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ROLES OF GIS IN CONSERVATION

The preservation of biological diversity in a world burdened with an exponentially growing human population requires a comprehension of spatial and temporal patterns in a broad array of physical and biological entities. The amount of data that will be needed to effectively inventory, monitor, and manage biodiversity so greatly exceeds the resources available to collect and analyze the data that conservation biologists will at best play a minor role in a losing struggle if they approach this challenge equipped with only traditional tools. Thoughtful application of GIS technology, however, can maximize the efficacy of planning based on limited time, money, and information. The capacity of GIS to perform spatial analyses with interactive physiographic and biotic data bases renders it an essential tool for interpreting complex biodiversity inventories, for designing and managing preserves at the ecosystem level, and for predicting the effects of climate change. GIS technology provides a modelling platform for critical investigation of the determinants of biodiversity and the effects of human activity on natural systems. This paper discusses how GIS analysis can be integrated with meteorological data, ecological data, and remote sensing technology to meet conservation challenges that were once formidable or insurmountable.

INTRODUCTION

Most conservation challenges ultimately stem from spatial issues. Biodiversity is eroding because spatial distributions of resources critical to its preservation are becoming too limited, dispersed, fragmented, or degraded. Concurrently, direct and indirect anthropogenic impacts on these resources are growing more intense and more widespread. This trend will accelerate as nations endeavor to meet the demands of increasing human populations by drawing ever more deeply on the finite productive and regenerative capacities of natural systems.

Human impacts on the biotic systems that sustain us are compounded by our fundamental ignorance of the depth and scope of these impacts. If we are to contain anthropogenic influences within sustainable bounds, we must understand the immediate and local effects of those influences, regional and global manifestations of cumulative local impacts, and the capacities of natural and semi-natural systems to absorb impacts on various spatio-temporal scales. Progress in building such an understanding is limited by human perception: an individual can be in only one place at a time. Furthermore, resources available to monitor, manage, and mitigate anthropogenic impacts are desperately limited.

If we are to meet pressing conservation challenges in spite of the practical constraints on our ability to address them, we must adopt more flexible approaches. Thoughtful application of Geographic Information System (GIS) technology is one such approach. GIS facility with spatial data renders it a powerful tool for studying spatial factors in the erosion of biodiversity and for designing ways to contain this erosion.

CONSERVATION RESEARCH

GIS analysis can contribute to the conceptual understanding that must inform conservation programs. GIS are themselves information-intensive, and initially they might seem to be the wrong tool to bring to information-poor problems. Creative GIS analysis, however, can expand the spatial extent of limited field data or make predictions about spatial patterns in biodiversity where field data are lacking entirely.

Spatial Patterns in Biodiversity

GIS can help clarify spatial patterns in biodiversity. If the factor(s) that limit a biotic distribution are known, information on topography, geology, or remotely sensed spectral data allows researchers to generalize field data to areas with similar topoclimatic exposures, hydrologies, soil conditions, or vegetation categories. The accuracy of predicted species, community or ecosystem distributions must be verified eventually with additional field data, but GIS enables researchers to generate preliminary estimates rapidly. This approach is particularly valuable for remote or rugged tropical regions, where information on biotic distributions is scarce and difficult to obtain (Rich, et al. 1992).

Conversely, GIS analysis can identify habitat variables that determine a known distribution. This application is more appropriate for well studied areas or regions where proximity to roads, agriculture, or other parameters of land use are important determinants of patterns in biodiversity.

Dispersal Characteristics

Dispersal behavior can be studied using GIS analysis combined with mark-release-recapture data or with historical records on species range expansions. This approach can be used to identify dispersal barriers or corridors (Soule 1991), to predict patterns of recolonization of vacant habitat (Harrison 1989, Harrison et al. 1988), or to study genetic mixing among partially isolated subpopulations. The

computational capacity of GIS promises to lend spatial realism to models of dispersal, most of which assume passive diffusion across homogeneous landscapes (Okubo 1980).

Variation in Predation or Herbivory

Data describing the distribution of predators or herbivores can be entered into a GIS to determine spatial patterns in the intensity of predation risk or herbivory. Delineation of territorial boundaries of predator individuals or social units enables researchers to identify potential prey refugia that occur between territories. Indirect measures of predation intensity may be determined by comparing prey densities within refugia with densities that occur outside refugia. Vegetation condition can be combined with herbivore densities and distributions in a GIS to determine actual or projected intensity of herbivory. Similar analyses may be performed in conjunction with studies of dispersal to predict outbreaks of forest pests and pathogens (Turchin et al. 1991).

