

Measuring And Monitoring Biodiversity in Nature Reserves, Forests, and Grasslands in the United States¹

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Abstract—Amazingly little is known about the biodiversity of the U.S. due to a lack of systematic, multi-scale surveys of multiple biological groups. Even the best studied areas, the U.S. National Parks, report a knowledge of only 50% to 80% (or less) of their species of vascular plants, birds, mammals, reptiles, amphibians, and fishes. More is known about “charismatic megafauna” and less is known about small creatures that contribute most to biodiversity. Wildlife surveys are not often coordinated with habitat surveys or controlled studies, so little is known about the causes of population trends. Often, poor sampling designs and field techniques are used to survey and monitor biodiversity. Many existing monitoring programs are poorly standardized and are not cost-effective. New resource inventory and monitoring programs must be carefully designed, statistically sound, peer reviewed, and well supported.

I discuss commonly used vegetation sampling designs that are poorly suited for monitoring plant diversity, grazing effects, and exotic plant invasions. I then discuss new approaches to surveying and monitoring large natural areas such as forests and grasslands. The new approaches rely on multi-phase sampling techniques: using two resolutions of remotely sensed information, cluster sampling for map accuracy assessments, and multi-scale field sampling techniques of multiple biological groups.

The protection of forest biodiversity relies on our ability to: (1) rapidly assess hot spots of biodiversity and areas of unique species assemblages at landscape scales; (2) quantify and predict spatial and temporal trends of key species; (3) maintain natural disturbance regimes and key ecological processes; (4) prevent detrimental effects of exotic species; and (5) limit harmful human activities. Our challenges in North America (and the world) are to: (1) develop and test various design strategies (optimum sampling strategy) and multiple-scale field methods for inventorying and monitoring multiple biological groups and ecosystem processes; (2) conduct standardized monitoring of key indicators of multiple stresses to biodiversity; and (3) develop better mapping, information management, and predictive modeling capabilities at multiple spatial scales.

The Status of Biotic Inventories

How much do we really know about the biodiversity in natural areas in the U.S.? In 1995, my colleagues and I found that managers in National Park System units thought their species lists of vascular plants, birds, mammals, reptiles,

amphibians, and fishes were, on average, only 50% to 80% (or less) complete (Stohlgren et al. 1995c). Most national parks and monuments knew far less about the diversity of aquatic and terrestrial invertebrates and non-vascular plants (Stohlgren and Quinn 1992).

There are many reasons why biodiversity data are uncommon in many national parks, national forests, state parks, and other natural areas. First, large-scale, systematic surveys for several biological groups are rarely conducted. The best studied group, vascular plants, is often surveyed with various “searching” techniques by different crews of botanists over the years. Because crews often searched selected areas (usually not remote or steep) with various levels of taxonomic skills, the spatial and taxonomic completeness of species lists was uncertain. In Rocky Mountain National Park, Colorado, for example, vascular plant collections over 80 years yielded about 920 species. However, large-scale, systematic plant surveys between 1989 and 1992 added more than 100 species to the Park’s species list (Stohlgren et al. 1997a). Similarly, animal studies have fallen short of inventorying biodiversity. More attention has been paid to “charismatic megafauna,” large predators and game animals, so less is known about small creatures that contribute most to biodiversity. Also, many studies involving small mammals, selected invertebrates (usually butterflies), amphibians, and fishes have been conducted in small study sites, making it difficult to generate complete species lists for larger landscapes (Stohlgren et al. 1995c).

Second, many field sampling techniques were poorly designed to capture large numbers of species. Survey and monitoring techniques for vascular plants, for example, often relied on small (e.g., 20 cm x 50 cm) quadrats or points along linear transects (Parker 1951, Daubenmire 1959). These transect based-techniques often missed about half the plant species in the local area due to their small sampling area and the patchy, nonlinear nature of species distributions (Stohlgren et al. 1998a). Similar methods problems affect inventory and monitoring of animals.

