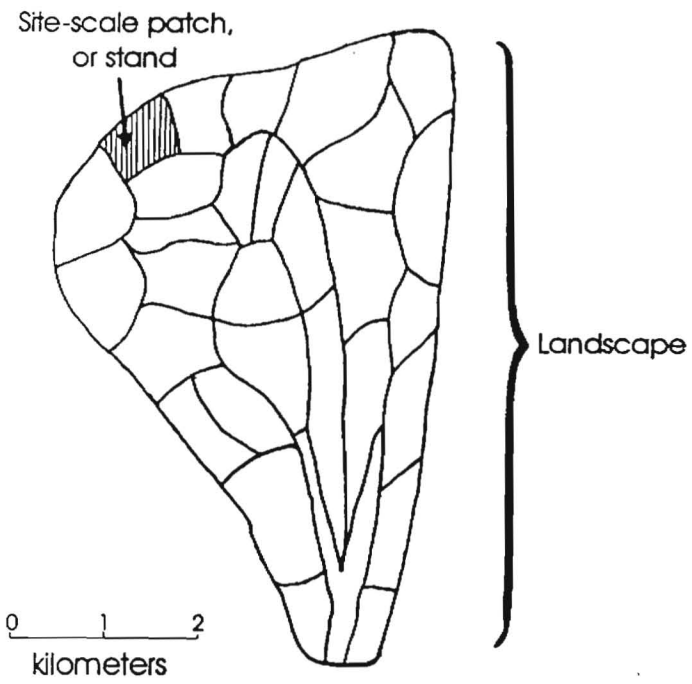

Figure 8.2 Schematic diagram of a landscape as a mosaic of site-scale patches.

plantation) is also essential because process and structure strongly interact to mold each other (e.g., the process and structural outcome of fire is quite different in a pine savanna than in a thicket). Indeed, an ecosystem perspective holistically views the ecological processes and structures of each patch as an integrated system rather than as isolated components. Overall, knowledge of site history is vital to understand observed ecological patterns and to recognize the ecological potential of any patch (Hamburg and Sanford 1986, Duffy and Meier 1992, Russell 1994). Intensive field observations are necessary to resolve this array of site-level ecological information that silviculturalists, wildlife biologists, and hydrologists require to develop sustainable management prescriptions. GIS and remote sensing applications may supplement but will never replace the primacy of field observations at this site-level scale where on-the-ground implementation occurs.

In contrast, management at the broader landscape scale is largely a planning task, implemented by designing the spatial and temporal distribution of the site-specific ecosystem patches that comprise the landscape mosaic; this requires the larger perspectives that current GIS and remote sensing approaches can provide. By managing the pattern of component patch types, sizes, and numbers in time and space the cumulative patterns and processes of the composite landscape mosaic can be managed (Franklin and Forman 1987, Rykiel et al. 1988). As at the site level, information on native landscape- (and regional-) scale structures, processes, disturbance regimes, and environmental histories is essential to develop ecology-based templates at these broader scales (Turner 1987, Urban et al. 1987). However, landscape-level information on sustainable ecological conditions is derived through somewhat different approaches (Turner and Gardner 1991) and is generally less available and less precise than more traditional site-level ecological information, in part due to the relative novelty of landscape ecology research. GIS and remote sensing methods are essential tools that will be increasingly used to develop the landscape-level spatial and temporal contexts needed for ecological management of landscapes.

The broad array of definitions and spatial scales applied to the term ecosystem necessarily makes ecosystem management a fuzzy term unless it is precisely defined. Some of the uncertainty at the field level in the U.S. Forest Service about the meaning of ecosystem management (like its "New Perspectives" progenitor [Salwasser 1992]) occurs because the different information needs and management operations of the site and landscape scales are not explicitly distinguished or outlined, as discussed above. Since ecological management must cover all aspects of ecosystem process and structure, there is a need to define ecosystem management in terms of ecological hierarchies.

From an ecological viewpoint, two core "new perspectives" may be identified in current formulations of ecosystem management: (1) increased emphasis on the use of historic, site-level, ecological processes and structures as a template for sustainable management of individual, stand-scale, ecosystem patches or sites; and (2) the importance of explicitly considering and managing the spatial and temporal patterns of the mosaic of ecosystem patches at larger landscape and regional scales. These two ideas are hierarchically linked along a continuum of spatial scales (Urban et al. 1987), and successful ecosystem management requires blending site-specific information into a landscape or regional context. Still, distinguishing the stand-scale operations at the ecosystem patch level (idea 1) as "ecological site management" and the landscape-mosaic level work (idea 2) as "ecological landscape management" would clarify understanding, and thereby improve implementation, of these new management paradigms by both field-level resource managers and the general

public. Incorporating the word "ecological" into this terminology emphasizes the factors that direct management and makes it more obvious that these terms are subsets of ecosystem management. Ecosystem management may then persist as a more generalized umbrella term that covers various spatial scales as well as enhanced integration of societal purposes through cooperative, participatory relationships among land management agencies and the public.

Distinguishing ecological landscape management as an identifiable component of ecosystem management could reduce ambiguity in communications among land managers, scientists, and the public at large. Landscape is a relatively well-defined level of spatial scale that is understood by the public and professionals alike (Forman and Godron 1986). Our sense of belonging to a place is associated with the landscapes where we live and work (Tuan 1974) and which we name and often value for spiritual reasons. This public attachment to local landscapes provides a focus for long-term human attention and care of landscapes and thus the impetus for increased public involvement in land management planning. Landscapes also provide a convenient framework for the conduct of cooperative, interagency operations, an increasingly important aspect of land management.

Ecosystem management is a conservative approach to land management that basically follows Aldo Leopold's (1949) admonition to "preserve all the parts of the land mechanism" and develop "gentler and more objective criteria for its [any land management tool's] successful use." Ecosystem management elaborates on ideas expressed in Leopold's famous essay "The Land Ethic," namely: (1) "A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community"; (2) ". . . native plants and animals kept the energy circuit [of the land community] open; others may not"; (3) ". . . man-made changes are of a different order than evolutionary changes, and have effects more comprehensive than is intended or foreseen" as "man's invention of tools has enabled him to make changes of unprecedented violence, rapidity, and scope"; and (4) "The combined evidence of history and ecology seems to support one general deduction: the less violent the man-made changes, the greater the probability of successful readjustment of the [land] pyramid." Ecosystem management may be seen as a modern effort to affirmatively answer two questions Leopold raised about land management: "Can the land adjust itself to the new order? Can the desired alterations be accomplished with less violence?" Leopold (1949:274) further noted that "A science of land health needs, first of all, a base datum of normality, a picture of how healthy land maintains itself as an organism." He believed

that the "most perfect norm is wilderness" while recognizing that long-sustained, cultural landscapes such as northeastern Europe could also serve as reference areas. The ecosystem management template of historic ecological conditions is an attempt to provide "more objective criteria" to the development of site-specific norms for healthy land.