RESERVE DESIGN

GIS technology is particularly well suited to the task of designing reserves. Information about habitat requirements can be added to maps of potential reserve sites in order to determine areas that offer the greatest potential for population persistence. This strategy may be refined further with the addition of temporal data on population densities or weather records to identify sites that offer the greatest capacity to buffer threatened species from demographic or environmental stochasticity. This approach can be expanded to the community or ecosystem level, as detailed below.

GAP ANALYSIS

The current rate of extinction is estimated at 1000 species/year (Meyers 1989). Scott et al. (1987) note that at this rate, simply determining species at risk is a formidable task. We are not equipped to assess even current species losses. Scott et al. (1987) recommend using a GIS to conduct such a risk assessment, which they termed "gap analysis." GIS capacity for mapping, storage, retrieval, and manipulation of data make it an ideal tool for biogeographic analyses of extinction risk. A GIS can combine abiotic site characteristics with species distribution data on biogeographic, regional, and local scales. The raw data required for GAP analysis include distributions of well-documented species, vegetation maps, land ownership maps, and boundaries of existing reserves. Many conservation questions can be answered by querying the GIS database. For example, GIS can generate maps of species ranges, maps of observed population locations, or maps of multiple species associations. Habitat/species relationships can be determined by analyzing relationships between population density and habitat characteristics such as substrate, soil type, vegetation type, solar exposure, elevation, or latitude. Prime sites for preservation can be determined by combining maps of land ownership with information on the locations of high species richness, high endemism, or high density for species of special concern. Centers of species richness can be compared with locations of existing reserves to reveal where biodiversity is currently well protected and where additional reserves will be most effective. GAP analysis can be used to calculate the proportion of threatened or endangered species in existing reserves, to identify the species or habitat types that are not protected by reserves, or to determine whether adequate corridors exist between areas of high species richness.

Viability of Metapopulations

Metapopulations pose challenges to reserve design that must be addressed in spatially explicit formats (Murphy et al. 1990). Metapopulation reserve design could begin by identifying potential and/or occupied habitat patches and by delineating their boundaries in a GIS database. Analysis of the database

would differentiate between reservoir and satellite patches (or population sources and sinks) and it would identify dispersal corridors and barriers. Data on dispersal rates and direction biases would permit calculation of the relative isolation of each patch and the degree to which viability of the entire metapopulation depends on the persistence of a given patch. With the latter calculation, GIS analysis would play a critical role in providing ecological information necessary for legal protection of each subunit of a metapopulation (Rohlf 1991). Alternatively, it would facilitate habitat triage, in which patches vital to metapopulation viability could be distinguished from those that merely augment its distribution.

Conflicts with Human Activities

Direct and indirect effects of human activity increasingly compromise the effectiveness of reserves. GIS can be used to identify potential reserve sites that are buffered most strongly against current or anticipated anthropogenic stressors. Land use information can be overlain on topographic maps to identify relatively pristine sites that are protected by natural barriers that could limit proximal development. Reserve location also could be determined by information on riparian networks in order to minimize exposure to artificial hydrologic regulation or waterborne pollutants.

CONSERVATION MANAGEMENT

GIS will play an increasingly more important role in the design and evaluation of conservation management. As managers address ecosystem viability on larger scales and with a better understanding of disturbance, dispersal, and climatic variation, they will find GIS to be indispensable in considering spatial heterogeneity and predicting effects of alternative management scenarios.

Recovery from States of Risk

GIS provides managers with the ability to determine spatial relationships between resources and habitats that are critical to threatened populations. For raptors and carnivores, these might be nest or den sites, productive hunting areas, and the travel routes between them. Invertebrates might require a sufficient number of suitable vegetation patches located within a maximum dispersal radius, or they might need appropriate habitat on adjacent and oppositely oriented slopes (Murphy et al. 1990, Rich and Weiss 1991). Threatened annual plants might depend on the shifting locations and constant availability of recently disturbed substrates. GIS analysis enables managers to determine the capacity of a landscape to provide these resources and habitats, and it suggests programs that could ensure their continued availability. A second level of analysis would involve simulation of the effects on target populations of alternative management strategies, and to use simulation results to select an optimal plan. GIS can play a role in evaluating the results of management by mapping the locations of management activities, the effects of these activities on target resources or habitats, and the subsequent response by the populations of management interest.

Disturbance Mosaics

Preservation of biodiversity in many systems depends on disturbance-generated spatiotemporal heterogeneity (Turner 1989). Agents of disturbance often are perceived to be incompatible with the presence of humans, who strive to suppress or construct defenses against the fires, floods, storms, and pathogens that maintain community mosaics. In addition, many systems have been fragmented or diminished to a point where they cannot sustain functional disturbance mosaics internally. Consequently, managers often must actively initiate disturbances or control naturally created ones so that only some fraction of the managed area becomes disturbed. The manager's job is complicated further by a demand that agents of disturbance do not escape the boundaries of the managed area.

