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Selecting a Suite of Ecological Indicators for Resource Management

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ABSRACT: We discuss the use of ecological indicators as a natural resource management tool, focusing on the development and implementation of a procedure for selecting and monitoring indicators. Criteria and steps for the selection of ecological indicators are presented. The development and implementation of indicators useful for management are applied to Fort Benning, Georgia, where military training, controlled fires (to improve habitat for the endangered red cockaded woodpecker), and timber thinning are common management practices. A suite of indicators is examined that provides information about understory vegetation, soil microorganisms, landscape patterns, and stream chemistry and benthic macroinvertebrate populations and communities. For example, plants that are geophytes are the predominant life form in disturbed areas, and some understory species are more common in disturbed sites than in reference areas. The set of landscape metrics selected (based upon ability to measure changes through time or to differentiate between land cover classes) included percent cover, total edge (with border), number of patches, mean patch area, patch area range, coefficient of variation of patch area, perimeter/area ratio, Euclidean nearest neighbor distance, and clumpiness. Landscape metrics indicate that the forest area (particularly that of pine) has declined greatly since 1827, the date of our first estimates of land cover (based on witness tree data). Altered management practices in the 1990s may have resulted in further changes to the Fort Benning landscape. Storm sediment concentration profiles indicate that the more

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highly disturbed catchments had much greater rates of erosion and sediment transport to streams than less disturbed catchments. Disturbance also resulted in lower richness of EPT (i.e., number of taxa within the aquatic insect orders Ephemeroptera, Plecoptera, and Trichoptera) than in reference streams but similar total richness of invertebrate species. Each indicator provides information about the ecological system at different temporal and spatial scales.
KEYWORDS: disturbance, forests, indicators, resource management

Introduction

The questions that our work addresses are on a local resource management level. What are the best indicators to be measuring? How can those metrics be properly interpreted? Because of its proactive mode of management, this effort focuses on lands owned and managed by the Department of Defense of the United States. We first examine criteria that are suitable for indicators and then consider steps of selection of indicators. A suite of indicators is proposed, and a case study dealing with potential indicators at Fort Benning, Georgia is presented. Overall, the paper provides insights into the value of indicators, how they are selected, and how they can be used.

Criteria for Selecting Ecological Indicators

Criteria for selecting ecological indicators were developed based on the goal of capturing the complexities of the ecological system but remaining simple enough to be effectively and routinely monitored (Dale and Beyeler 2001):

• *Be easily measured.* The indicator should be easy to understand, simple to apply, and provide information that is relevant, scientifically sound, easily documented, and cost-effective (Lorenz et al. 1999).

• *Be sensitive to stresses of the system.* Ecological indicators should react to anthropogenic stresses placed on the ecological system, while also having limited and documented sensitivity to natural variation (Karr 1991).

• *Respond to stress in a predictable manner.* The response of the indicator should be decisive and predictable even if the indicator responds to the stress by a gradual change. Ideally, there is some threshold level at which the observed response is lower than the level of concern of the impact.

• *Be anticipatory: signify an impending change in key characteristics of the ecological system.* Change in the indicator should be measurable even before substantial change in the ecological system occurs.

• *Predict changes that can be averted by management actions.* The value of the indicator for management depends on its relationship to changes in human actions.

• *Be integrative: together with the full suite of indicators, provide a measure of coverage of the key gradients across the ecological systems (e.g., soils, vegetation types, temperature, etc.).* The full suite of indicators for a site should provide a synchronized perspective of the key attributes of major environmental gradients. These gradients may relate to time, space, soil properties, elevation, or any other factor that is important to the ecological system (e.g, see Figure 1).

• *Have a known response to natural disturbances, anthropogenic stresses, and ecological changes over time.* The indicator should have a definitive reaction to both natural disturbance and to anthropogenic stresses in the system. As ecological conditions change in a system (e.g., via succession), the response of the indicator should be predictable. This criterion most often pertains to metrics that have been extensively studied and have a clearly established pattern of response.

