Ecological Applications, 9(4), 1999, pp. 1179–1188

OVERVIEW OF THE USE OF NATURAL VARIABILITY CONCEPTS IN MANAGING ECOLOGICAL SYSTEMS

Peter B. Landres,[1,4] Penelope Morgan,[2] and Frederick J. Swanson[3]

[1]*USDA Forest Service, Aldo Leopold Wilderness Research Institute, P.O. Box 8089, Missoula, Montana 59807 USA*
[2]*College of Forestry, Wildlife, and Range Sciences, University of Idaho, Moscow, Idaho 83844 USA*
[3]*USDA Forest Service, Pacific Northwest Research Station, 3200 Jefferson Way, Corvallis, Oregon 97331 USA*

Abstract. Natural resource managers have used natural variability concepts since the early 1960s and are increasingly relying on these concepts to maintain biological diversity, to restore ecosystems that have been severely altered, and as benchmarks for assessing anthropogenic change. Management use of natural variability relies on two concepts: that past conditions and processes provide context and guidance for managing ecological systems today, and that disturbance-driven spatial and temporal variability is a vital attribute of nearly all ecological systems. We review the use of these concepts for managing ecological systems and landscapes.

We conclude that natural variability concepts provide a framework for improved understanding of ecological systems and the changes occurring in these systems, as well as for evaluating the consequences of proposed management actions. Understanding the history of ecological systems (their past composition and structure, their spatial and temporal variability, and the principal processes that influenced them) helps managers set goals that are more likely to maintain and protect ecological systems and meet the social values desired for an area. Until we significantly improve our understanding of ecological systems, this knowledge of past ecosystem functioning is also one of the best means for predicting impacts to ecological systems today.

These concepts can also be misused. No a priori time period or spatial extent should be used in defining natural variability. Specific goals, site-specific field data, inferences derived from data collected elsewhere, simulation models, and explicitly stated value judgment all must drive selection of the relevant time period and spatial extent used in defining natural variability. Natural variability concepts offer an opportunity and a challenge for ecologists to provide relevant information and to collaborate with managers to improve the management of ecological systems.

Key words: disturbance; ecosystem management; historical range of variability; landscape management; management of ecological systems; natural variability; restoration; variation, spatial and temporal scales.

Introduction

Natural resource managers increasingly rely on the ''range of natural variation,'' or simply ''natural variability,'' to develop plans that guide management within the range of ecological and evolutionary conditions appropriate for an area. Developed through a collaborative effort of applied scientists and managers, the use of natural variability relies on two intertwined concepts: (1) that past conditions and processes provide context and guidance for managing ecological systems today, and (2) that disturbance-driven spatial and temporal variability is a vital attribute of nearly all ecological systems.

Management use of natural variability concepts began out of a search for a legally defensible strategy for maintaining biological diversity and sustaining the viability of threatened and endangered species. Initially, ''vignettes'' of naturalness (Leopold et al. 1963) were used by national park managers to establish broad management goals to protect wildlife and other natural resources. These concepts are now being used in situations where sustaining ecological integrity is the primary goal, where a structural stage such as old-growth forest has been significantly altered, or where key processes such as fire and flooding have been excluded. Recently, these concepts were proposed for establishing benchmarks for evaluating whether observed changes in protected areas such as wilderness are caused by human actions (Morgan et al. 1994, Landres et al. 1998). Despite the large role that natural variability concepts have played, and will likely continue to play, in setting management direction, research ecol-

Manuscript received 18 May 1998; accepted 2 February 1999. For reprints of this Invited Feature, see footnote 1, p. 1177.
[4] E-mail: plandres/rmrs_missoula@fs.fed.us

ogists have largely been silent on the use and limitations of these concepts.

The purpose of this paper is to review, from an ecological perspective, the applications and limitations of natural variability concepts to managing ecological systems and landscapes. We examine key premises behind the use of these concepts, evaluate commonly used terms and statistical descriptors of natural variability, discuss barriers and challenges to the use of these concepts, examine management application of these concepts, and discuss key research issues and questions. We conclude that natural variability concepts provide a framework for understanding the ecological context of an area and in evaluating ecosystem change. Therefore, they are useful in managing ecological systems. However, these concepts can be easily misused and misapplied. Natural variability concepts offer both a challenge and an opportunity for ecologists to become meaningfully involved with managers in defining ecologically appropriate goals and practices for an area.

Background and Premises

Natural spatial and temporal variation has long provided ecologists insight into understanding ecological processes and the implications of ecological change (e.g., Cowles 1899, Shelford 1913). Today, historical ecologists use paleoreconstructions of climate, vegetation, and disturbances to understand past conditions and illustrate the importance of natural variability and disturbance processes on many different ecosystem types (e.g., Baker 1992, Swetnam 1993, Tausch et al. 1995, Foster et al. 1996). Natural spatial and temporal variation is a cornerstone of the contemporary non-equilibrium paradigm of ecology (e.g., Wu and Loucks 1995) and its metaphor, the ‘‘flux of nature’’ (Pickett and Ostfeld 1995). Further, understanding local ecological communities requires understanding at broad spatial and long temporal scales, the ‘‘regional–historical viewpoint’’ (Ricklefs 1987).

This use of natural variability concepts draws upon many fields of knowledge. Geography, watershed science, and landscape ecology contribute concepts for understanding temporal and spatial patterns and processes. Disturbance ecology contributes understanding about the temporal and spatial dynamics of ecological systems and the myriad ecological responses to disturbance. Wildlife, plant, and stream ecology provide understanding of ecological responses to environmental change. Each of these fields strongly contributed to the development of landscape-scale planning and management, as well as to the following premises on which the use of natural variability concepts is based:

1) Contemporary anthropogenic change may diminish the viability of many species adapted to past or historical conditions and processes (Swanson et al. 1994).