Limitations to This Ecosystem Management Approach

There are a number of conceptual and practical problems with the ecological reference-template approach to ecosystem management outlined here. First of all, while ecosystem management aims to sustain the integrity of ecosystems yet still provide for human use of landscapes, the core concepts of ecosystem sustainability and integrity remain controversial (Noss 1990, Jackson 1991, Costanza and Daly 1992, Kohler 1992a, Kay 1993, Ludwig et al. 1993).

Second, the proper role of humanity in shaping ecosystem processes and patterns is subject to ongoing debate. A focus on ecological reference conditions recognizes that ecosystems do not follow the power, prestige, and monetary rules of human political, social, and economic systems, even though the entire earth is increasingly molded by these human conventions (see Cronon 1991 and Turner II et al. 1990). Environmental reconstructions often attempt to isolate the historic role of post-European-settlement land uses as "unnatural" influences, while the significant ecological effects of indigenous peoples on North American landscapes (Cronon 1983, Pyne 1982, Anderson and Nabhan 1991, Denevan 1992), including portions of the Southwest (Betancourt and Van Devender 1981, Kohler 1992b), are generally ignored or incorporated into the template descriptions of native, "natural" ecosystems. This is philosophically problematical since all people may be considered equally natural parts of landscapes. The U.S. Forest Service clearly recognizes that human purposes must be incorporated into ecosystem management through public participation in the resource management planning process (Robertson 1992, Salwasser 1992).

Third, we will always lack perfect knowledge of past and present ecosystem conditions. Relatively little ecological history work has been conducted to date and as time passes it is increasingly difficult to reconstruct bygone conditions as the evidence is lost or degraded, sometimes due to our management actions (e.g., prescribed burns can destroy the fire scars needed to develop accurate fire histories). Further, the resolution of environmental reconstruction methods is often too coarse to assemble an

adequate reference template of historic ecosystem patterns and processes for practical use by managers. There are methodological limits on the quality of information we can collect on certain ecosystem parameters, such as below-ground ecological phenomena. The costs of collecting high-quality information preclude complete inventories, further constraining our knowledge of current ecological conditions. Also, more information is not always useful, as it is possible to get bogged down in trivial details or unresolvable complexities with excessive or even contradictory data. This is especially true given that our understanding of how ecosystems function is culturally mediated and continuously evolving (Botkin 1990). The necessity of working with incomplete knowledge suggests that ecosystem management will always be as much an art as a science, and that we should manage landscapes with less hubris and more humility (Kellert and Bormann 1991:210, Ehrenfeld 1993).

Fourth, the past is not a perfect guide to the future, especially in an increasingly human-altered world. When defining historic ecosystem conditions as a range to manage within, it must be recognized that environmental change is axiomatic, pervasive, and in some cases chaotic (Delcourt and Delcourt 1988, Botkin 1990, Sprugel 1991). Indeed, paleoecology shows that most modern biotic communities are not tightly coevolved and organized units but rather transitory assemblages of individual species (Hunter et al. 1990). Further, global change scenarios indicate that the use of templates based on the past several hundred to several thousand years may not be appropriate for many sites where the climate will likely be pushed out of its Holocene envelope within decades, dragging ecosystem processes and structures along to some new state (Peters 1988). Land managers will increasingly need to become facilitators of ecological changes to meet objectives such as minimizing the loss of global biodiversity. Still, by conservatively managing our landscapes to limit the rate, extent, and intensity of human interactions, many ecosystems may prove resilient enough to sustain their evolutionary potential despite the effects of climate change. For example, ecosystem resiliency is enhanced by intact plant-soil linkages (Perry et al. 1990) and by the ecological legacies of persistence and multiple possibilities inherent in biologically diverse ecosystems.

Finally, even if perfect information existed, implementation of ecosystem management would be difficult because recent human activities such as widespread habitat alteration and fragmentation (Wilcove et al. 1986), fire suppression (Covington and Moore 1992), and introduction of aggressive alien species (Westman 1990) have pervasively altered the

structures and processes of many wildland ecosystems outside the ranges of historic conditions (Crosby 1986, Bahre 1991, Schwartz 1994). This is true even in our most protected southwestern landscapes (deBuys 1985, Allen 1989). The proliferation of human communities within wildland matrices increasingly constrains management options (e.g., the use of prescribed fire is limited by smoke concerns). Undertaking needed ecosystem restoration measures will be challenging from logistical, economic, and political perspectives.

Despite uncertainties in our knowledge and methodological imperfections, ecosystem management provides a conservative, reasoned approach to sustaining relatively whole, functional ecosystems in the face of accelerating global change. The increasingly apparent cumulative impacts of exponential human population growth and escalating resource consumption highlight the need to move toward such ecology-based approaches to landscape management if we are to maintain the ecosystem services and amenities we need and value.

Applications of GIS and Remote Sensing Technologies to Ecosystem Management in a Southwestern U.S. Landscape

Examples of GIS and remote sensing applications to ecosystem management are presented from the landscape of the Jemez Mountains of north central New Mexico, which includes Bandelier National Monument and portions of the Santa Fe National Forest.