Third, little has been done to investigate the relationship of diversity between multiple biological groups. While there may be predictable relationships in the spatial patterning of diversity of multiple biological groups on the landscape, these surveys have usually taken place in relatively small areas, such as the rare and expensive “all taxa biodiversity inventories” underway in Costa Rica (Janzen 1997) and planned for Great Smoky Mountain National Park. Although much of the diversity of life is found in smaller creatures such as insects and soil organisms, these systems have been very poorly surveyed in nearly all natural areas. We are left with precious little information on the

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biodiversity in most natural areas in the U.S. Improving research on the diversity of relationships of multiple biological groups would greatly increase our knowledge of ecosystem biodiversity.

The Status of Biotic Monitoring Programs

Several monitoring programs have been designed to assess single biological groups. The U.S. Geological Survey's Breeding Bird Survey uses volunteer bird enthusiasts to survey thousands of kilometers of roadways each year. The program has proved invaluable for detecting significant trends in many species of birds throughout the U.S.. However, the survey techniques are questionable for many rare, remote, and high-elevation birds species, and population trends are not easily linked to habitat change or other causes. Similarly, the USDA Forest Health Monitoring Program provides adequate monitoring of tree species diversity in the U.S., and has recently expanded their surveys to include understory vegetation. However, non-forested areas are not monitored, rare habitats may be missed by the sampling design, and little information is collected on animal diversity.

There is an urgent need to develop strategies to quantify the biological diversity of landscapes and regions (e.g., Magurran 1988, Wilson 1988, Soulé and Kohm 1989, Peters and Lovejoy 1992, Noss and Cooperrider 1994). A starting point would be linking vegetation analyses across scales (Franklin 1993, Short and Hestbeck 1995). There are active research programs, for example, to quantify some aspects of biological diversity at national and statewide scales (Palmer et al. 1991, Messer et al. 1991, Austin and Heyligers 1991, Scott et al. 1993). However, there are no generally accepted "off-the-shelf" sampling protocols for biological monitoring at landscape scales (Stohlgren et al. 1995a).

Few monitoring programs are specifically designed to monitor biodiversity. The best example may be the Smithsonian Institution's biodiversity monitoring plots (Dallmeier 1992), where species of trees, birds, reptiles, amphibians, and some invertebrates are measured in selected 1.0 ha plots. The expense of establishing long-term plots that large often limits the number of replicate plots that can be established in a given landscape. Therefore, it is often unknown how representative these few sampling plots are in relation to the larger, unsampled landscape. Thus, these plots are designed primarily to monitor the diversity within 1.0 ha plots over time, rather than monitoring the changes in biodiversity throughout a landscape or natural area. If progress is to be made in surveying and monitoring biodiversity, new cost-efficient, unbiased sampling designs are needed to assess multiple biological groups at multiple spatial scales with known levels of precision, accuracy, and completeness.

Landscape-Scale Assessments of Biodiversity: A Methodology In Progress

Our research team is designing field techniques to survey and monitor biodiversity at landscape scales (Stohlgren et al.

1997a,b, c, Simonson 1998, Suzuki et al. 1998). We focus on improving field techniques for vascular plants, butterflies, and birds. The study design relies on multi-phase sampling, unbiased site selection using stratified random sampling in common and rare habitats, multi-scale field sampling by professional taxonomists, cluster sampling, and accuracy assessments (Figure 1).