GIS is suited particularly well to designing ways to satisfy these conflicting requirements. A manager's first step would be to plot relative susceptibility to disturbance of subregions within the managed area. Then the manager could delineate highly susceptible regions that are likely to sustain and propagate disturbance, such as nutrient stressed forests that would be unable to resist pathogens. S/he also could identify barriers to disturbance, such as recently burned areas that would limit spread of subsequent fires. More complex analysis would locate potential refugia for animals and proximal seed sources for disturbance-sensitive plants. GIS would be used to create management plans by combining the preceding steps to (1) locate sites that would support adequately contained disturbance, (2) identify additional barriers that will be necessary to prevent excessive disturbance or escape beyond management borders, and (3) prescribe appropriate timing, frequency, and location of disturbance initiation. Finally, GIS would be used to evaluate the results of disturbance management programs in order to refine management protocols and to enhance understanding of the role that disturbances play in managed ecosystems.

Coordination Among Management Agencies

Adjacent regions in an ecosystem often are managed by different agencies for different purposes. Biotic entities do not observe administrative boundaries, however, and biodiversity may slip through cracks between uncoordinated management programs. GIS coverage of an entire ecosystem can help to monitor the consequences of diverse management practices and to suggest ways to reconcile inter-agency differences to ensure the health of the ecosystem and its components. This will prove to be essential in systems affected by species that migrate across administrative boundaries to reach seasonal foraging areas (Turner et al. 1992) and in areas with a mosaic of public and private lands that face intense development pressures (O'Leary et al. 1992, Atwood 1992, Curran 1991). GIS also can be used to illustrate the economic value of nature reserves, particularly in the tropics, through watershed analyses that demonstrate the role of intact forests in maintaining water quality and in reducing erosion of private and commercial lands downslope (Rich et al. 1992).

Example: Ungulates, Plants, and Snow in the Greater Yellowstone Ecosystem

Ungulate interaction with potential winter forage in the Greater Yellowstone Ecosystem is regulated by snow conditions (Wallace et al. 1992). Deep snow reduces the amount of accessible forage directly by covering it, and indirectly by limiting ungulate mobility to reach it. During particularly severe winters, ungulates become restricted to critical winter range, which they subsequently deplete. Thus, ungulate survival is a function of herd size, winter temperature, snow depth, forage condition, and forage distribution. The situation is further complicated by fire, which can be a factor in the reproduction of aspen, whose seedlings are a preferred ungulate winter food source (Wallace et al. 1992).

GIS can play a useful role in efforts to manage ungulates and aspen. First, GIS coverage of the region can be used to identify potential ungulate winter range and recently burned areas that could support aspen germination. Next, snowpack data could be extrapolated to monitor the distribution of potential forage from autumn through spring. Third, information on ungulate abundances and mobilities could be used to determine actual forage availability and its decline through time. Data on ungulate mobility also would permit prediction of aspen seedling survival by overlaying maps of potential ungulate foraging onto maps of conditions favorable to seedling germination. Knowledge of forage availability would facilitate prediction of ungulate winter mortality. Slope and aspect data for spring and early summer range would permit calculation of snowmelt and subsequent exposure of alternative forage.

Thus, GIS analysis could provide predictions of ungulate population dynamics and aspen seedling survival resulting from different combinations of ungulate abundance, weather conditions, and recent fire

history. These predictions in turn could inform decisions about appropriate fire and ungulate management practices. It also could facilitate communication among the many federal and state agencies charged with management of the Greater Yellowstone Ecosystem, if only by providing a vision of the degree to which system structure and function transcend administrative boundaries.

CONSERVATION AT THE ECOSYSTEM LEVEL

Ecosystem-level conservation is a popular phrase that enjoys wide intuitive appeal but that has undergone little conceptual development. Most conservation biologists understand what it is, yet few can provide specific directions on how to accomplish it. Much of this dilemma traces to a lack of communication between two complementary approaches toward studying natural systems: ecosystem ecology and community ecology. Conservation biology developed largely within the population-species-community paradigm (Soule and Wilcox 1980, but see Hall 1987). Consequently, most conservation on small to medium scales has been at the species or population level, as most people and legislatures identify more readily with tangible entities (organisms) than with less tangible cycles or flows.