Use of GIS and Remote Sensing to Provide a Landscape Context for Ecosystem Management

A landscape ecology research project (Allen 1989) used site-level fieldwork, landscape-level interpretations of aerial photographs, and GIS applications to develop ecological information at multiple spatial scales for the landscape in and around Bandelier National Monument (Figure 8.3). Bandelier, at 13,307 hectares, comprises only 2.4 percent of the land area in the Jemez Mountains. The headwater portions of most park watersheds are located on adjacent U.S. Forest Service land (Figure 8.4). Field information was collected from 969 sample points covering the Rito de los Frijoles watershed in Bandelier (Figure 8.4); this watershed provides a representative elevational transect of this landscape with a 1480-meter rise from the Rio Grande to the crest of the Jemez Mountains. At each point data were collected on numerous ecological characteristics of the

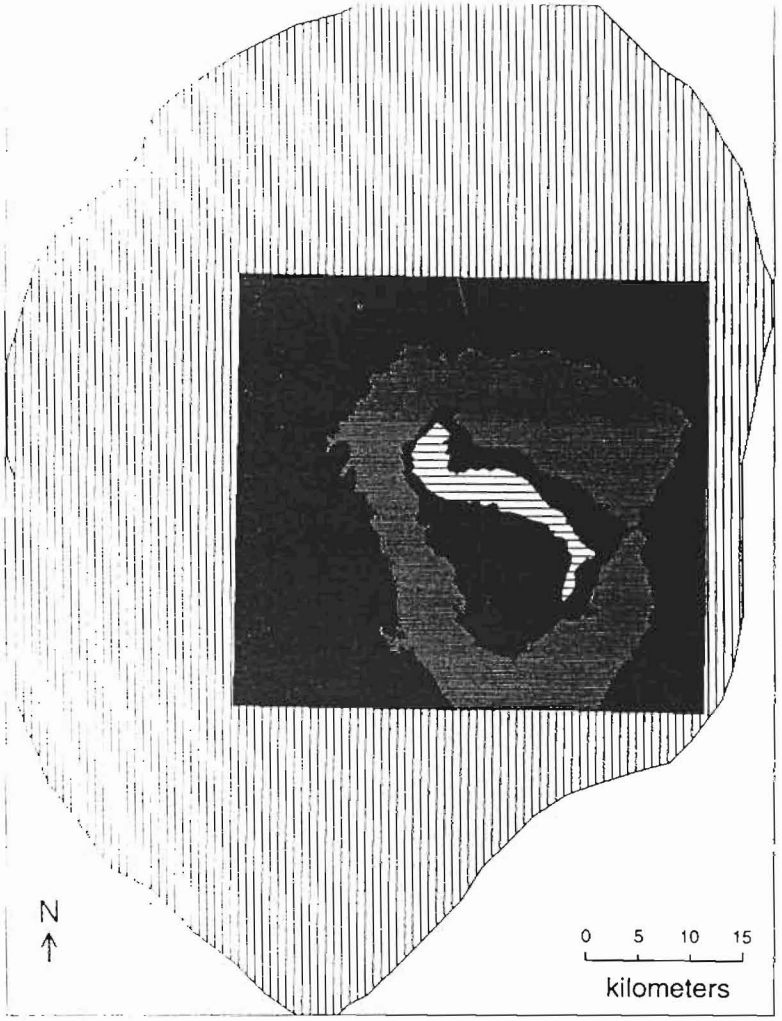

Figure 8.5 Locations of mapped areas within the 543,522-ha Jemez Mountains (vertically striped area). The black square defines the 187,858-ha area mapped from 1935 and 1981 airphotos for road networks (see Figures 8.6 and 8.7), the gray patch (85,726 ha) was mapped from 1935 and 1981 airphotos for landscape-cover types (see Figure 8.5), the irregular black area (28,684 ha) was mapped from 1981 airphotos for ecosystem patches, and the horizontally striped area is the Frijoles watershed (6500 ha), which was sampled with 969 points in the field (see Figure 8.4).

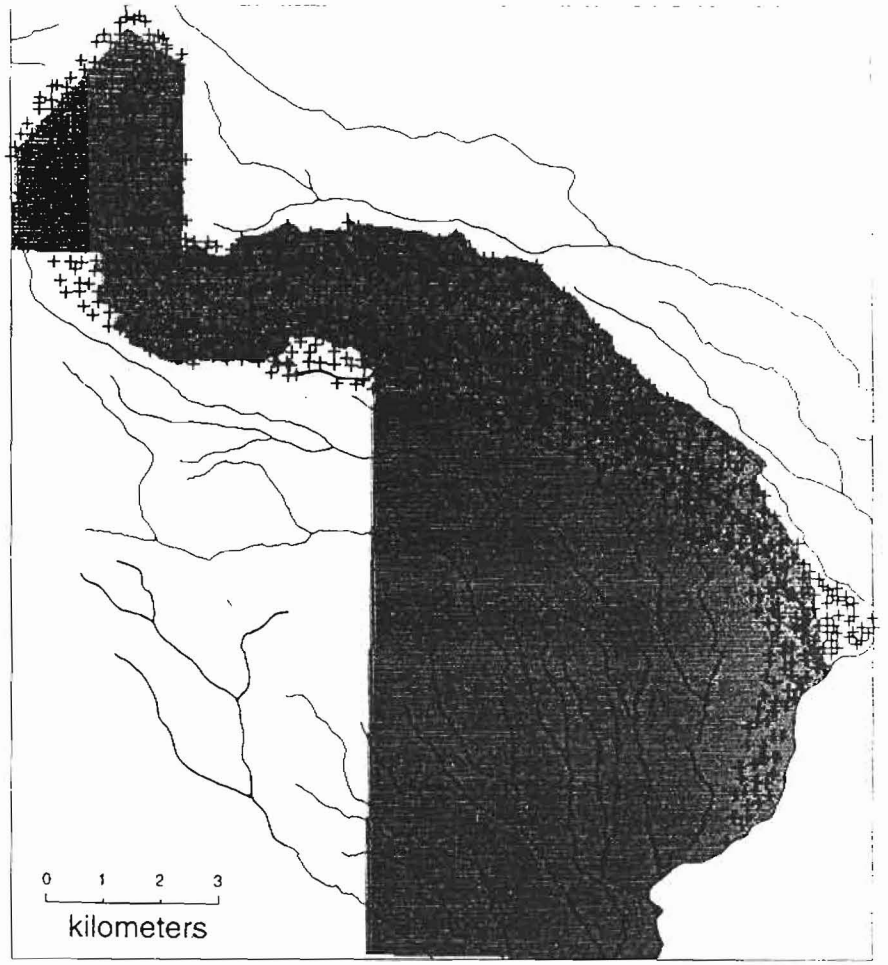

Figure 8.4 Locations of 969 field sample points in the Frijoles watershed, with the main portion of Bandelier National Monument shown in gray and canyon stream drainages as lines. The displayed headwaters area of the southern portion of Bandelier is Santa Fe National Forest land and contains the Dome Diversity Unit.

site, ranging from detailed information on vegetation and landform to evidence of processes such as erosion, fires, or floods. Changes in land cover and road networks were mapped by interpreting 1935 and 1981 aerial photographs (Figure 8.3). Combinations of vegetation, percent tree canopy cover, and landform were mapped as "ecosystem patches" at a 1.5-hectare level of resolution across Bandelier and surrounding areas by

interpreting the 1981 aerial photographs (Figure 8.3). The field data provided ground truth information for the aerial photograph interpretations. These and other data were entered into a GIS (see Allen 1989 for details).