• *Have low variability in response.* Indicators that have a small range in response to particular stresses allow for change in the response value to be distinguished from background variability.

Selecting Ecological Indicators

Identification of the key criteria for ecological indicators sets the stage for a seven-step procedure for selecting indicators. These steps are discussed in view of land use decisions on military lands but are applicable to resource issues on other public and private lands.

Hierarchical Overlap of Suite of Ecological Indicators Over Time

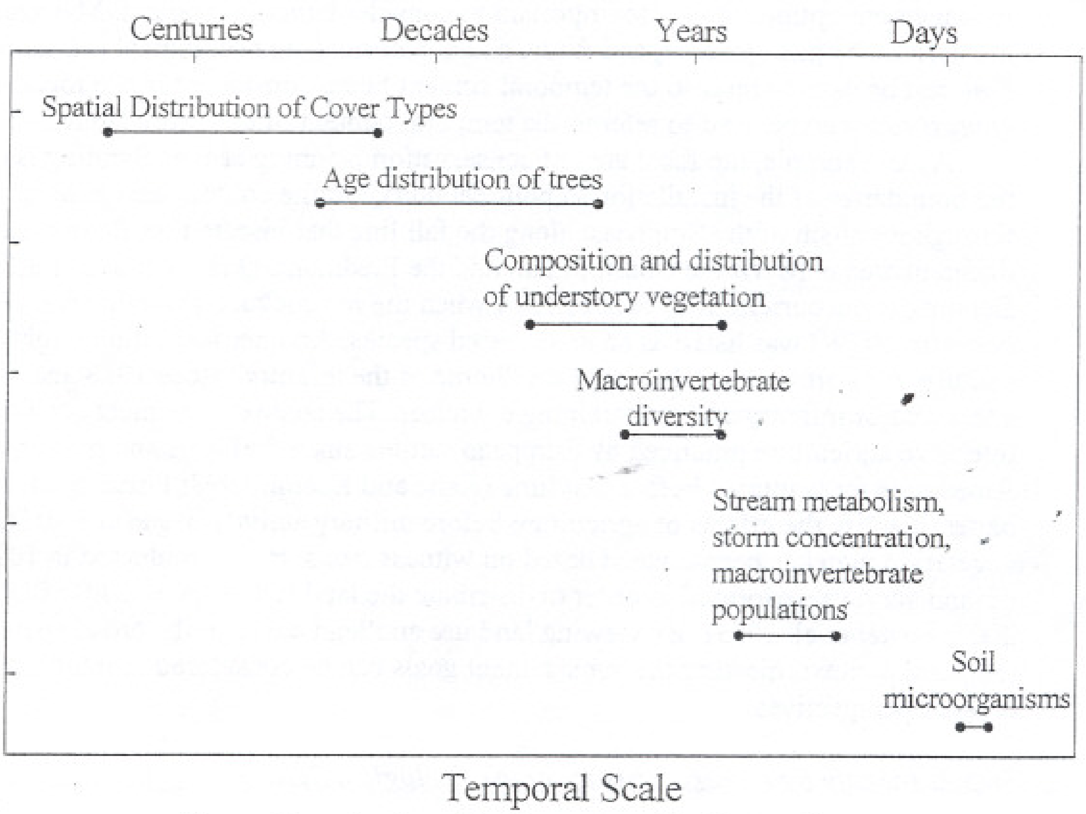

Figure 1 — *A suite of indicators can be depicted across time*

Step 1: Identify Goals for the System.

The first step in problem solving is to define the issue and develop clear goals and objectives. Often, goals are a compromise among the concerns of interested parties. Sometimes objectives change as adherence to one target compromises another. The more complex the nature of the problem, the more important it becomes to establish clear goals and objectives within the spatial and temporal parameters of the system. The selection of ecological indicators is complex in the sense that many factors are involved, feedbacks are common, and diverse groups of stakeholders have different perspectives, value systems, and intentions.