Biodiversity is eroding so rapidly, however, that a species by species approach to conservation is no longer adequate (Myers 1988, Noss 1990). In fact, species have gone extinct while awaiting listing for federal protection. Conservation efforts that protect entire ecosystems hold more promise, but ecosystem-level conservation remains to be clearly understood and implemented. GIS could play a pivotal role in this important conceptual and practical advance.

Community-Level Conservation

Expanding species by species conservation to the community level represents a first step in the development of ecosystem-level conservation. Examples of such an approach include prairie restoration in the U.S. midwest (Jordan 1988, Nelson 1987), protection of coastal sage-scrub communities in southern California (O'Leary 1990, O'Leary et al. 1992), and management of plant community mosaics in Connecticut (Niering 1987). The species-level approach long has been recognized as a means of effecting community-level conservation in a legal environment that recognizes only endangered species (Rohlf 1991): protecting the habitat of conspicuously endangered species often acts as a conservation "umbrella" that includes less charismatic members of a threatened community, (Murphy and Weiss 1988, Murphy and Noon 1992). GIS can facilitate community-level conservation through development of a community analog of species-based GAP analysis.

Definition of Boundaries for Ecosystem Reserves

Conceptually, the simplest approach to ecosystem-level conservation would be to define the boundaries of an ecosystem and to "protect" everything encompassed by them. This could work with small, well-defined ecosystems, but complete protection of large systems often would exceed available conservation resources. Even in large public lands such as the Greater Yellowstone Ecosystem, management policies often compromise functional and structural health (e.g. via fire suppression or resource extraction). GIS, however, could play an important role in the delineation of reserve boundaries in ecosystem-level conservation. In short, GIS could be used to render an ecosystem-level analog of population viability analysis.

A second approach would be to implement protective measures that would guarantee the integrity of all material and nutrient cycles. Caution is advised with a strict ecosystem approach, however, for similar species are not interchangeable units. This would entail providing for "closed" cycles in as many ecosystem components as possible. For example, reserves that contain intact watersheds would be more

viable than reserves that lie downslope from timber extraction activity. GIS would be an effective tool in the delineation of boundaries necessary for intact cycles, and for the location of nutrient sources and sinks.

A more sophisticated approach would be to define boundaries that encompass the full range of physiographic conditions (or some other primary determinant of spatio-temporal heterogeneity) that exist within the system. This would provide spatio-temporal refuges for constituent populations in times of climatic stress, permitting migration to cooler and wetter areas in warmer and drier years or seasons and vice-versa in cooler and wetter periods. Full physiographic representation also would provide a longer temporal window of availability of resources and activity of ecosystem processes. For example, pollinators could track peak flowering by migrating among slopes of different aspects, thus sustaining reproduction of both plants and pollinator predators. The boundaries so defined also must be sufficient to maintain disturbance regimes responsible for the generation of complete successional mosaics. GIS facility in conducting physiographic inventories (Rich et al. 1992) make it particularly suited to this approach.

RAPID ASSESSMENT OF IMMANENTLY THREATENED AREAS

As biodiversity became popularized in the late 1980's, many scientists agreed that more information was needed for quick determination of conservation priorities in disappearing rainforest ecosystems. Murray Gell-Mann proposed rapid assessment to study poorly understood forests in the tropics (Wolf 1991). Rapid assessment (RAP) teams have been deployed to regions that are threatened with imminent loss of biodiversity. This "kamikaze" approach involves flying into the region a team of taxonomic experts, who quickly gather collections and site information. RAP teams identify areas that merit highest protection priority. Their findings are applied immediately and directly to conservation and land-use planning through close work with local colleagues. RAP teams meet with non-governmental organizations to discuss preliminary assessments. They also send data to the U.S. for more complete analysis (Wolf 1991). Where loss of habitat is inevitable, the work of RAP teams is a salvage operation, representing the last chance to gather biological information that would be lost otherwise.

GIS is the most appropriate tool for targeting RAP efforts and for organizing the massive data sets that are collected. Although preliminary assessments are conducted on site, more detailed analysis can confirm initial conservation decisions and it can direct the assessment at each step. Although the technology exists and the data currently is being collected, there is still a big gap in implementation of GIS for immediate needs of RAP teams. The immediacy of decisions requires quick action and sophisticated facilities. At this time, the GIS analysis must be conducted in the U.S., but in the future, it could become a great asset for RAP teams on site.

ASSESSING ANTHROPOGENIC IMPACTS

The scale and scope of human influence on natural systems is becoming increasingly profound. Our global experiment not only is uncontrolled and unplanned, its future course is essentially unknown. One of the most promising applications of GIS technology is its role in projecting anthropogenic impacts on natural systems, and thereby informing decisions about our fate before they are made for us.