Combining this GIS information with additional field data and historical information provides multiple perspectives on the dynamics of various ecosystems that have been used to support ecosystem management in the Jemez Mountains. For example, field studies of montane grasslands (Allen 1984) had shown that these ecosystems were found in a distinctive landscape pattern on the upper slopes of most of the larger peaks in the Jemez Mountains. Several lines of evidence indicated that these grasslands have existed for millenia on these sites. Increment core dates from hundreds of trees demonstrated that tree invasion in the last 75 years has greatly reduced the extent of these grasslands, due to fire suppression and livestock grazing histories. The addition of landscape-scale information from aerial photography and GIS-generated displays and analyses of the magnitude of the grassland loss to tree invasion has triggered ecosystem management action (Figure 8.5). Tree cutting and prescribed burning have been conducted for several years in the Cerro Grande grassland in Bandelier, and a recent grassland restoration project took place on Quemazon Mountain, with other sites under consideration for treatment in the Santa Fe National Forest.

Field observations of soil erosion in Bandelier were scaled up from individual sample points to the larger landscape using the GIS, revealing extensive erosion in piñon-juniper woodlands that affects about 40 percent of Bandelier's land area. This erosion is also a cultural resource problem, as 70 percent of 1600 archeological sites surveyed between 1988 and 1991 displayed evidence of erosion damage. The GIS-supported ability to display the widespread nature of soil erosion has helped elevate this issue to the top of Bandelier's resource-management priorities, and it has fostered funding support for ongoing ecological research on the causes of the erosion and on effective treatments to restore historic ecological conditions.

GIS analyses also documented some obvious human-induced changes in this landscape. In 1935, 0.9 percent of the landscape was mapped as anthropogenic cover-type patches dominated by human land uses, primarily as dry-farmed bean fields on the mesas north of Bandelier. By 1981 the portion of this landscape converted into anthropogenic patches had increased to 6.3 percent, as the bean fields were replaced by the technical areas of Los Alamos National Laboratory and the towns of Los Alamos, White Rock, and Cochiti Lake developed. Other new cultural features include 53 pumice mines, 12 large-stock ponds, three golf courses, a ski

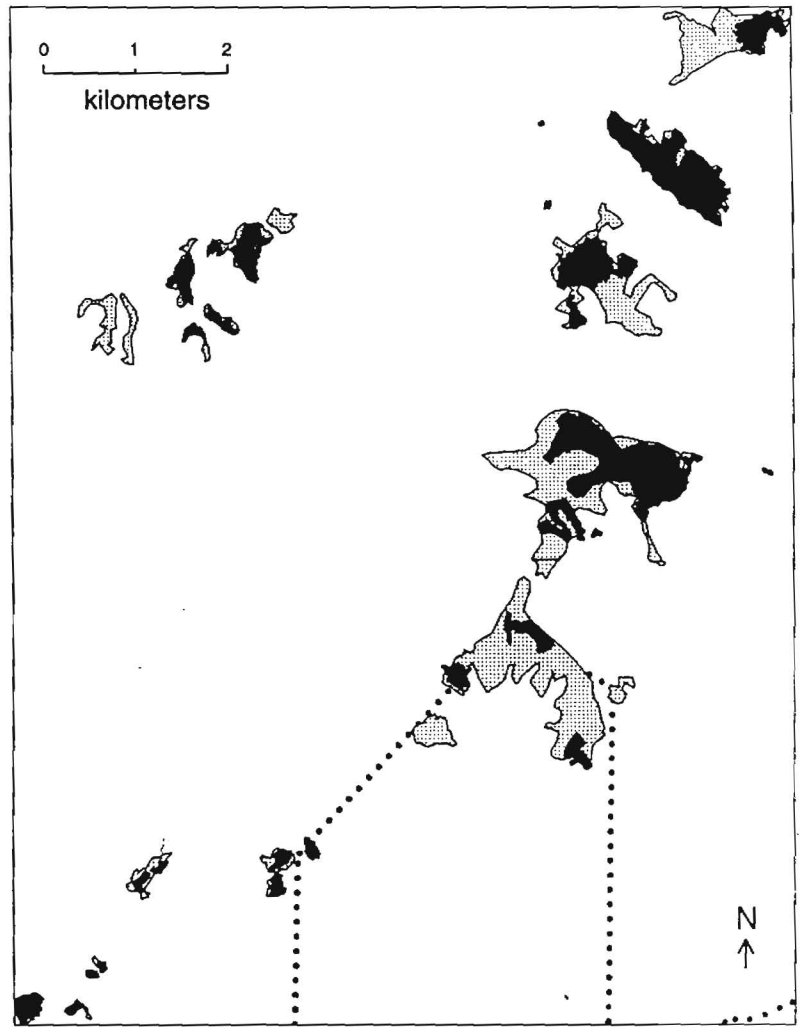

Figure 8.5 Map of reduction in montane grassland area between 1935 and 1981. Area of open grassland (with less than 10 percent tree canopy cover) is shown with a grey pattern for 1935 and as solid black patches for 1981. The dotted line encloses a portion of Bandelier National Monument.

area, and Cochiti Reservoir on the Rio Grande. Logging occurred along 11 percent of Bandelier's main unit boundaries between 1977 and 1984.