For spatial analysis, it is useful to consider both the immediate area of interest and a broader perspective. The area contained inside the socio-politically delineated boundary can be referred to as the *focal area*, for it is the area of immediate concern to the resource manager. In dealing with ecological management issues, situations often arise when it is useful to look outside of the focal area to a *context area*. Both the focal and context areas can be defined by ecological, social, or political concerns influencing system characteristics.

For the same reason that it is important to consider spatial context when assessing management options, it is also important to consider temporal context. Management areas are defined by past, present, and future social, political, and ecological influences. *Focal time* can be used to refer to the temporal context being considered in the focal area, and *context time* can be used to refer to the temporal context of the entire situation.

As an example, the focal area of conservation planning at Fort Benning is defined by the boundaries of the installation (a political unit), but the context area extends throughout much of the Southeast along the fall line that bisects Fort Benning and differentiates between the Coastal Plain and the Piedmont. One focal time for Fort Benning is the current time back to 1974 when the red cockaded woodpecker (*Picoides borealis,* RCW) was listed as an endangered species. Another focal time might be the last century, for Fort Benning has been the "home of the infantry" since 1918 and is now the site of major infantry and tank training exercises. The context time must consider the intensive agriculture practiced by European settlers since the1800s and by Native Americans for centuries before that time (Kane and Keeton 1998; Foster et al. 2003). To better quantify the effects of agriculture before military activity began at Fort Benning, a vegetation map has been created based on witness tree surveys conducted in 1827 as part of land surveys performed in order to distribute the land (Olsen et al. 2001; Black et al. 2002; Foster et al. 2003). By viewing land use and land cover in the broad spatial and temporal context, meeting the management goals can be considered in light of these broader perspectives.

Step 2: Identify Key Characteristics of the Ecological System

Characteristics are the specific functional, compositional, and structural elements that, when combined, define the ecological system. All ecological systems have elements of composition and structure that arise though ecological processes. The characteristic conditions of an area depend on sustaining key ecological functions that, in turn, produce additional compositional and structural elements. If the linkages between underlying processes, composition, and structural elements are broken, then sustainability is jeopardized and restoration may be difficult and complex.

Key characteristics include the physical features that allow species, ecosystems, or landscapes to occur. For example, at Fort Knox, Kentucky, locations of threatened calcareous habitats of rare species can be predicted based on a combination of soils, geology, and slope (Mann et al. 1999). This edaphic-based approach has also been used to identify locations of Henslow's sparrow (*Ammodranmus henslowii*) habitat at Fort Knox and sites at Fort McCoy, Wisconsin, that can support wild lupine (*Lupinus perennis*), the sole host plant for the larvae of the endangered Karner blue butterfly (*Lycaecides melissa samuelis*) (Dale et al. 2000).

Identification of the key ecological characteristics of a system also involves attention to social, economic, and political features of a site. Combinations of social, economic, political, and ecological concerns, such as laws and regulations, peoples' values, regional economics, and ecological conditions, determine the importance of a characteristic. The Southern Appalachian Assessment (SAA) provides an example of multiple agencies working together to identify key characteristics of a large area (USDA 1996). The first step in this identification process was to determine the major concerns about the system emanating from social, economic, and ecological perspectives of the eight-state region. The assessment focused on terrestrial, aquatic, atmospheric, and social/cultural/economic conditions. Thus, the assessment was concerned with the condition of the natural resources as well as how people use the resources and their expectations. Because the SAA covers such a large area and such broad topics, a list of key terrestrial characteristics was developed for categories of forest health, wildlife and plant species, and important habitats. Aquatic characteristics include water quality, aquatic species, and habitats. The influences on ecological conditions of historical disturbances, land uses, and social and political forces were also considered, and both local environments and landscape perspectives were evaluated.

Once the important characteristics of a system are identified, the typical range of variation in those characteristics can be established within the focal and context areas and times. This information on the range of terrestrial, aquatic, atmospheric, and social/cultural/economic conditions provided the bulk of the five-volume Southern Appalachian Assessment (USDA 1996). The variability in these characteristics can be presented with regard to changes over time, environmental gradients in the area, or different levels of anthropogenic influences.