2) Approximating historical conditions provides a coarse-filter management strategy that is likely to sustain the viability of diverse species, even those for which we know little about (Hunter et al. 1989, Swanson et al. 1994). Similarly, because of limited understanding about ecosystems, approximating past conditions offers one of the best means for predicting and reducing impacts to present-day ecosystems (Kaufmann et al. 1994).

3) Managing within the constraints of site variability and history is easier, requires fewer external subsidies, and is more cost effective than trying to achieve management goals that are outside the bounds of the system (Allen and Hoeskstra 1992).

4) Natural variability is a useful reference for evaluating the influence of anthropogenic change in ecological systems, including lakes (Smol 1992, Anderson 1995), commodity production lands (Morgan et al. 1994), and protected areas such as wilderness (Haila 1995).

5) Analysis of an ecological system at different sites and over long time frames provides the context that hierarchy theory suggests is important in understanding the driving variables, constraints, and behavior of a system at local and shorter time scales (Allen and Hoekstra 1992). Such analysis yields essential understanding about the dynamic ecological processes that drive both spatial and temporal variation in ecological systems, as well as the influence of this variation on evolution and biological diversity (Landres 1992, Pickett and Ostfeld 1995).

6) Similar to the classic driving variables of moisture and temperature, disturbances such as fire and insect outbreaks have a strong and lasting influence on species, communities, and ecosystems (White 1979, Sousa 1985), and have been called a ‘‘key structuring process’’ at midscales, i.e., the scale of forest stands (Holling 1992).

7) Spatial heterogeneity per se is an important component of ecological systems. Reducing spatial variability typically results in declining biological diversity (Petraitis et al. 1989), increased vulnerability to insects, pathogens, or other disturbances (Lehmkuhl et al. 1994), and decreased resiliency to subsequent disturbances (White and Harrod 1997).

Defining Natural Variability

We define natural variability as the ecological conditions, and the spatial and temporal variation in these conditions, that are relatively unaffected by people, within a period of time and geographical area appropriate to an expressed goal. One of the major aims of characterizing natural variability is to understand how driving processes vary from one site to another, how these processes influenced ecological systems in the past, and how these processes might influence ecological systems today and in the future. Several phrases have been used by ecologists and managers to describe these past conditions and processes, as well as how they change spatially and temporally. These include ''range of natural variability,'' ''natural range of variability,'' ''historical range of variability,'' and ''reference variability.'' However, we suggest that the phrase ''natural variability'' most clearly and simply conveys this idea.

A lack of precision and clarity in the terms ''natural,'' ''range,'' and ''historical'' has generated considerable debate over the appropriate time period and spatial extent used in defining and evaluating ''natural variation'' (e.g., Morgan et al. 1994). Much of this debate has centered on whether impacts of native Americans are considered natural or not, and on defining a point in time when ecological systems were relatively unaffected by people, usually considered the time before Euro–American settlement (e.g., Schrader-Frechette and McCoy 1995, Hunter 1996). Joining this debate and attacking what he calls the ''myth of the humanized landscape,'' Vale (1998) asserts that for many areas, especially the western United States, the influence of native people is overstated, and that ''honest assessments to determine where, how, and to what degree the pre-European landscape was a product of people and their activities needs to be undertaken, unencumbered by commitment to a preconceived notion of the ubiquity of human agency.'' Landres et al. (1998) review this debate, suggesting that the use of these concepts will always depend on the ecological *and* social context of the area and the issue. We emphasize that clearly defined goals, objectives, assumptions, value judgements, and spatial and temporal bounds must always be explicit parts of the definition and use of natural variability concepts.

Describing Natural Variability

In a recent set of papers on ecological variability, Kareiva and Bergelson (1997) pointed out problems of imprecisely using the common terms ''variation'' and ''variability.'' Managers need descriptions of natural conditions and how these conditions vary spatially and temporally. These descriptions need to be precise and relevant to setting management goals and making decisions based on those goals.

A crucial part of describing natural variability is selecting the time period and geographical extent used to characterize system dynamics. There is no single, widely applicable optimal period, and relevance is lost if too long a time period is used, because conditions such as climate and species composition may have changed drastically. Displaying major sources of relevant information along spatial and temporal scale (see Fig. 1 in Swetnam et al. 1999) allows managers to identify what types of information are most applicable to meet stated goals. Other considerations in selecting spatial and temporal extent include the presence of exotic species, known climate changes, human influences, and record length and quality. Morgan et al. (1994) suggested that natural variability be assessed over relatively consistent climatic, edaphic, topographic, and biogeographic conditions. For the Interior Columbia Basin Ecosystem Management Project, for example, Hann et al. (1997) used the last 2000 yr as the appropriate temporal depth, based on studies showing the vegetation in this area was in relative equilibrium with the macroclimate and native Americans during that time (Schoonmaker and Foster 1991).

Choosing the appropriate geographic extent is particularly critical where management issues extend beyond the scale of the planning area, as is commonly the case. A regional scope is often needed to inform planning efforts that address local ecological and social issues. Many bioregional assessments and conservation strategies do this, providing context for local analysis and planning (see Knight and Landres [1998] for several examples). Wide-ranging, legally-protected species, for example, must be evaluated at the scale of their range, even if this extends beyond the local planning area (Cissel et al. 1994). DellaSala et al. (1995) assert that a regional extent is necessary in applying natural variability concepts to setting forest health goals.

Quantifying natural variability

Quantifying natural variability requires information on the conditions of interest and their variation over set periods of time and space. Common metrics used to describe these conditions and their variation include mean, median, percentile, range, standard deviation, coefficient of variation, skewness, frequency, spatial arrangement, and size and shape distributions. Different attributes of interest require different descriptors. Fire, for example, might require descriptors of frequency, severity, size, and spatial arrangement across the landscape. In contrast, an endangered plant might require descriptors of the number of individuals, aspects of population viability, and metapopulation structure. The overall form of a distribution (e.g., negative exponential) is also useful for describing attributes such as patch size distribution of a forest type, or the frequency and intensity of disturbances such as fire.