Further fragmentation of this landscape is apparent in the striking development of road networks in recent decades, as shown in Figures 8.6 and 8.7. I mapped five types of roads: railroad, paved, gravel, dirt, and

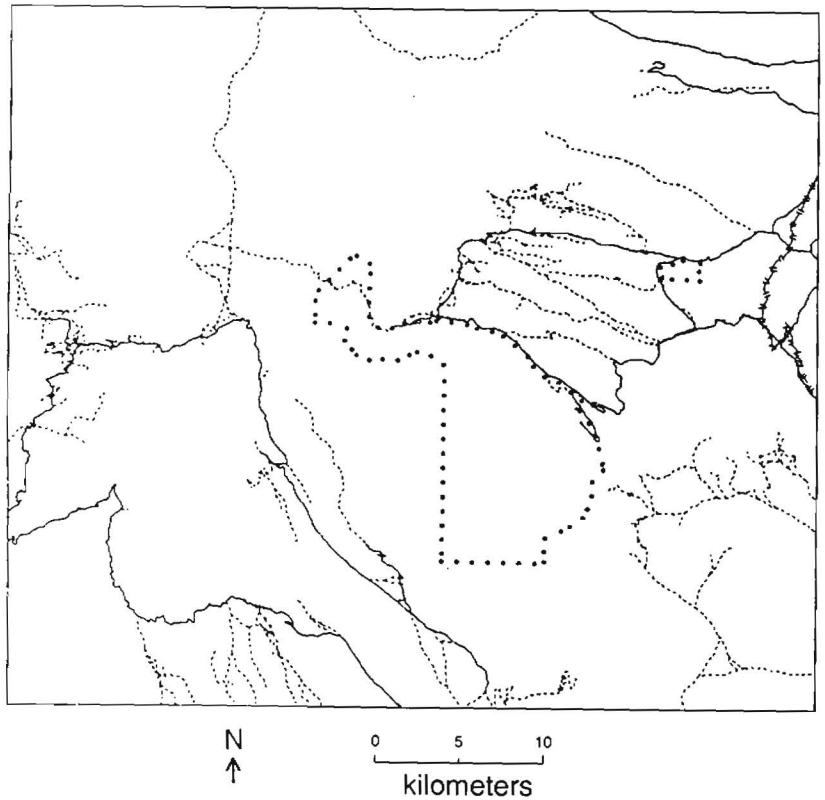

Figure 8.6 Map of all roads in 1935 across 187,858 ha of the Jemez Mountains. The crosshatched line is a railroad, the solid lines are dirt roads, the thin dashed lines are primitive roads, and the dotted lines show the current boundary of Bandelier National Monument.

primitive. Overall there was a 12-fold increase in total road length from 718 kilometers in 1935 to 8450 kilometers in 1981. Roads are indicators of direct and indirect human effects on landscapes. Examples of road impacts include: (1) roads as fire breaks, which also allow widespread access for fire suppression; (2) facilitation of motorized disturbance of wildlife; (3) introduction of edge conditions into forest interiors; and (4) roads as weedy paths whereby alien species move into new areas. In the forested portions of the Jemez Mountains roads are usually a signature of past timber harvests. By 1981 roads covered at least 1.7 percent of the mapped landscape (Allen 1989:240), with obvious implications for erosion rates, stream sediment loads, and overall landscape productivity (Maser 1988:161) in the Jemez Mountains. These GIS maps of road networks have been widely disseminated and have supported efforts by various land management

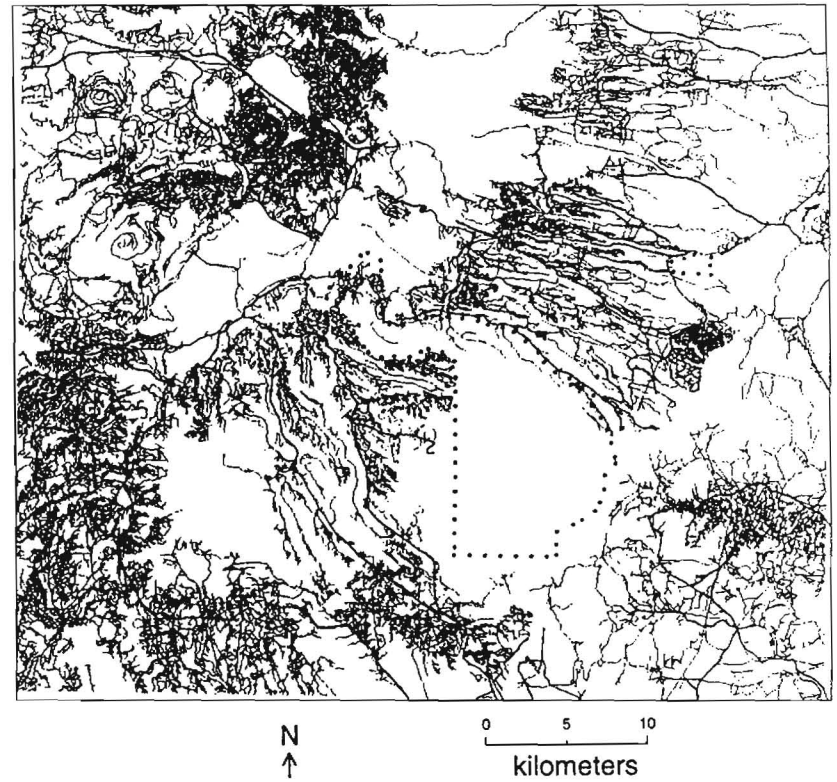

Figure 8.7 Map of all roads in 1981 across 187,858 ha of the Jemez Mountains. Distinctions between the various types of road are obscured in this black-and-white figure. The dotted lines mark the boundary of Bandelier National Monument. The roadless area of the Bandelier and adjoining Dome wildernesses is apparent. Several townsites, Los Alamos National Laboratory technical areas, powerline corridors, and many logging roads are prominent by 1981.

agencies and citizen groups to reduce open road densities and manage for less fragmented landscapes in northern New Mexico.

These landscape-scale GIS and remotely sensed data proved valuable in the most recent U.S. Forest Service planning effort in Bandelier's headwaters area, called the Dome Diversity Unit by the Forest Service (see Figure 8.4). Three timber sales had been carried out with increasing controversy in this 4630-hectare area between 1981 and 1988, and planning was underway for a fourth sale in 1989. Participation by Bandelier staff on this planning team provided an opportunity to work with the Forest Service to develop a more ecologically oriented management plan for the Dome area. Overall management direction as well as specific guidelines were derived from the Santa Fe National Forest Plan (USDA

Forest Service 1987), which provided a coarse resolution template for the Dome landscape as a cultural resource and wildlife emphasis area. GIS analysis of the canopy cover and distribution of vegetation types at a landscape level was used in consort with site-level information on vegetation structure from forest inventories and other fieldwork to assess forest structural conditions across the planning unit. These analyses demonstrated that past management actions had left Dome area resources far outside the Forest Plan standards for important structural criteria, ranging from acreages and distributions of old-growth forest stands to overall densities and distributions of snags. While the Forest Plan directs that "road use will be managed with the objective of limiting open road density to 0.3 to 1.5 miles per square mile," our GIS analysis showed 10.93 miles of road per square mile in 1981 (prior to three additional timber sales), with 2.3 percent of the Dome area in road surface (not including road shoulders and right of way). The graphic presentation of data relevant to Forest Plan standards led to substantive changes in the management plan that was developed for the Dome area (USDA Forest Service 1991), resulting in a 500-percent reduction in harvested timber volume during the current entry, designation of 27 percent of the planning area as "future old-growth forest," and widespread obliteration and closure of roads to drop open road density to 1.3 miles per square mile and provide opportunities for snags to develop in the absence of fuelwood poaching. The information produced by GIS and remote sensing methods was essential to support planning for ecological landscape management in this politically sensitive boundary area, and this success has bolstered other efforts to promote interagency cooperation in managing resources of mutual concern in this landscape.