In their consideration of key characteristics, military natural resource managers have focused on endangered species and systematic inventories of vascular plant and wildlife. For example, the Army has instituted the Land Condition-Trend Analysis (LCTA) program as a standardized way to measure, analyze, and report data from inventory plots on plant communities, habitat, disturbances, impacts of military training, soil erosion potential, allowable uses, and restoration needs (Diersing et al. 1992). The purpose of that program was both to characterize the vegetation and to monitor change and detect trends in natural resources (Bern 1995). Sample plots were established in a stratified random manner using satellite imagery. Because the military testing and training typically result in intense, local, and broadly spaced impacts, the LCTA plots often do not capture the spatial distribution of the effects. For example, at Yuma Proving Ground, Arizona, about 60 to 70% of the plots had no land use over the period 1991 to 1993 even though the actually land use was more extensive (Bern 1995). Therefore, the LCTA approach needs to be supplemented by a scheme designed to focus on discerning impacts and to integrate over broad spatial scales. Yet to relate the characteristics to the impacts, the stress also needs to be identified.

Step 3: Identify Key Stresses

Stress to an ecological system is typically defined as any anthropogenic action that results in degradation (e.g., less biodiversity, reduced primary productivity, or lowered resilience to disturbances) (Odum et al. 1979; Barret and Rosenberg 1981; Odum 1985; Mageau et al. 1995). Stress can be classified into four categories: physical manipulations, changes in disturbance regimes, introduction of invasive species, and chemical changes [a slight revision of Rapport and Whitford's (1999) categories that use "stress" for anthropogenic activities]. Physical manipulations include human activities that can change soil conditions or construction of structures. Human activities may also cause fragmentation or eliminate critical habitats for some species.

Changes in disturbance intensity, frequency, duration, and extent can have major impacts on ecological systems (Dale et al. 1998). Disturbances are considered to be those events that are not typical of a system. For example, fires within a fire-moderated system, such as the lodgepole pine (*Pinus contorta*) forest of the western United States, would not be a disturbance to the system (even though individual organisms are impacted) (Fahey and Knight 1986). It is the absence of such fires that may cause a disturbance, for fires are an integral part of establishment and development of community structure of these forests. Thus, disturbances must be considered with regard to the life history of the major organisms in the community.

The introduction of invasive species is a major problem in many ecological systems. Often these introductions are nonnative species that do not have predators or competitors within the new system and thus become out of control. These introduced species can physically override the presence of other organisms and replace them quickly. There are numerous examples of such replacements (Westbrooks 1998). Occasionally invasive species may take over because of the elimination of some physical or biological constraints that may have been in the system in the past. *Lonicera maackii* (Rupr.) Herder (Amur honeysuckle), a large invasive shrub introduced into the United States in the late 19th century, has naturalized in at least 24 eastern states. It is abundant in habitats ranging from disturbed open sites to forest edges and interiors. *Lonicera maackii* negatively impacts native species, especially tree seedlings and forest herbs. Open, disturbed forests (e.g., Fort Campbell, Kentucky, where training can open forest canopies) are especially susceptible to colonization (e.g., Deering and VanKat 1998).

Chemical changes in the environment typically occur as a direct result of human activities. Point sources of toxins that result from spills or groundwater movements are a common cause of such a chemical change. Air pollution can also cause widespread and non-point source solution changes in systems.

Stress can be depicted as a gradient or a threshold such as intensity of impact, duration of event, or frequency of impact. Stresses are ultimately what most management plans are for, both preventively and retrospectively. Often, changes in characteristics of a system result directly from one or more stresses. Typically, stresses interact and may exacerbate conditions for biotic survival or maintenance (Paine et al. 1998). Multiple stresses may be simultaneously analyzed or considered one at a time, depending on the goal of the analysis.