Range is often used to describe natural variability and to evaluate when current conditions are beyond the bounds of natural conditions. When used alone, we suggest that the range is not appropriate for this purpose, because rare, extreme events define these bounds and spatial and temporal limits usually are not defined in sufficiently explicit terms.

Two additional types of descriptors may be useful in quantifying variability. Spike descriptors quantify short-term, extreme, or high magnitude changes caused by discrete disturbance events and the relatively short-term ecological responses to these events. Spike descriptors include the rate of change, severity, season-

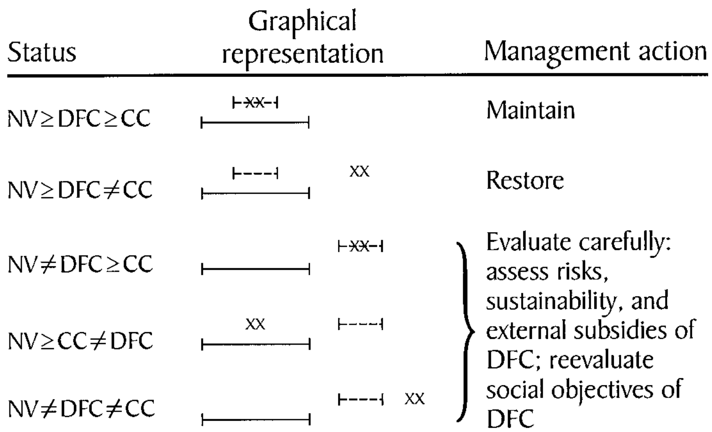

FIG. 1. Diagrammatic comparison of current conditions (CC, denoted as XX in the graphical representation), desired future conditions (DFC, – – –) or the social objectives for public lands jointly decided by managers and stakeholders, and the ecological conditions defined by natural variability (NV, ———), illustrating the range of differences among these. The width of the bars represent the spatial or temporal variation in conditions. DFCs are portrayed as narrower than (or as a subset of) NV. Only extreme cases are shown here; partial overlap among NV, DFC, and CC will likely be more common. A ''greater than or equal to'' sign (≥) denotes that a condition is within the bounds of the preceding condition (e.g., in the top row, current conditions are within the bounds of desired future conditions, and these are within the bounds of natural variability).

ality, and size and severity frequency distributions. Moritz (1997) described the ''extremal fire regime'' as the time series of the largest fire per year, to test for spatial and temporal differences due to fire suppression and the effect of climate forcing on the fire regime in southern California. Trend descriptors, for example time series analysis, quantify the low magnitude and rate changes that occur over longer time frames through succession or chronic disturbances, such as habitat fragmentation or acid deposition.

In addition, probabilistic descriptors of spikes and trends may be especially useful in detecting trends and estimating the probability that a particular type, direction, and magnitude of change from historical conditions will occur. The probability that current conditions are similar to past conditions could be derived from data-driven statistical models. Some models yield empirical relationships and probabilities associated with change along environmental gradients or gradients of human impact. Another type of analysis could assess the probability that a given current or future condition is consistent with past system behavior. For example, frequency analysis, a standard hydrology technique for estimating probabilities of future events such as floods from historical data, was used by Erman and Jones (1996) to assess change in fire frequencies over time, across seven national forests in the Sierra Nevada.

MANAGEMENT APPLICATIONS

Historical information has been used to guide management decisions in many different systems. For example, it has been used to understand the impacts of altered flow regimes on the ecology and geomorphology of the Colorado River (Poff et al. 1997); to assess the impacts of altered fire regimes on the structure and composition of forest ecosystems (Skinner and Chang 1996); to assess the effectiveness of prescribed natural fire programs in wilderness (Brown et al. 1994); to understand the impacts of altered freshwater flows on the Everglades in southern Florida (Harwell 1997); to assess the current spatial patterns of boreal (Gauthier et al. 1996), midwestern (Baker 1992), and western (Ripple 1994, Camp et al. 1997) old-growth forests; to monitor the condition of eastern temperate deciduous forests (Keddy and Drummond 1996); and to understand the processes that influenced the structure of old-growth forests in the Midwestern (Mladenoff and Pastor 1993), southwestern (Fulé et al. 1997), and northwestern (Lesica 1996, Lertzman et al. 1997) United States.

Current agency implementation of ecosystem management also relies heavily on the ''historical range of variability'' (Kaufmann et al. 1994) or ''reference variability'' (Manley et al. 1995) in defining target conditions for the full array of managed lands, from timber harvest areas to wilderness. In developing a vegetation management strategy for the Six Rivers National Forest in northwestern California, for example, the planning team relied on natural disturbance processes and rates, rather than silvicultural prescriptions, ''. . . to provide a near-natural range and distribution of habitat types throughout the forest'' (Wright et al. 1995).

Natural variability is a useful tool for understanding and evaluating change (Morgan et al. 1994). Hypotheses about the drivers and mechanisms of ecosystem change can be developed and tested with spatial and temporal data (Swetnam et al. 1999). This understanding is helpful for predicting how ecosystems will change, even in response to novel structures and processes, and nonnative species. Until we fully know how ecosystems function, the past is one of the best means for understanding and predicting impacts to ecological conditions.