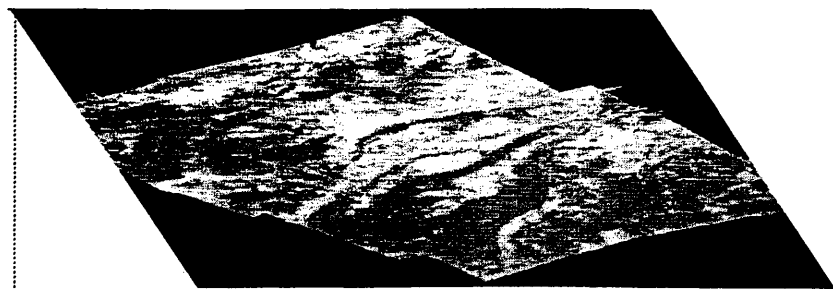
Multi-Phase Sampling

Multi-phase sampling allows the extrapolation of information from high-resolution field data of selected study sites to the larger, unsampled landscape (Kalkhan et al. 1995). Typically, this requires the use of two sets of remotely sensed imagery (Figure 1). For example, low-resolution but inexpensive satellite imagery can be linked to high-resolution aerial photographs and ground truth data, which are more expensive and accurate, but spatially limited. Statistical techniques can assess the changes in accuracy and precision when extrapolating site-specific field data to the larger landscape (Kalkhan et al. 1998). Separate error matrices are developed between the classifications on the satellite image and the aerial photography, and between the aerial photography and ground observations. The error matrix provides the user with information on the accuracy of individual categories, and both errors of commission and omission in the classification (Congalton 1991). Validating the accuracy of maps of biological data using multi-phase sampling requires accurate estimates of bias and variance at multiple spatial scales (Maybeck 1979, Kalkhan et al. 1995). Since we cannot afford to collect detailed data on biological diversity at all sites, multi-phase sampling is a cost-efficient necessity in landscape-scale assessments (Kalkhan et al. 1995, 1998).

Unbiased Site Selection Using Stratified Random Sampling in Common and Rare Habitats

For many long-term biodiversity monitoring plots (Dallmeier 1992) and forest dynamics studies (Hawk et al. 1978, Riegel et al. 1988), investigators have selected "typical" sample units (or "reference stands"). It is not a coincidence that many of these typical plots are close to roads, on flat terrain, and are commonly very dissimilar to the surrounding landscape. Only data produced from unbiased study plots can be evaluated by the theorems of probability theory (Krebs 1989). Unbiased plot selection using random sampling, stratified random sampling, or systematic sampling provides ecologists with an important tool to extrapolate information from plots to landscapes, and from landscapes to regions (Stohlgren 1994, Kalkhan et al. 1998).

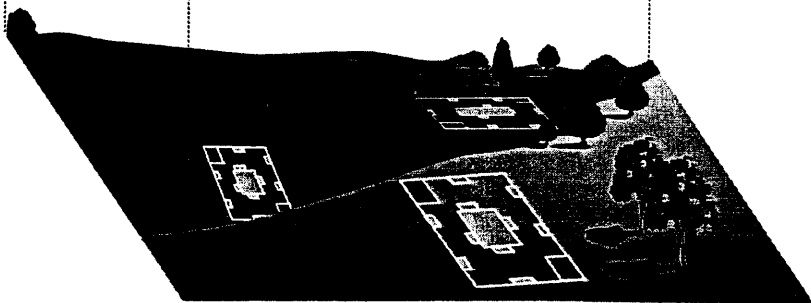
Sample sites are selected in an unbiased manner using remotely sensed information and a stratified random sampling design (Figure 1). High-resolution aerial photography can be used to stratify vegetation to include homogeneous plant communities (typically recognized in most vegetation mapping efforts), heterogeneous communities of special interest (e.g., ecotones and ecoclines, mixed stands and communities), and keystone ecosystems. Keystone ecosystems are ecosystems that contain high plant species richness, distinctive species compositions, or distinctive



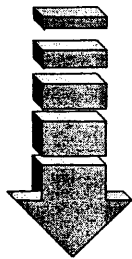
**Satellite Imagery
for broad-scale
extrapolation**



**High Resolution
Aerial Photographs
with common and
rare habitats
stratified**



**Field Sampling
subset of random
plots selected in
common and rare
habitats for long-term
monitoring**



**GIS Based
Predictive Model
links to causal
mechanism**

Figure 1.—Generalized multi-phase sampling design for biodiversity used in several landscape-scale studies (adapted from Stohlgren et al. 1995b, 1997a,b,c, 1998c).

ecological processes that benefit many other species and ecosystems (Stohlgren et al. 1997a,b). The size of the minimum mapping unit must be selected to accommodate particular keystone ecosystems such as aspen (Stohlgren et al. 1997c). After a preliminary vegetation map is prepared, four or five ground truth plot locations per vegetation type are selected randomly using a randomizing function in a geographic information system (GIS), or with a grid system on a plastic overlay atop the aerial photograph. We then locate the points in the field with the aid of the photographs, other maps, and a compass, and check and map the locations with a global positioning system (GPS; Figure 1).