The stresses on military installations fit into the four categories of physical manipulations, changes in disturbance regimes, introduction of invasive species, and chemical changes. The training and testing typical of most installations creates a diversity of physical stresses ranging from soil erosion to vegetation removal. Alterations to fire frequency and intensity are the most common form of changing disturbance regimes. In some cases (such as Eglin Air Force Base on the Florida Panhandle), a prior landowner controlled fires, and the Department of Defense is now reinstituting a regular fire regime. The introduction of invasive species is a common problem on most installations. At Fort McCoy, Wisconsin, the leafy spurge (*Euphorbia esula*) threatens to encroach into oak savannas and outcompete the wild lupine. Kudzu (*Pueraria thunbergiana*) is present on most military installations in the Southeast where it literally overgrows anything in its path. Chemical changes on most installations occur as point sources in areas devoted to intense military activities (e.g., painting of aircraft). Usually, these sites are considered sacrifice areas in terms of conservation goals. However, chemical control of introduced species or along roadsides can also affect ecosystem management.

Step 4: Determine How Stresses May Affect Key Characteristics of the Ecological System

Once the process of selecting potential issues and identifying ecological characteristics and stresses within the context and focal systems is completed, the indicator selection process moves into the more specific stage of indicator selection. The process of developing and evaluating landscape-based ecological indicators is large and complicated, varies by region, and requires conceptual and causal links between stresses and the resulting ecological change (Brooks et al. 1998). Each concern that has been determined through the issue identification process needs to be analyzed in order to identify associated stresses, the cause of those stresses, the scope of those stresses on the management area, and the resulting changes in the characteristics of the management area.

Stresses are important to an ecological system in that they can disrupt composition, structure, or function. To the extent that these changes alter key characteristics of a system, the effect is significant. For example, insects or pathogens can increase tree mortality, reduce growth, and eventually change species composition and habitat patterns. Yet stresses that disrupt rare communities may be of the greatest concern to composition. For example, in the Southern Appalachians, 84% of the federally listed species occur in 31 rare communities and streamside habitats (USDA 1996), which means that management for endangered species can concentrate on select sites. However, there are considerable challenges to managing large tracts of land on the basis of a few endangered species.

Matrices that relate stresses to key ecological characteristics may be the best way to depict the effect that human activity may have on a system. For example, matrices containing the ways that military use can affect different types of vegetation at Fort

McCoy, Wisconsin have been developed (Dale et al. 2002b). The focus is on vegetation structure of the ground layer and the shrubs and trees because the wild lupine on which the larvae of the endangered Karner blue butterfly exclusively feeds occurs in the ground layer, and the shrub and tree layers provide the oak savanna system in which the lupine thrives. Such a matrix brings attention to those characteristics that are likely to change under current stresses and, thus, provides a way to identify indicators.

In much the same way that the spatial and temporal scales of the focal and context areas need to be defined, so too do the spatial and temporal scales of the individual stresses. As a result, stress effects may be limited to certain places or times. For example, ozone damage to sensitive trees may be greater at higher elevations where sufficient moisture is available from cloud cover to prevent stomata closure and allow more ozone to be absorbed. As a temporal example, some organisms are only susceptible to stress during their dispersal phase, while stresses at other times have little effect. For example, tank activity at Fort McCoy, Wisconsin actually enhances the presence of wild lupine upon which the endangered Karner blue butterfly ovipost (Smith et al. 2001). Yet, tank activity during the larvae stages can kill the insect.

Step 5: Select Indicators

The selected indicators should reflect the criteria (discussed earlier) and identify stress effects on key characteristics of the system. In general, these criteria call for indicators that are sensitive to the identified stressors in the system, sophisticated enough to capture the ecological system complexities, and responsive to identified stressors in such a way that they can be easily measured and monitored. Knowing how the stresses affect the key characteristics of the ecological system assists in the selection of indicators.