Natural variability is also useful as a reference for setting general management goals. Comparing current conditions, desired future conditions (an expression of ecosystem conditions preferred by stakeholders and managers), and natural variability clarifies management direction (Fig. 1). Maintaining situations where current and desired conditions are within natural variability, or restoring current conditions to that state, are just two of the many possible situations managers face. Desired future conditions may or may not be equivalent to either natural variability or current conditions. When they are not (Fig. 1; rows 3, 4, and 5), desired conditions may need to be reevaluated. The actions needed to move current conditions to desired conditions, and the external subsidies required to maintain those desired conditions, need to be evaluated for their ecological and socioeconomic acceptability. For example, the restoration of fire to old-growth forests may be desired in the long-term, but in the short-term fire may reduce the amount of habitat that is critical to endangered species. Similarly, restoring intense crown fire to forests that historically experienced such fire may pose unacceptable social costs today. This analysis of trade-offs is relevant to all lands, because we choose to sustain artificial conditions to a lessor or greater degree everywhere.

Using these concepts in the process of ecosystem assessment, and in the setting of specific landscape management goals, requires several steps. First, site interpretation derived from the history of several individual sites, using techniques such as dendrochronology and stand analysis, allows understanding the specific forces influencing current conditions. Second, the landscape history is compiled based on the individual site histories. Third, the landscape-scale disturbance regime is interpreted from the site-specific understanding of factors controlling disturbance processes, a general understanding of disturbance mechanisms, and simulation models that may be used to extend these inferences to areas where site-specific data are lacking. And fourth, the landscape management plan is developed based on an understanding of the landscape-scale disturbance regime, current landscape conditions, and the desired future conditions (or social objectives) for the landscape. Cissel et al. (1999) apply this process in old-growth forests of the Pacific Northwest. Value judgements will always be part of this process. When made explicit, the merits and impacts of these judgements can be openly discussed.

Under certain social and biophysical conditions, alternative approaches to managing ecosystems may be more useful. Where single or small numbers of species are pivotal issues, an emphasis on reserves may be most appropriate biologically and legally. If historical relationships between ecosystem components and their functions cannot be determined or restored, the natural variability approach has little utility. When the size, intensity, or effect of a disturbance (e.g., fire) is so great as to be socially or politically unacceptable, other approaches to landscape management will be needed. Where past management activities have pushed ecosystems into undesired conditions, measures such as strict reserve systems or intensive restoration may be needed before less intensive management under a natural variability-based system is appropriate (Wallin et al. 1996). In such cases, the transition in management from a restoration focus to a natural variability-based maintenance approach may not be appropriate for many decades.

Several conclusions may be drawn from the examples discussed here. Natural variability concepts compel a regional and historical perspective that provides a deeper understanding of the processes and mechanisms that drive ecological systems. This deeper understanding can then be used to evaluate causes of ecological change and predict the consequences of current management actions. These concepts are often used in setting goals that ''. . . guide the *direction* but not the *detail* of what a desired condition might be . . .'' (Millar 1996; emphasis in original). These general directions may in turn significantly help managers understand the potential consequences of proposed goals and actions.

Barriers and Challenges

Significant concerns remain about the use of natural variability concepts: the relevance of these concepts to environments that are different today from what they were; the amount and quality of information and understanding about natural variability may be insufficient; and the difficulty of managing dynamic ecological systems, especially at scales large enough to be meaningful.

Is natural variability relevant?

In a world that is constantly changing and increasingly altered by people, primary criticisms against the use of natural variability include the following: (1) Native and contemporary people have so altered natural systems that there are no pristine natural areas left on our planet, making information derived from the past difficult to interpret or irrelevant. (2) Each point in time and space is unique, and dominant climate patterns are continually changing, therefore a description of past patterns and processes is largely irrelevant today or in the future. (3) Management goals based on natural variability seek to recreate past environments and then maintain those environments in a static condition.

There is no question that ecological systems are constantly changing, and that people have extirpated and altered the distribution of many species, introduced exotic species, released pollutants, eroded soils, altered fluvial processes, restructured landscapes, and altered the frequency, type, and intensity of disturbances. Humans can also change ecosystem patterns and processes at rates that limit the abilities of species to adapt or disperse to suitable habitat. Although native people burned and otherwise altered floral and faunal compositions, they did not occupy all areas or all ecosystems, nor impose broad-scale and intense impacts in all the areas they did occupy (Swetnam and Baisan 1996, Delcourt and Delcourt 1997). Historical analyses demonstrate that contemporary aspects of ecological systems, including species composition, distribution patterns of vegetation and animals, and rates of nutrient turnover, are often contingent on past conditions and processes (see review by Swetnam et al. [1999] in this Feature). In this context, the legacy of past management actions may have significantly altered the natural state of an ecosystem, thereby altering the actions that may be necessary to restore that system (Frissell and Bayles 1996). In general, understanding past conditions, and the natural processes that influenced those conditions, yields insight into why and how current conditions developed, and what changes might be expected in the future.

One of the primary objectives in using natural variability concepts is to better understand ecological change, as well as the past and current impacts of people. Furthermore, the use of these concepts is not necessarily an attempt to simply mimic or recreate the processes that occurred on a site long ago, or to return managed landscapes to a single and unchanging past condition. Rather, it is an attempt to improve understanding about the ecological context of an area and the landscape-scale effects of disturbance. This understanding may then be used to make existing and future conditions more relevant and variable, and thereby ecologically sustainable (Covington et al. 1994, Wallin et al. 1996, Lertzman et al. 1997). It has also been suggested that natural variability is irrelevant, because our current understanding of ecosystems is sufficient to allow the achievement of any desired goal. However, it is only with great hubris that we ignore or claim to understand the ecological interactions and processes that have operated for thousands of years and that have shaped the ecological systems of today.

Is there sufficient understanding about natural variability?