Multi-Scale Field Sampling

At each ground truth sampling point, a Modified-Whittaker nested vegetation sampling plot is established (Stohlgren et al. 1995b). The Modified-Whittaker plot (Figure 2) is 20 m x 50 m, with ten 0.5 m x 2 m (1-m^2) subplots arranged systematically inside the plot, and a 5 m x 20 m (100-m^2) subplot in the plot center. Two 2 m x 5 m (10-m^2) subplots are placed in opposite corners of the plot (Figure 2). Both the percent cover and average height-by-species are recorded in

the 1-m^2 subplots. Cumulative species (additional species found in the subplot or plot) are recorded successively in the ten 1-m^2 subplots, the two 10-m^2 subplots, the 100-m^2 subplot, and the remaining unsampled areas of the 20 m x 50 m plot. For small vegetation communities, the dimensions of all the subplots and plots can be shrunk proportionately.

Cumulative species data from the 1-m^2 , 10-m^2 , and 100-m^2 subplots from each 1000-m^2 plot can be fit to linear regressions of cumulative species-area curves, species-log(area) curves and log(species)-log(area) curves. To validate the selected model, the estimated total number of species in each 1000-m^2 plot based on the 1-m^2 , 10-m^2 , and 100-m^2 data can be compared to the observed number of species recorded in each plot. The regression model with the least difference between observed and expected values should be used.

Butterflies are surveyed in six 10-m^2 subplots, a 100-m^2 subplot, and in the 1000-m^2 plots in the spring and early summer on warm, sunny afternoons (Simonson 1998). Birds are sampled at two spatial scales (50 m radius and 100 m radius) for three five-minute intervals. This multi-scale approach assesses aspects of spatial and temporal variability within and between habitats (Figure 2).