Using GIS in Fire History Research to Support Ecosystem Management

Fire is an important disturbance process in most southwestern forests (Swetnam 1990). Recent fire history research conducted by the National Park Service and University of Arizona Tree-Ring Lab cross-dated 1180 fire scars on 74 trees within five vegetation types across a 900-meter elevation gradient in the Rito de los Frijoles watershed of Bandelier National Monument (Allen 1989, 1990). Sampled vegetation ranged from the lowest, mesatop stands of ponderosa pine (*Pinus ponderosa*) up to montane mixed-conifer forests, as well as riparian, mixed-conifer forest in Frijoles Canyon. In an ongoing cooperative project with the Santa Fe National Forest this fire history research has been extended to date fire scars from 299 trees, snags, and logs from 15 additional ponderosa pine

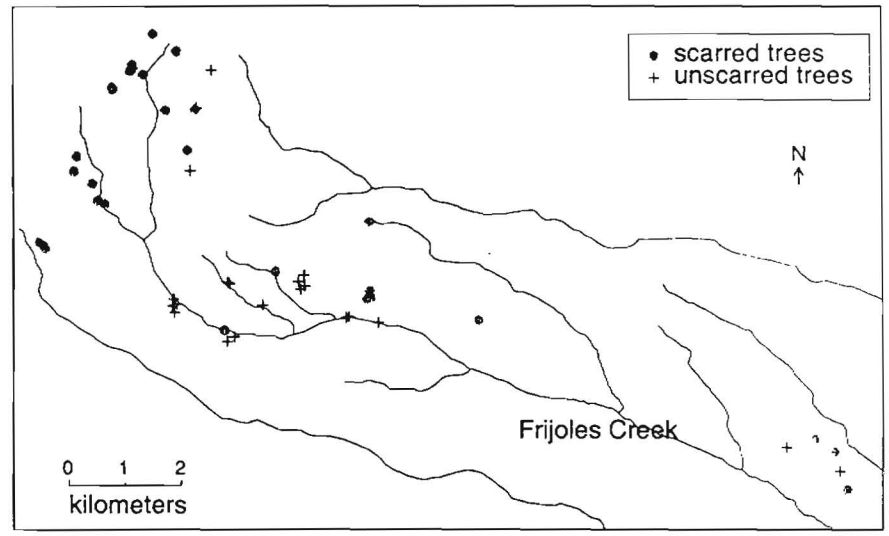

Figure 8.8 Map showing sample trees scarred by fire in 1748 in the Frijoles watershed. Similar watershed-wide fire years occurred about every 16 years, on average, between 1684 and 1851 in this watershed.

and mixed-conifer forest sites spread around the Jemez Mountains (Touchan and Swetnam 1992). Fire dates extend back to A.D. 1480, with mean fire intervals for major fires ranging from 6 to 22 years at all sites prior to the late 1800s, when fire frequencies plummeted, apparently due to the onset of heavy livestock grazing in the region (Wooton 1908, Allen 1989). GIS applications are being used to scale site-level information up to the landscape level, as in Figures 8.8 and 8.9, which display the extent of fires in the Frijoles watershed and Jemez Mountains in 1748. These data show that in many years fires burned widely across the Jemez Mountains (Allen and Touchan 1994).

Blending these fire history data with other historical and ecological information documents how fire suppression has induced major changes in the structure and function of many local ecosystems (Allen 1989). GIS analysis of the field sample-point data from Bandelier show that the distributions of many fire-sensitive species expanded markedly, for example upslope in the case of *Juniperus monosperma* and downslope in the case of *Pseudotsuga menziesii*. Formerly open ponderosa pine forests in the Jemez Mountains and throughout the Southwest have been converted into dense thickets, eliminating herbaceous understories and interrupting

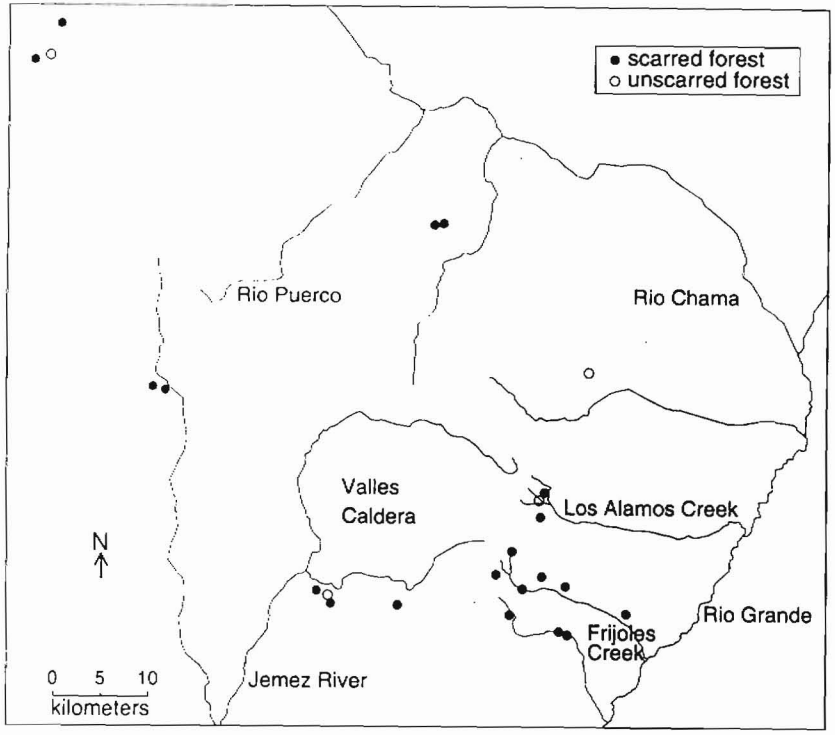

Figure 8.9 Map of the widespread 1748 fires in the Jemez Mountains. Forest sites where at least 25% of the sampled trees recorded a fire in 1748 are shown as scarred. Note that the Frijoles watershed (Figure 8.8) is located in the southeast portion of this map.

nutrient cycles (White 1991), while the potential for unprecedented high-intensity crown fires has developed (Covington and Moore 1992). The 1977 La Mesa fire concretely illustrated this structure-function relationship by converting 4000 hectares of dense ponderosa pine forest to grassland in and around Bandelier National Monument (Foxx and Potter 1984, Allen 1989).