For many areas, sufficient data exist for a general understanding of the recent history of disturbances, such as fire and insect outbreaks. For a few areas (such as the Long-Term Ecological Research program sites) there is substantial knowledge of structures and processes. Site-specific data, however, are lacking for most areas, and there is insufficient temporal depth for many of the areas that have been studied, requiring inference and extrapolation such as space-for-time substitutions (e.g., Pickett 1989). The effect of these inferences on our understanding of past conditions and variation is poorly known (Clark 1990), especially in topographically complex landscapes and when extrapolating the effects of disturbances across a landscape. Furthermore, the spatial arrangement of patches and severity of disturbances are not usually identified with confidence from historical data, resulting in a general lack of information about the spatial variation of past conditions.

Compounding this lack of understanding, estimates derived from paleoreconstructions become more uncertain further back in time for several reasons including the following: fewer data are available further back in time; the probability of rare events increases with longer time frames; and rare events may skew the data record, because they are often intense and their impacts may be retained longer. Furthermore, for earlier times, there is only limited information about disturbance processes, as well as the interactions of these processes with dominant driving variables such as climate. Together, these sources of uncertainty make analysis of long-term trends difficult. This lack of data is especially problematic when statistical power is needed to detect trends that have important consequences, such as change in the amount of forest needed for an endangered species.

Swetnam et al. (1999) discuss the variety of data used for understanding past ecological structures and processes, and the spatial and temporal resolution of these data. Similarly, White and Walker (1997) discuss the benefits and limitations in selecting and using different types of reference information in restoration ecology. Both papers conclude that information, from multiple sites and times that are both similar *and* different from the target area, provides necessary spatial and temporal context and understanding. Likewise, in applying natural variability concepts, multiple sources of information are needed, ranging from site-specific data and simulation models, to expert opinions and judgements. These disparate types of information allow for the forming and testing of hypotheses about how natural variability concepts can best be applied to managing ecological systems.

The current theoretical understanding of natural variability, especially related to disturbances, is also poorly developed, hampering application of these concepts. While the factors promoting spatial variability (e.g., patterns of topography, soil, precipitation, and disturbances) are generally well known for individual sites, the causes and effects of historical contingency and spatial and temporal variation at the landscape scale are poorly understood. Likewise, interactions among disturbances at different spatial and temporal scales are not well understood. This lack of understanding is illustrated by the contentious and long-standing debate over natural variability, disturbance regimes, and structural- vs. process-based management of giant sequoia (*Sequoiadendron giganteum*) forests in California (Stephenson 1996, 1999).

How are natural variability concepts used in managing dynamic systems?

Three issues are paramount as barriers to managing dynamic systems. First, our understanding of spatial and temporal dynamics in ecological systems will never be complete. Determining the appropriate spatial extent and temporal depth for analysis of natural variability is difficult. Goals of the analysis, specific ecological attributes of concern (such as a species, or a disturbance process such as fire), specific decisions that need to be made, information currently available, costs of gathering new information, time constraints, and political influence, for example, all affect the spatial and temporal scale of analysis. Second, management plans based on disturbance processes will always be somewhat uncertain, because large and infrequent disturbances have significant long-term consequences for ecosystems (Turner et al. 1997). In the Black Hills of South Dakota and Wyoming, for example, infrequent catastrophic fires maintained large patches of old-growth ponderosa pine (*Pinus ponderosa*) in a non-equilibrium state (Shinneman and Baker 1997). And third, even in those cases where there is sufficient ecological understanding of how to manage the processes that drive dynamic systems, there may be insufficient social or political will to maintain or restore these processes.

In general, management systems are not geared for managing moving targets or coping with the uncertainty and surprise that are inherent and fundamental aspects of ecological systems (Ludwig et al. 1993, Haila 1995, Christensen 1988, 1997). Most large land and water resource management organizations approach the world in a deterministic manner. Ecosystems, on the other hand, are variable in time and space, and relations among vegetation patterns, topography, and disturbance regimes may not be sharply defined. This complexity may be a critical aspect of long-term ecosystem dynamics and function. In parts of the Pacific Northwest, for example, substantial components of old-growth ecosystems may have persisted on the landscape over millennia as a result of the highly variable frequency, severity, and spatial patterning of wildfires (Agee 1993). This is challenging for land managers, because historical variability does not provide a simple, clear blueprint that can be easily followed. Furthermore, extreme disturbance events, which may have strongly structured ecosystems in the past, may be socially unacceptable today. Recognizing this, and that managers have no practical control over extreme events, Manley et al. (1995) recommend that a subset of the full range of natural variability, or ''management variability,'' is a more practical goal in applying natural variability concepts. Even in situations where a decision is made to not allow certain disturbance events, natural variability concepts are still useful in improving understanding about ecological conditions and the potential consequences of management actions.

Managing for natural variability allows greater latitude, and requires greater flexibility, than traditional stand-level management prescriptions. However, this latitude and flexibility can also be misused and misapplied in setting management goals and targets that push a landscape outside the range of historical conditions. Some forest managers, for example, have used past fire and windstorm disturbances to justify timber harvest targets, but timber harvesting and ecological disturbances may have profoundly different long-term ecological consequences (DellaSala et al. 1995). Greater latitude and flexibility also require greater communication with stakeholders and greater public trust; for many agencies in many areas, this communication and trust is currently lacking.

Key Research Issues and Questions

Research is needed to improve the basic understanding and management application of natural variability, especially at broader spatial and longer time scales. Both site-specific and general cross-cutting research can be focused on three issues: describing past conditions and disturbance regimes, understanding the landscape-scale effects of disturbance regimes, and understanding the cumulative effects of management actions.