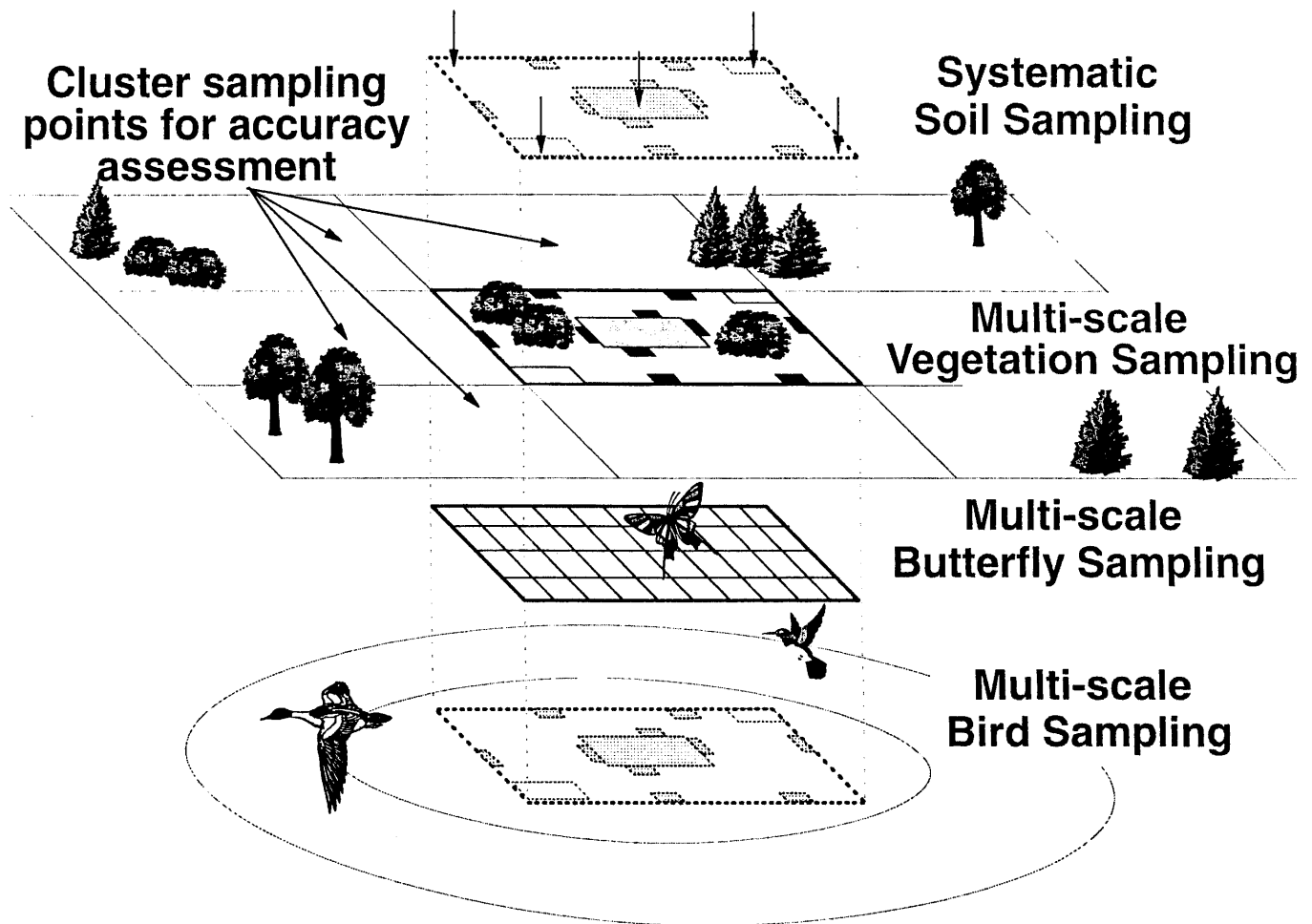


Figure 2.—Generalized multi-scale sampling design for biodiversity used in several landscape-scale studies (adapted from Stohlgren et al. 1995b, 1997a,b,c, 1998c).

Cluster Sampling and Accuracy Assessments

Much of the expense of field sampling is getting field crews to and from sample sites. In addition, assessing the accuracy of maps of biological data is often limited by small sample sizes of ground truth data. Cluster sampling is a cost-efficient technique that optimizes field crew efforts by collecting ancillary data around the primary sampling site. For example, a field crew may travel to a randomly selected remote site to collect data on the diversity of plants, birds, and butterflies. While at the site, they also collect additional data on the vegetation classes surrounding the sample point (i.e., at cardinal directions 100 meters from the plot corners) to assess the accuracy of the vegetation map that is used to extrapolate the species diversity data (Figure 2).

Attributes of Strong Monitoring Programs

There is no shortage of advice available on the design of monitoring programs (Hinds 1984, Hurlbert 1984, Strayer 1986, Eberhardt and Thomas 1991, Palmer 1993). The attributes that follow (Table 1) are based on several previous studies, and much trial and error (Stohlgren 1994, Stohlgren et al. 1995b, 1997a,b,c, 1998a,b). Obviously, a long-term commitment of funding and support are essential, as is strong leadership and cooperation within and among monitoring programs.

Lessons Learned

1. Scale Matters. The appropriate scale of study is determined by many factors including cost, the minimum amount of information needed to make current and future management decisions, and the extent to which the investigators

wish to extrapolate results. Often data at one spatial scale can be contradicted by data collected at another spatial scale. In 1-m² plots in the Central Grasslands, for example, exotic plant species were found to invade areas of low native plant diversity. In four 1000-m² plots in the same areas, exotic plant species were found to invade areas of high native plant diversity (Stohlgren et al. 1999). Sampling vegetation at multiple spatial scales (Fig. 1) is important to understand species-area relationships and to evaluate local- and broad-scale patterns of plant diversity (Shmida 1984, Stohlgren et al. 1995b, 1997a,b). Multi-scale sampling techniques have worked well in desert environments (Stohlgren et al. 1998c), grasslands (Stohlgren et al. 1998a,b), montane forests (Stohlgren et al. 1997a,b), and tropical rain forests (S. Mistry, Smithsonian Institution, unpublished data).

2. Resolution Matters. Coarse-scale maps, with large minimum mapping units and few classes, will miss rare habitats (Stohlgren et al. 1997c). In Rocky Mountain National Park, Colorado, stands of aspen (*Populus tremuloides*), which are important contributors to plant, bird, and butterfly species diversity (DeByle 1985a,b, Simonson 1998), are severely missed with the commonly used 2-ha minimum mapping unit. Coarse-scale maps may miss rare habitats such as riparian zones, wetlands, and other small, unique habitats, thus grossly underestimating biodiversity (Stohlgren et al. 1997c).