These spatially explicit data unequivocally demonstrate the central role of fire in shaping ecological patterns at site and landscape levels in the Jemez Mountains. As a result, local land-management agencies are developing more aggressive prescribed fire programs to begin restoring historic vegetation mosaics and their associated fire regimes. The staff at Bandelier have drafted a new fire management plan that combines the ecosystem patch map and fire history data to outline the park as a mosaic of site-level patches with similar vegetation structures and fire history patterns. The patches in this landscape mosaic are being scheduled for management actions such as prescribed burns and thinning designed to restore each patch to a condition somewhere within its historic ecological envelope. This same landscape mosaic of site-level patches is also being used as the framework for an intensive fire-effects monitoring program (USDI National Park Service 1992), designed to provide information for managers on the ecological effects of management fires. Despite its small size Bandelier now has one of the most vigorous prescribed-fire programs between California and Florida in the National Park Service, with more than 500 hectares burned in 1992.

Similarly, the Santa Fe National Forest is using these high-resolution fire history data to strengthen their prescribed-fire program. For example, as I write (April 1993), smoke scents the air from a 6000-hectare prescribed burn on the west side of the Jemez Mountains, one of the ecosystem management demonstration projects on this national forest. This fire is being conducted on lands of the U.S. Forest Service, Jemez Pueblo, and Zia Pueblo by crews from the Forest Service, Jemez and Zia Pueblos, U.S. Bureau of Indian Affairs, National Park Service, U.S. Fish and Wildlife Service, and the State of New Mexico's Game and Fish Department and Forestry Division in a concrete example of cooperative management at a landscape level.

Limitations of GIS and Remote Sensing Technologies for Ecosystem Management

GIS and remote sensing approaches will become increasingly essential to implement ecological landscape management. However, many potential applications of GIS and remote sensing to ecosystem management are not yet feasible at the level of a Forest Service ranger district. Land managers must become aware of the limitations as well as the potential of these new tools (see Hoffer, Chapter 3), while proponents should avoid overselling these technologies. Otherwise, many ecosystem management applications of GIS and remote sensing will founder on unanticipated problems that may impede the adoption of these important new approaches to landscape management.

A major limitation on use of GIS and remote sensing methods is the time and expense required to develop landscape-level data and train personnel. GIS and remote sensing users must invest considerable front-end time to learn complex software packages and become familiar with the large quantities of data used in landscape-level applications. As a result

land management agencies are creating positions for GIS and remote sensing specialists, but once trained these specialists are hard to retain "in the field" because they can typically command higher salaries elsewhere as their computer skills are in general demand. Rapid improvements in computer technology and reduced costs have largely removed hardware availability as a restriction on use of these methods, although systemwide procurement issues have slowed USDA Forest Service efforts to apply GIS approaches. A primary limitation on the use of these technologies for ecosystem management is the availability of trained personnel, and this will become increasingly apparent as data and hardware become ever more accessible.

A variety of data-related issues require consideration when applying GIS and remote sensing methods to ecological landscape management (Hoffer, Chapter 3). GIS applications are subject to the classic computer maxim "garbage in, garbage out." While a variety of general data layers of known resolution and quality (e.g., topography, hydrography, land ownership) can now be purchased inexpensively from sources such as the U.S. Geological Survey, the development of high-quality, ecological data to meet landscape-specific needs can be expensive. Indeed, the potential to collect data at landscape scales for low cost per unit area covered is one of the primary attractions of remote sensing approaches to data collection. However, users need to recognize that the utility and accuracy of remote sensing applications are greatly affected by the resolution of the sensor, the experience of the analyst, and the classification methodologies employed.

The data underlying land management applications of GIS continually become obsolete as forest stands and landscapes change. Thus land management agencies must plan to constantly update their GIS data in order to maintain current information over large areas, such as national forests.

Data compatibility and interpretation issues emerge when a GIS application is used to collate and integrate diverse data sets for ecological landscape management. Data resolution and accuracy may differ between data layers, which often originate from multiple sources with variable standards of quality control and documentation. Accuracy may even vary within a single layer (e.g., certain vegetation types may be classified more accurately than others). It is difficult to explicitly assess and document site-specific uncertainties in spatial data—GIS users are unable to see error bars for each pixel in a map layer. As a result, unquantified uncertainties are often layered atop one another in GIS applications, yielding outputs of unknown validity. A GIS model is subject to the limitations of all its data; therefore, the use of more data may result in a less certain

output. It is already common to see naive GIS applications that overlook the limitations and uncertainties inherent in the data, leading to precise but inaccurate results or overgeneralized outputs that ignore the local complexities observed in the field (Scott et al. 1994). The flood of GIS data and rising intricacy of analytical procedures could exacerbate this problem by fostering specialized analysts who become increasingly office-bound and isolated from the field data underlying their GIS applications.

Similarly, the much-vaunted ability to easily manipulate GIS data in generalized modeling applications has a downside, as it leads to the creation of internally generated "virtual" data, which may be difficult to distinguish from "real" data that have been externally collected and physically verified (e.g., by ground-truthing). Indeed, it may be impossible to verify such model-derived "virtual" data (Oreskes et al. 1994), yet once created these data are subject to use without critical assessment of their validity.

These data issues can make the use of GIS for ecological interpretations challenging and fraught with potential for error. The illusions contained in modern television advertisements demonstrate the power that images have to deliberately or inadvertently misinform unwary consumers of visual information. The consumers of GIS outputs (including the general public, resource managers, and academics) need to critically review the validity of the "virtual worlds" presented to them, while ecosystem managers need to use the power of GIS applications with caution and awareness of the uncertainties in their spatial data. It is important to continually remind ourselves and the public that the beautiful GIS and remote sensing images we create are only simplified representations of landscapes, often removed by several interpreted steps from the external physical reality.