Describing past conditions and disturbance regimes

More information is needed on past conditions and disturbance regimes, as well as better quantitative descriptions of how these vary over large areas of complex terrain and over long periods of time. Our current understanding of landscape-scale variation and the processes driving this variation is meager, and ''. . . fine-scale knowledge of autecology cannot simply be aggregated to represent [ecosystem] behavior at scales beyond the scale of a patch or gap'' (Holling 1992). Indeed, combining broad spatial and deep temporal analyses is likely to be one of the more important and exciting challenges for landscape ecologists. Such analyses allow insight into whether there are ecological patterns that can be discerned only at certain spatial and temporal scales, whether extrapolating information on natural variability across spatial and temporal scales is reliable, and whether extrapolations are more robust for certain system attributes under certain conditions.

Understanding landscape-scale effects of disturbance regimes

Better understanding is needed on the effects of multiple disturbance events on vegetation and wildlife over large areas and long time flames. Disturbances have effects that may last hundreds of years, allowing ample time for multiple disturbances and cumulative effects across a landscape. Currently, little information exists on the short- and long-term interactions among multiple disturbances (e.g., overlapping patterns of fire and insect outbreaks) in spatial pattern, frequency, intensity, or the effects of multiple disturbances on landscape-scale patterns of distribution and abundance of vegetation and wildlife. Furthermore, analyses that sacrifice local-scale detail, but answer crucial broader-scale questions, are needed to understand landscape-level controls on disturbance frequency, intensity, and spatial pattern (e.g., see McKelvey and Busse 1996).

Cumulative effects of management

Just as current system attributes are contingent on historical influences, future system attributes will be contingent on current conditions and planned management actions influencing the composition, structure, and disturbance regimes of ecosystems. For example, the combined long-term effects of altering spatial patterns of forest vegetation, excluding fire from fire-dependent ecosystems, and introducing exotic species, will certainly be great. Research built upon a basic understanding of disturbance interactions and effects over large areas and long times is needed to predict probable vegetation and wildlife outcomes from different management strategies. Practically, logical frameworks are needed for determining the appropriate spatial and temporal scales that are relevant to a particular management goal, as well as for understanding the implications when inappropriate spatial and temporal scales are used. For example, modeling could help address to what degree multiple small and manageable disturbance events could be used to accomplish the important effects of a single large, and unmanageable, disturbance, as is often discussed for the restoration of fire regimes (e.g., Christensen 1995).

Conclusions

Our world is highly modified from the past, and creating static reproductions of past ecosystems is neither possible nor the desire of most managers. Understanding past ecological systems, their composition and structure, how they changed from one place to another and over time, and the principal interactions and processes that influenced them, helps managers set goals that respond to the ecological context and social values of an area. The use of natural variability concepts compels recognition of processes that cause spatial and temporal variation, such as disturbances, and illustrates their important role in sustaining ecological systems and the species that depend on them. The use of these concepts also compels acknowledging the important role of regional and historical perspectives in setting management goals, even for local actions. Recognizing these processes and perspectives further reinforces the uncertain and surprise-filled ecological realities in managing ecosystems. Conversely, managing for goals informed by natural variability likely reduces uncertainty and surprise, because these goals would be set within the ecological constraints of an area.

Using natural variability concepts in developing management plans requires specific, clearly defined management goals, as well as information about the specific landscape. In addition, no a priori time period or spatial extent can be used in defining natural variability. Specific goals and explicitly stated values must always drive selection of the relevant time period and spatial extent. Understanding a landscape's past and present spatial and temporal variation usually requires a combination of site-specific field data, inferences derived from data collected elsewhere, simulation models, and expert judgement. When used judiciously and collectively, this information provides valuable insight that is useful for developing the general direction of management plans and goals. Research can help define the set of ecological conditions and social goals that require a natural variability approach for effective and successful management.

Variability is a key attribute of natural systems, as well as a practical and realistic foundation for landscape-scale management. Sustaining ecosystems, viable species populations, and the amenities and commodities our society desires from natural ecological systems will require a long-term, landscape-scale approach to management that balances the needs, capabilities, and impacts among different areas within that landscape. Management goals and actions cannot be applied uniformly across a landscape without causing a loss of species and ecosystem functions.

Finally, natural variability provides a foundation for improving discussion among managers, scientists, and the public about the desirability and feasibility of different values and goals for an area, the resulting impacts and tradeoffs that occur from these different management goals, and how to improve the management of dynamic ecosystems. Applying natural variability concepts to management is a new and developing field, where there is much to learn and improve upon. Active collaboration between researchers and managers will profoundly improve the management of ecological systems.

Acknowledgments

In developing this paper we have greatly enjoyed and benefited from our discussions with Greg Aplet, Steve Bunting, John Cissel, Wendel Hann, Lee Harry, Paul Hessburg, Merrill Kaufmann, Pat Manley, Madeline Mazurski, Kevin McKelvey, Connie Millar, Dave Parsons, Nate Stephenson, Tom Swetnam, Peter White, the attendees at the Georgetown Lake Workshop, and the managers who are leading this important and difficult task of managing ecological systems.

Literature Cited

Agee, J. K 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C., USA.

Allen, T. F. H., and T. W. Hoekstra. 1992. Toward a unified ecology. Columbia University Press, New York, New York, USA.

Anderson, N. J. 1995. Using the past to predict the future: lake sediments and the modelling of limnological disturbance. Ecological Modelling **78**:149–172.

Baker, W. L. 1992. Effects of settlement and fire suppression on landscape structure. Ecology **73**:1879–1887.

Brown, J. K., S. F. Arno, S. W. Barrett, and J. P. Menakis. 1994. Comparing the prescribed natural fire program with presettlement fires in the Selway-Bitterroot Wilderness. International Journal of Wildland Fire **4**:157–168.

Camp, A., C. Oliver, P. Hessburg, and R. Everett. 1997. Predicting late-successional fire refugia pre-dating European settlement in the Wenatchee Mountains. Forest Ecology and Management **95**:63–77.