Resource Extraction

The individual and collective effects of agricultural, livestock, timber, mining, and petroleum industries rarely have been studied in an integrated and spatially explicit manner. GIS provides the ability to plot the spatial and temporal scale of these industries, and hence to determine the magnitude of their

direct disturbance. More importantly, however, GIS can be a tool for monitoring and a modelling platform for predicting indirect effects of extractive industries: soil erosion, air and water pollution, reduction in regional primary productivity (carbon dioxide uptake), and immediate and long-term changes to natural communities.

Road Construction

GIS analysis of the cumulative effect of the cumulative effect of roads would represent a major advance over current environmental impact studies of proposed road construction. GIS capacity for integrated analyses of diverse spatial databases permits detailed assessment of system fragmentation and the introduction of dispersal barriers that accompany road construction. Data on animal dispersal and habitat requirements could be combined with information on the size and distribution of habitat patches to determine road-induced biodiversity loss through direct mortality, restriction of dispersal, and habitat fragmentation. Additional analyses could treat roads as permanent gaps that propagate wind-borne disturbance and erosion.

Pollution

Spatial analyses of water flow and wind currents, combined with data on point and dispersed sources of herbicides, pesticides, fertilizers, industrial wastes, sewage, and petrochemical combustion offer the means to assess current toxic loads and projected impacts on water quality, air quality, and the distributions of pollutants throughout natural and semi-natural ecosystems. GIS capacity for such analyses will establish it as an essential tool for prioritizing pollution reduction and clean-up efforts. GIS can play an additional role by identifying current and future sources of toxic stressors on reserves and sensitive ecosystem components.

Recreation

Growth in recreational use of natural ecosystems far exceeds rates of human population increase, and it poses difficult challenges for managers of public lands (Hammit and Cole 1987). Many detrimental impacts of recreational activities stem from regionally under-dispersed and locally over-dispersed patterns of use. GIS can aid chronically understaffed and underfunded recreation management offices in the formulation of effective regulations, permit quotas, and user education programs. It also can assist officials in efforts to minimize exposure of protected populations to recreational impact during particularly sensitive seasons.

GIS and EMAP

The Environmental Monitoring and Assessment Program (EMAP) of the U.S. Environmental Protection Agency involves GIS tracking of environmental parameters on an unprecedented scale (Messer, et al. 1991). It promises to provide ecological data that will serve as a reference for many, if not most future large scale U.S. conservation programs. The enormity of such a task necessitates careful planning of data collection and management, however. One of the primary dilemmas that remains unresolved is the manner in which to reconcile data collected at different scales and with different technologies. At present, EMAP is concerned chiefly with environmental monitoring. A primary conservation application of EMAP data will be toward the prediction of future biodiversity indices from current values, and the effect of different alternative decisions in shaping potential futures.

COPING WITH CLIMATE CHANGE

In this time of rapid climate change, there are critical needs for improved understanding of spatial interactions and for formulation of more accurate global and regional climate models (Committee on

Global Change 1988, Houghton and Woodwell 1989). It is through the combined efforts of talented theoretical and field scientists that we have reached the verge of being able to understand and model ecosystem flux processes. Many problems remain, including limited means for direct sampling at the mesoscale, high variability, and emergent properties resulting from complex linkages between biological, chemical, and physical processes. Recent attempts to address these challenges include NASA's Boreal Ecosystem Atmospheric Study (BOREAS), the DOE's Atmospheric Radiation Measurement (ARM) program to improve general circulation models, and experimental ecosystem approaches to understanding implications of elevated CO₂ (Mooney 1991). While remote sensing offers the means by which much landscape-level data will have to be collected, GIS offers the only means to build models that can integrate to the landscape scale. Shifts in community structure resulting from global climate change could be predicted in GIS-based models of compositional changes along environmental gradients (Rich et al. 1992).

FUTURE ISSUES FOR GIS IN CONSERVATION

GIS must address many future issues, including several that relate to interaction with complementary technologies and with field data. A primary concern is how to scale up from local field data and physiological measurements to landscape-level GIS analysis. A related issue involves accuracy in the conversion of remote sensing data to GIS maps of plant community distributions. GIS interaction with simulation models must become more seamless to better predict species responses to habitat loss, shifts in community distributions, encroaching desertification, and the results of climate change. Since greatest biodiversity loss is occurring in tropical regions, GIS must be put into the hands of trained citizens of tropical nations. A final issue concerns interaction between GIS and field study, or the importance of ground-truthing the results of GIS analysis. GIS will never be a substitute for muddy boots.

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