The selection of indicators is best made in a hierarchical manner. The selection process is initiated by considering the entire area of interest. For most military applications, this perspective would entail the installation as the focal site and the present as the focal time. However, the larger spatial and temporal context should also be considered. Thus, examination of the major physical gradients across the landscape or region should consider topography, soils, geology, land-use history, disturbance history, patterns of water (streams, lakes, and wetlands), and human use (roads, trails, buildings, and training and testing sites). Often the vegetation type, size, or density reflects the combination of these physical forces and serves as a useful indicator of their strength. For example, at Fort Stewart, Georgia, the amount of hardwood ingrowth into longleaf pine (*Pinus palustris*) stands indicates the time since the last growing-season fire. Thus, the pattern of vegetation types, such as hardwood ingrowth, or other land covers should be evaluated to see if it portrays features of the landscape that are indicative of stresses at the site and that may affect the ecological properties of the site. At Arnold Air Force Base in Tennessee, the high degree of forest fragmentation is indicative of past timber-harvesting practices and may portend effects on neotropical migrants (Robinson et al.1995).

Ideally the suite of indicators should represent key information about structure, function, and composition. Yet the complexity of the relationship between structure function, and composition only hints at the intricacy of the ecological system on which it is based. Often it is easier to measure structural features that can convey information about the composition or functioning of the system than to measure composition or function. Sometimes measures from one scale can provide information relevant to another scale. For example, the size of the largest patch of a habitat often restricts the species or trophic levels of animals that are able to be supported based solely on their minimal territory size (Dale et al. 1994). Analysis of patch size for Henslow's sparrow at Fort Riley, Kansas indicates that the largest patch on the installation supports a declining population (the population's finite rate of increase is less than one) (Dale et al. 2000).

After the landscape is analyzed, the ecosystem and the species levels should be investigated. This process of considering characteristics of the system and potential indicators in a spatially hierarchical fashion needs to apply to each gradient of importance at the site. Placing the information on a spatial or temporal axis provides a means to check that information at all spatial scales. Alternatively, it is important to include indicators that encapsulate the diversity of responses over time (so that one is not just measuring immediate responses of the system). All major gradients are included in the analysis. We have focused on spatial and temporal scales, but it is also useful to consider the representativeness of indices across major physical gradients (soils, geology, land use, etc.).

Step 6: Test Potential Indicators Against Criteria

A crucial aspect for legitimizing the selection procedures for ecological indicators is the establishment of a scientifically sound method of monitoring system change. Each of the potential indicators needs to be tested to determine if it effectively measures the system characteristics of interest and meets the other criteria for indicators. This test should follow scientific procedures (e.g., theory and hypothesis development, hypothesis testing with control comparison, statistically significant results, etc.). The working hypotheses should reflect how specific indicators measure changes in key characteristics under stress. Experiments should be designed to compare measures of the indicators and key characteristics with and without stress events. For example, the condition of these indicators both before, during, and after documented stresses can then be compared with similar data collected in control sites. Based on the results of the tests for each potential indicator, the final set of ecological indicators can then be selected that is believed to be the most effective combination of indicators for monitoring the characteristics of interest to the management planners. The statistical analysis of such indicators is a basic aspect of most statistical text books.

Step 7: Select Final Indicators and Apply Them to the Decision-Making Process

The final ecological indicators are selected based on the test in Step 6. Then, management can implement monitoring of the suite of selected indicators. Long-term monitoring is an essential part of all environmental management programs, with adjustment of management activities based on indicator information and its relationship to overall management goals. The process of linking management to monitoring is part of adaptive management that views management actions as experiments and accumulates knowledge to achieve continual learning (Holling 1978; Walters 1986).

Often the application of measuring indicators or of adding refinements to measures can occur very quickly. This implementation aspect is especially rapid on Department of

Defense installations where the mentality is to act. For example, after we had used soil, geology, and slope to identify the sites at Fort McCoy, Wisconsin, that the wild lupine could occupy (Dale et al. 2000), the environmental site manager modified his monitoring program for wild lupine to focus only on areas that the analysis indicated could support the plant. This modification allowed the monitoring program to focus on those sites of greatest importance.