Christensen, N. L. 1988. Succession and natural disturbance: paradigms, problems, and preservation of natural ecosystems. Pages 62–86 *in* J. K. Agee and D. R. Johnson, editors. Ecosystem management for parks and wilderness. University of Washington Press, Seattle, Washington, USA.

———. 1995. Fire and wilderness. International Journal of Wilderness **1**:30–34.

———. 1997. Managing for heterogeneity and complexity on dynamic landscapes. Pages 167–186 *in* S. T. A. Pickett, R. S. Ostfeld, M. Shachak, and G. E. Likens, editors. The ecological basis of conservation: heterogeneity, ecosystems, and biodiversity. Chapman and Hall, New York, New York, USA.

Cissel, J. H., F. J. Swanson, W. A. McKee, and A. L. Burditt. 1994. Using the past to plan the future in the Pacific Northwest. Journal of Forestry **92**:30–31, 46.

Cissel, J. H., F. J. Swanson, and P. J. Weisberg. 1999. Landscape management using historical fire regimes: Blue River, Oregon. Ecological Applications **9**:1217–1231.

Clark, J. S. 1990. Fire and climate change during the last 750 yr in northwestern Minnesota. Ecological Monographs **60**:135–159.

Covington, W. W., R. L. Everett, R. Steele, L. L. Irwin, T. A. Daer, and A. N. D. Auclair. 1994. Historical and anticipated changes in forest ecosystems of the inland west of the United States. Pages 13–63 *in* R. N. Sampson and D. L. Adams, editors. Assessing forest ecosystem health in the inland west. Haworth Press, Binghamton, New York, USA.

Cowles, H. C. 1899. The ecological relations of the vegetation on the sand dunes of Lake Michigan. Botanical Gazette **27**:95–117, 167–202, 281–308, 361–391.

Delcourt, H. R., and P. A. Delcourt. 1997. Pre-Columbian native American use of fire on southern Appalachian landscapes. Conservation Biology **11**:1010–1014.

DellaSala, D. A., D. M. Olson, S. E. Barth, S. L. Crane, and S. A. Primm. 1995. Forest health: moving beyond rhetoric to restore healthy landscapes in the inland Northwest. Wildlife Society Bulletin **23**:346–356.

Erman, D. C., and R. Jones. 1996. Fire frequency analysis of Sierra forests. Pages 1139–1153 *in* Status of the Sierra Nevada, Volume II: Assessments and scientific basis for management options. Sierra Nevada Ecosystem Project, Final Report to Congress. Wildland Resources Center Report No. 37, Centers for Water and Wildland Resources, University of California, Davis, California, USA.

Foster, D. R., D. A. Orwig, and J. S. McLachlan. 1996. Ecological and conservation insights from reconstructive studies of temperate old-growth forests. Trends in Ecology and Evolution **11**:419–425.

Frissell, C. A., and D. Bayles. 1996. Ecosystem management and the conservation of aquatic biodiversity and ecological integrity. Water Resources Bulletin **32**:229–240.

Fulé, P. Z., W. W. Covington, and M. M. Moore. 1997. Determining reference conditions for ecosystem management of southwestern ponderosa pine forests. Ecological Applications **7**:895–908.

Gauthier, S., A. Leduc, and Y. Bergeron. 1996. Forest dynamics modelling under natural fire cycles: a tool to define natural mosaic diversity for forest management. Environmental Monitoring and Assessment **39**:417–434.

Haila, Y. 1995. Natural dynamics as a model for management: is the analogue practicable? Pages 9–26 *in* A.-L. Sippola, P. Alaraudanjoki, B. Forbes, and V. Hallikainen, editors. Northern wilderness areas: ecology, sustainability, values. Arctic Centre Publications 7, Arctic Center, University of Lapland, Ravaniemi, Finland.

Hann, W. J., J. L. Jones, M. G. Karl, P. F. Hessburg, R. E. Keane, D. G. Long, J. P. Menakis, C. H. McNicoll, S. G. Leonard, R. A. Gravenmier, and B. G. Smith. 1997. Landscape dynamics of the Basin. Pages 363–1055 *in* T. M. Quigley and S. J. Arbelbide, technical editors. An assessment of ecosystem components in the Interior Columbia Basin and portions of the Klamath and Great Basins, volume II. U.S. Forest Service General Technical Report **PNW-GTR-405**, Pacific Northwest Research Station, Portland, Oregon, USA.

Harwell, M. A. 1997. Ecosystem management of south Florida. BioScience **47**:499–512.

Holling, C. S. 1992. Cross-scale morphology, geometry, and dynamics of ecosystems. Ecological Monographs **62**:447–502.

Hunter, M. L. 1996. Benchmarks for managing ecosystems: are human activities natural? Conservation Biology **10**:695–697.

Hunter, M. L., G. L. Jacobson, and T. Webb. 1989. Paleoecology and the coarse-filter approach to maintaining biological diversity. Conservation Biology **2**:375–385.

Kareiva, P, and J. Bergelson. 1997. The nuances of variability: beyond mean square error and platitudes about fluctuating environments. Ecology **78**:1299–1230.

Kaufmann, M. R., R. T. Graham, D. A. Boyce, W. H. Moir, L. Perry, R. T. Reynolds, R. L. Bassett, P. Mehlhop, C. B. Edminster, W. M. Block, and P. S. Corn. 1994. An ecological basis for ecosystem management. U.S. Forest Service General Technical Report **RM-GTR-246**, Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Keddy, P. A., and C. G. Drummond. 1996. Ecological properties for the evaluation, management, and restoration of temperate deciduous forest ecosystems. Ecological Applications **6**:748–762.

Knight, R. L., and P. B. Landres, editors. 1998. Stewardship across boundaries. Island Press, Washington, D.C., USA.

Landres, P. B. 1992. Temporal scale perspectives in managing biological diversity. Transactions of the North American Wildlife and Natural Resources Conference **57**:292–307.