Finally, several data-management issues merit highlighting. Careful archiving of original data and documentation of any data alterations are required to maintain the integrity and quality of ecological data and any dependent applications. Data security will receive increasing attention as locational information on sensitive resources such as endangered species or archeological sites becomes incorporated into GIS databases, which can easily be transferred into unfriendly hands via modem links or a small diskette. GIS data management is challenging for land management agencies because of the increasingly large quantities of data used in GIS, the significant potential for deliberate and inadvertent modifications of data files without adequate documentation, difficulties in creating new positions for full-time system managers in these fiscally tight times, and the lack of continuity associated with the high turnover rates of experienced computer personnel.

Using GIS and Remote Sensing to Model Old-Growth Forests on the Santa Fe National Forest

Gonzales (Chapter 10) provides detailed information on a recent effort to use GIS and remote sensing methods to model old-growth forest locations in part of the Jemez Mountains on the Santa Fe National Forest. This project offers lessons on the use of GIS and remote sensing for ecosystem management as it concretely illustrates some of the limitations listed above.

First of all, this project depended on Landsat thematic mapper data, which lack adequate resolution to distinguish the essential structural attributes of local old-growth forests. These resolution problems apparently led the Santa Fe project to avoid consideration of the numbers of large trees and snags per acre, which are the most important structural attributes used in the Region 3 old-growth definitions and guidelines (Southwestern Region Old-Growth Core Team 1992, Popp et al. 1992). The Santa Fe model had to rely heavily on measures of canopy closure, which are not well correlated with old-growth forests in the southwest because of the historic importance of high-frequency surface fires in molding open-stand structures.

The complex and steep canyon and mountain terrain of the project area further complicated vegetation classification efforts, as did the heterogeneous structural composition of local forests. Smoothing algorithms that were applied to create polygons out of finely jumbled raster classifications likely further degraded the accuracy of the model of probable old-growth. It is clear that this model had difficulty in accurately locating old-growth stands, although the map of probable old-growth has yet to be distributed to, or reviewed by, the project's advisory group or local ecologists.

Specific goals and expected products were not clearly articulated in the early stages of the project, although the project's proposal indicated a core purpose to "spatially analyze old-growth stands within the project area" and included more than 30 "questions the project is designed to answer" (Gonzales 1991). This proposal raised expectations among some U.S. Forest Service staff and members of the outside advisory group, which led to disappointment in the outcome as few of the questions were addressed and the products of this project have not contributed significantly to the resolution of old-growth management issues on the Santa Fe National Forest. GIS and remote sensing approaches are certainly important for ecological landscape management, but managers must become aware of limitations and work closely with the analysts if they are to receive a

productive return on their investments in GIS and remote sensing and see these tools achieve their potential to develop needed information products.

Conclusion: Potential Uses of GIS and Remote Sensing Approaches for Ecosystem Management

Franklin (Chapter 2) reviews the utility of a variety of GIS and remote sensing tools for ecosystem management. Several potential uses merit mention here.

Myriad possible applications of remote sensing for ecological inventory and monitoring have barely been explored, ranging from image processing of repeat photography for assessing the ground cover of small plots to satellite monitoring of global-scale phenomena such as tropical deforestation (see Skole and Tucker 1993). Remote sensing can improve the repeatability of ecological monitoring and avoid certain research impacts, such as the trampling of microphytic soil crusts in arid landscapes.

As the variety and volume of ecological data required to implement land management increases, the combined use of GIS with other computer applications will prove increasingly valuable to land managers by allowing the collation, storage, integrated analysis, and dissemination of spatial data as well as associated data, text, and graphics files. For example, one can already link the locational data for permanent vegetation plots through a GIS to computer files containing scanned images of plot photographs, raw field data, graphs of the analyzed data, and journal references relevant to the plot. One of the most important uses of GIS might emerge from its application as a focal point for tracking all land management actions and associated inventory and monitoring data, so that adaptive management can become a reality (managers cannot learn from past actions if the data from these management "experiments" is continually being lost). Also, GIS will help managers and the public keep track of the large number of promised actions contained in current land management plans (e.g., the maintenance of designated "future old-growth forest" areas in the Dome Diversity Unit).

Land managers will continue to expand their use of GIS and remote sensing approaches for assessing cumulative impacts of potential land management scenarios, as well as for envisioning desired future conditions at landscape scales. GIS and remote sensing will also be increasingly used by a diverse array of interest groups in efforts to mold public perspectives on land use issues and thereby put political pressure on land management

agencies and other social institutions (e.g., the recent Project Lighthawk and Wilderness Society analyses of remaining old-growth forest in the Pacific Northwest). Indeed, many anachronistic land-use situations exist where a graphic presentation of the present ecological status, current trends, and possible future conditions under different management scenarios could serve to productively focus public attention on deadlocked issues and thereby catalyze action toward solutions.

Overall, applications of GIS and remote sensing to ecosystem management are promising means for implementing a modern land ethic. Still, these more rigorous, technologically supported approaches to land management will supplement but cannot substitute for human intuition, wisdom, and humility in decision-making, based on familiarity, respect, and appreciation for a place (Lopez 1992). Long-term intimacy with a particular landscape is essential to learn enough about the diverse verities and uncertainties of a place to develop the multiscale spatial and temporal perspectives needed to implement ecosystem management well (Jordan III 1994)—ecosystem "health is a judgment that can be made only by someone who has been intensely familiar for a long time with what is being judged" (Ehrenfeld 1993:145). Resource management agencies must provide career options that allow land managers and affiliated researchers to become knowledgeable about and attached to the landscapes in which they work—to develop a sense of place. Ultimately, sustainable land management requires more integrated, long-term relationships between people and their landscapes; this imperative may well call each of us to explore the satisfactions and obligations of "the heritage of place and the responsibility of time" (Ruch 1992).

A transformation to a more sustainable society requires changes in the ways we see and think about our relationships with landscapes. GIS and remote sensing approaches to land management have great potential to promote increased awareness and acceptance of the duty of careful stewardship implicit in the powerful, beautiful, and frightening images they produce of a living earth being rapidly changed by humans. Thus over the next decade the greatest contribution of GIS and remote sensing tools to ecosystem management may come indirectly through fostering a more universal land ethic in society at large.

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