Case Study

The objective of this case study is to identify indicators that signal ecological change in intensely and lightly used ecological systems at Fort Benning. Currently, military training, controlled fires (to improve habitat for the endangered red cockaded woodpecker), and timber thinning are common management practices on the installation. All of Fort Benning has experienced some anthropogenic changes either from past farming, logging, absence of burning, or military testing. Because the intent is that these indicators become a part of the ongoing monitoring system at the installation, the indicators should be feasible for the installation staff to measure and interpret. The focus is on Fort Benning, but the goal is to develop an approach to identify indicators that would be useful at several military installations. Because some of these effects may be long-term or may occur after a lag time, early indications of both current and future change need to be identified. The intent of this identification of indicators is to improve managers' ability to manage activities that are likely to be damaging and to prevent long-term, negative effects. Therefore, a suite of variables is needed to measure changes in ecological conditions. The suite that we are examining includes measures of terrestrial understory and overstory vegetation, soil microbial biomass and community composition, landscape patterns, and instream physiochemical and biotic water quality conditions. Because of the limited space in this publication, for further details we direct the reader to the project web site: (http://www.esd.ornl.gov/programs/SERDP/research_projects.html#conservation).

The analyses of vegetation data collected from sites at Fort Benning with five discrete land-use histories showed high variability in species diversity and lack of distinctiveness of understory cover and led us to consider life form and plant families as indicators of military use (Dale et al. 2002a). Life form successfully distinguished between plots based on military use. For example, phanerophyte species (trees and shrubs) were the most frequent life form encountered in sites that experienced infantry foot traffic training. Analysis of soils collected from each transect revealed that depth of the A layer of soil was significantly higher in reference and infantry foot traffic training areas which may explain the life form distributions. In addition, the diversity of plant families and, in particular, the presence of grasses and composites were indicative of training and remediation history. These results are supported by prior analysis of life form distribution subsequent to other disturbances (Adams et al. 1987; McIntyre et al. 1995; Stohlgren et al. 1999) and demonstrate the ability of life form and plant families to distinguish between military uses in longleaf pine forests.

The soil microbial community of a longleaf pine ecosystem at Fort Benning also responds to military traffic (Peacock et al. 2001). Using the soil microbial biomass and community composition as ecological indicators, reproducible changes showed increasing traffic decreases soil viable biomass, biomarkers for microeukaryotes and Gram-negative bacteria, while increasing the proportions of aerobic Gram-positive bacterial and actinomycete biomarkers. Our results indicate that as a soil is remediated it does not escalate through states of succession in the same way as it descends following military use. We propose to explore this hysteresis between disturbance and recovery process as a predictor of the resilience of the microbial community to repeated disturbance/recovery cycles.

The landscape metrics for Fort Benning were calculated and analyzed, and an assessment was made of the accuracy of the land cover estimates obtained from remote sensing as compared to *in situ* observations of land cover (Olsen et al. 2001). Metrics at the class and landscape level were compiled and analyzed to determine which were the best indicators of ecological change at Fort Benning. A set of metrics was selected, based upon change through time or ability to differentiate between land cover classes. We found the most useful metrics for depicting changes in land cover and distinguishing between land cover classes at Fort Benning were percent cover, total edge (with border), number of patches, mean patch area, patch area range, coefficient of variation of patch area, perimeter/area ratio, Euclidean nearest neighbor distance, and clumpiness. An accuracy assessment was performed of the 1999 land cover classification that was created using a July 1999 Landsat ETM image as compared to a 0.5-m digital color orthophoto of Fort Benning taken in 1999. The overall accuracy was found to be 85.6 for the 30-m resolution data (meaning that 85.6% of the test sites were correctly classified).