3. Taxonomic Expertise Matters. Having taxonomic experts in the field is essential. Everywhere our research teams have sampled, we have found that most species are rare, and small areas of any landscape can contain hundreds of species. For example, a 754-ha area of Rocky Mountain National Park, Colorado, contained over 550 plant species (Stohlgren et al. 1997a). In vegetation types throughout the Rocky Mountains and Central Grasslands, about 50% of the plant species at each sampling site have <1% foliar cover. In ten 0.1 ha vegetation plots in tropical forests in Peru, 250 out of 500+ species of trees were represented by a single individual (S. Mistry, Smithsonian Institution, unpublished

Table 1.—Key monitoring program attributes and reasons for the attributes.

Key monitoring program attributes	Reason
1. Clearly define goals and objectives	Sees that priority management needs are met
2. Use a multi-scale sampling design	Insures extrapolation to larger unsampled areas
3. Stratify/monitor common and rare habitats	Rare habitats contain much of the biodiversity
4. Sample multiple taxonomic groups	Improves cost-efficiency, maximize information
5. Sample key environmental factors	Soils and topography data improve models
6. Reduce bias in site selection	Allows for unbiased extrapolations
7. Assess species-area relationships	Projects results to larger, unsampled area
8. Assess species accumulation with time	Assesses effects of duration of sampling for animals
9. Assess within-strata variation	Evaluates appropriate sample size per strata
10. Assess between-strata variation	Evaluates appropriate sample size for the study
11. Assess effects of spatial scale on results	Study results are often scale-dependent
12. Assess effects of resolution on results	Asks the question "What did we miss?"
13. Develop spatially explicit predictive models	Extrapolates data to larger unsampled area
14. Validate the models with new data	Proves the accuracy and precision of models
15. Provide adequate funds for data management	Usually this is grossly underestimated
16. Provide comparable data to other programs	Strengthens small programs, allows for synthesis
17. Seek periodic statistical and program review	Improves program, strengthens credibility
18. Make data accessible	Improves use of data, creates credibility
19. Publish results frequently	Creates and maintains credibility
20. Provide adequate outreach	Shows that the monitoring program is meeting goals

data). Most species are rare, and knowledgeable taxonomists are needed to identify and monitor species diversity. Poorly trained para-taxonomists and volunteers may capture common, dominant species at each site, while missing key aspects of biological diversity.

4. Assessing Multiple Biological Groups, Habitats, and Environmental Factors Matters. One way to optimize information and understand ecological determinants of diversity is to sample multiple biological groups, habitats, and environmental data in interdisciplinary teams at co-located sites, rather than sampling different groups in different places at different times. For example, in Rocky Mountain National Park, our research is coordinated between plant, butterfly, and bird taxonomists. By coordinating our efforts to sample different biological groups on the same sites, our understanding of many layers of diversity increases. In this way, multi-taxa predictive models can be developed for the larger, unsampled landscape (Fig. 1).

5. Sampling Design is the Key. The most important phase of an inventory and monitoring program is the design phase. Surveys are expensive and long-term monitoring is more so. Much of the cost associated with inventory and monitoring projects is getting field crews to and from sampling sites. There are many ways to reduce costs and maximize information gain, including cluster sampling, multi-scale sampling, and sampling multiple biological groups. No single sampling design will answer all monitoring questions. Cost constraints and the spatial and temporal variation of biological diversity will always restrict monitoring capabilities. However, well-designed multi-scale monitoring techniques that are tested in several vegetation types and biomes may have distinct advantages over many currently used single-scale and single-objective techniques.

Recommendations for Monitoring Forest Biodiversity

The protection of forest biodiversity relies on our ability to: (1) rapidly assess hot spots of biodiversity and areas of unique species assemblages at landscape scales; (2) quantify and predict spatial and temporal trends of key species; (3) maintain natural disturbance regimes and key ecological processes; (4) prevent the detrimental effects of exotic species; and (5) limit harmful human activities.

With continued population growth and current patterns of urbanization and development (Vitousek et al. 1997), it is urgent that we identify and map hot spots of biodiversity, areas of unique species assemblages, and areas most vulnerable to change (Stohlgren et al. 1997a). This must be done at local, regional, national, and international scales to guide inevitable human developments to less-important and more resilient sites, and to guide site selection for open space, parks, or other less-developed landscapes for conservation. The hot spots of diversity and areas of unique plant assemblages, identified quickly on the basis of plant species richness and composition, should be surveyed for other biological groups and environmental data.

Quantifying the spatial patterns of key indicator species relative to environmental data is the first step towards monitoring and predicting temporal trends of the species.

Not all species can be monitored at all locations so key indicator species and sensitive habitats must be selected. Conducting broad-based surveys prior to establishing long-term monitoring sites is very important. This way, sites can be randomly selected from a larger sample of survey sites to allow for an unbiased extrapolation of results. Meanwhile, an understanding of temporal variation in key indicator species is usually only possible after several years of monitoring (Hinds 1984, Eberhardt and Thomas 1991). Thus, sampling design is an iterative process. A finding of high temporal and spatial variation may require establishing additional monitoring sites, or waiting longer to detect significant change.

Maintaining natural disturbance regimes and key ecological processes may be important in protecting native species. Most forest species are adapted to living in a landscape with occasional wildfires, blow-downs, hurricanes, floods, or insect outbreaks. In the Rocky Mountains, fire suppression may result in a loss of aspen and riparian habitat, and an increase in the spatial extent of closed-canopy forests. Because aspen, riparian, and open forest types have higher diversity than closed-canopy forests, fire suppression could greatly reduce habitat for many species of plants, birds, and butterflies (DeByle 1985a,b, Stohlgren et al. 1997a, Simonson 1998). Likewise, riparian plants and aquatic species that rely on occasional floods will do poorly in environments of constant or lower water tables caused by dams and water diversions.

It will become increasingly difficult to prevent exotic species from gaining dominance in natural systems (Vitousek et al. 1996). Plant species are invading riparian zones (Stohlgren et al. 1998b) and along roads. These "evil corridors" provide access for invasive plants throughout forested and grassland ecosystems. Non-native insects and diseases such as gypsy moth, chestnut blight, and white pine blister rust are escalating problems with potentially severe indirect consequences to biological diversity (Vitousek et al. 1996). Exotic fishes have effected native species in most interior U.S. waters. Our best hope is to detect and control invasive species early in the invasion process.

Our ultimate social challenge is to limit human activities that harm our ecosystems (Vitousek et al. 1997). Modern society is likely to continue converting land from forests or grassland to agricultural and urban landscapes, excessively using natural resources, altering hydrologic and fire regimes, and spreading invasive species. The rate at which we continue these activities will likely define the rate of the loss of biodiversity.

Monitoring biodiversity in the U.S. is in its infancy (Bricker and Ruggiero 1988). Current national-level monitoring focuses on a few outweighing species such as dominant trees, common birds, and vascular plants. Local-scale monitoring is uncoordinated, with little opportunity to compare data on multiple biological groups at multiple spatial scales. Ideas are surfacing about the need for a new network of "index sites" for monitoring biodiversity and long-term change in 200 or more sites in many of the Nation's ecosystems (H. Ron Pulliam, personal communication). Given the current dearth of comparable information on biodiversity in natural areas (Stohlgren et al. 1995c), I think that such a monitoring network is badly needed.

Conclusions

Our science and land management challenges in North America (and the world) are to: (1) develop and test various design strategies (optimum sampling strategy) and multiple-scale field methods designed for inventorying and monitoring multiple biological groups and ecosystem processes; (2) conduct standardized monitoring of key indicators of multiple stresses to biodiversity; and (3) develop better mapping, information management, and predictive modeling capabilities at multiple spatial scales.

I am optimistic that surveying, monitoring, and predicting patterns of biodiversity can guide responsible land management decisions. Science can help guide decision-makers to avoid development in hot spots of biodiversity and where unique species assemblages occur. Science also can guide restoration and mitigation activities. A new, well-designed network of index sites to monitor biodiversity in national parks, wildlife refuges, national forests and grasslands, and other natural areas is needed.

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