Landscape metrics indicate that the forest pattern (particularly that of pine) has declined greatly since 1827 (e.g., the area of pine forest declined from 78% to 34% of the current installation). Altered management practices in the 1990s may have resulted in changes to the landscape at Fort Benning. Several trends, such as an increase in non-forested and barren lands in riparian buffers were slowed or reversed in the last decade. Pine forest, on the other hand, appears to have been increasing in the last ten years. Improved monitoring techniques coupled with an aggressive management strategy for perpetuating pine forest at Fort Benning may have resulted in an increase in pine populations and a decrease in hardwood invasion. This management strategy includes harvesting timber and burning to establish and maintain viable pine communities. While it appears that the percentage of non-forest land has been slowly increasing, the number of non-forest patches has increased tremendously in the last decade. In other words, the non-forest land has become more fragmented over time. Consequently, the size of these patches has decreased significantly.

We are evaluating the efficacy of several stream chemistry and biology parameters as indicators of disturbance associated with military training and natural resource management activities at Fort Benning. This work is based on the idea that stream ecosystems are sensitive to disturbances within their catchments because many disturbances alter the patterns of runoff, drainage water chemistry, and inputs of biologically important materials to receiving streams. In addition, stream ecosystems are important components of the landscape and indicators of disturbance to stream biological communities and biogeochemical processes are an important part of any assessment of ecosystem health. Our research uses a disturbance gradient approach in which 1st- to 3rd-order streams draining catchments with strongly contrasting disturbance levels have been selected for study. These catchments are distinguished by percent bare ground for some have little disturbance and others have widespread erosion caused by regular tank traffic. The inclusion of several reference streams in our study design provides data on the range of values for physicochemical and biological parameters expected for catchments showing minimal level of disturbance. Data from streams along the disturbance gradient are being compared to evaluate the suitability and sensitivity of specific disturbance indicators. The potential aquatic indicators at Fort Benning have been narrowed to:

- Suspended sediment concentrations (both baseflow and storms) and baseflow (PO_4, DOC) and stormflow (NH_4, NO_3, and PO_4) nutrient concentrations (indicator of erosion and biogeochemical status)
- Diurnal dissolved oxygen profiles (indicator of in-stream metabolism)
- Streambed organic matter content (indicator of food or habitat), and sediment movement dynamics (indicator of in-stream habitat stability or quality)
- Macroinvertebrate populations and communities, including EPT richness, Shannon diversity, biotic tolerance indices, and Bray-Curtis similarity of disturbed and reference streams (indicator of biological response)

For example, storm sediment concentration profiles show that streams in highly disturbed catchments had much higher rates of erosion and sediment transport than streams in less disturbed catchments.

The effects of historical land use / disturbance on stream macroinvertebrates are also being examined. Using remotely sensed imagery from 1974 and 1999, we used the GIS extension ATtILA to estimate areal percentage of 1) bare ground on slopes >3%, 2) successional stage of vegetation (early-regeneration forested land) on slopes >3%, and 3) road density (km road/km^2 catchment) for each catchment. These three land use variables were then combined to derive a disturbance index (DI), which was used to rank and compare each catchment's historic and contemporary disturbance level. With these data we are examining the degree to which current measures of biotic water quality relate to historical vs. contemporary disturbance conditions. Preliminary analysis indicated that percent silt in the streambed was positively correlated with levels of historical (1974) land use among the catchments. Moreover, relative abundance of macroinvertebrate functional feeding groups also was related to historical land use. Disturbance also resulted in lower richness of EPT (i.e., number of taxa within the aquatic insect orders Ephemeroptera, Plecoptera, and Trichoptera) than in reference streams but similar total richness of invertebrate species. These data indicate 1) a legacy of environmental disturbance in Fort Benning catchments that spans at least 25 years, and 2) knowledge of historical land use conditions may be critical in interpreting contemporary water quality conditions.

Conclusions

Ecological indicators offer a means to measure the effects of resource management. A key challenge is dealing with the complexity of ecological systems. Criteria and procedures for selecting indicators offer a way to deal with this complexity. The Department of Defense is developing ways to implement the use of ecological indicators for ecosystem monitoring and management. The next step is implementing indicators into resource-management practices.

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