Landres, P. B., P. S. White, G. Aplet, and A. Zimmermann. 1998. Naturalness and natural variability: definitions, concepts, and strategies for wilderness management. Pages 41–50 *in* D. L. Kulhavy and M. H. Legg, editors. Wilderness and natural areas in eastern America: research, management, and planning. Center for Applied Studies, College of Forestry, Stephen F. Austin University, Nacogdoches, Texas, USA.

Lehmkuhl, J. F., P. F. Hessburg, R. L. Everett, M. H. Huff, and R. D. Ottmar. 1994. Historical and current forest landscapes of eastern Oregon and Washington. Part I: Vegetation pattern and insect and disease hazards. U.S. Forest Service General Technical Report **PNW-GTR-328**. Pacific Northwest Research Station, Portland, Oregon, USA.

Leopold, A. S., S. A. Cain, C. M. Cottom, I. N. Gabrielson, and T. L. Kimball. 1963. The wildlife management in the national parks. Transactions of the North American Wildlife and Natural Resources Conference **28**:28–45.

Lertzman, K., T. Spies, and F. Swanson. 1997. From ecosystem dynamics to ecosystem management. Pages 361–382 *in* P. K. Schoonmaker, B. von Hagen, and E. C. Wolf, editors. The rain forests of home: profile of a North American bioregion. Island Press, Washington, D.C., USA.

Lesica, P. 1996. Using fire history models to estimate proportions of old growth forest in northwestern Montana, USA. Biological Conservation **77**:33–39.

Ludwig, D., R. Hilborn, and C. Walters. 1993. Uncertainty, resource exploitation, and conservation: lessons from history. Science **260**:17.

Manley, P. N., et al. 1995. Sustaining ecosystems: a conceptual framework. USDA Forest Service, Pacific Southwest Region and Station. **R5-EM-TP-001**. Berkeley, California, USA.

McKelvey, K. S., and K. K. Busse. 1996. Twentieth-century fire patterns on Forest Service lands. Pages 1119–1138 *in* Status of the Sierra Nevada, Volume II: Assessments and scientific basis for management options. Sierra Nevada Ecosystem Project, Final Report to Congress. Wildland Resources Center Report No. 37, Centers for Water and Wildland Resources, University of California, Davis, California, USA.

Millar, C. I. 1996. The Mammoth–June Ecosystem Management Project, Inyo National Forest. Pages 1273–1304 *in* Status of the Sierra Nevada, Volume II: Assessments and scientific basis for management options. Sierra Nevada Ecosystem Project, Final Report to Congress. Wildland Resources Center Report No. 37, Centers for Water and Wildland Resources, University of California, Davis, California, USA.

Mladenoff, D. J., and J. Pastor. 1993. Sustainable forest ecosystems in the northern hardwood and conifer region: concepts and management. Pages 145–180 *in* G. H. Aplet, J. T. Olsen, N. Johnson, and V. A. Sample, editors. Defining sustainable forestry. Island Press, Washington, D.C., USA.

Morgan, P., G. H. Aplet, J. B. Haufler, H. C. Humphries, M. M. Moore, and W. D. Wilson. 1994. Historical range of variability: a useful tool for evaluating ecosystem change. Journal of Sustainable Forestry **2**:87–111.

Moritz, M. A. 1997. Analyzing extreme disturbance events: fire in Los Padres National Forest. Ecological Applications **7**:1252–1262.

Petraitis, P. S., R. E. Latham, and R. A. Niesenbaum. 1989. The maintenance of species diversity by disturbance. Quarterly Review of Biology **64**:393–418.

Pickett, S. T. A. 1989. Space-for-time substitution as an alternative to long-term studies. Pages 110–135 *in* G. E. Likens, editor. Long-term studies in ecology: approaches and alternatives. Springer-Verlag, New York, New York, USA.

Pickett, S. T. A., and R. S. Ostfeld. 1995. The shifting paradigm in ecology. Pages 261–278 *in* R. L. Knight and S. F. Bates, editors. A new century for natural resources management. Island Press, Washington, D.C., USA.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The natural flow regime. BioScience **47**:769–784.

Ricklefs, R. E. 1987. Community diversity: relative roles of local and regional processes. Science **235**:167–171.

Ripple, W. J. 1994. Historic spatial patterns of old forests in western Oregon. Journal of Forestry **92**:45–49.

Schoonmaker, P. K., and D. R. Foster. 1991. Some implications of paleoecology for contemporary ecology. The Botanical Review **57**:204–245.

Schrader-Frechette, K., and E. D. McCoy. 1995. Natural landscapes, natural communities and natural ecosystems. Forest and Conservation History **39**:138–142.

Shelford, V. E. 1913. Animal communities in temperate America. University of Chicago Press, Chicago, Illinois, USA.

Shinneman, D. J., and W. L. Baker. 1997. Nonequilibrium dynamics between catastrophic disturbances and old-growth forests in ponderosa pine landscapes of the Black Hills. Conservation Biology **11**:1276–1288.

Skinner, C. N., and C. Chang. 1996. Fire regimes, past and present. Pages 1041–1070 *in* Status of the Sierra Nevada, Volume II: Assessments and scientific basis for management options. Sierra Nevada Ecosystem Project, Final Report to Congress. Wildland Resources Center Report No. 37, Centers for Water and Wildland Resources, University of California, Davis, California, USA.

Smol, J. P. 1992. Paleolimnology: an important tool for effective ecosystem management. Journal of Aquatic Ecosystem Health **1**:49–58.

Sousa, W. P. 1985. The role of disturbance in natural communities. Annual Review of Ecology and Systematics **15**: 353–391.

Stephenson, N. 1966. Ecology and management of giant sequoia management groves. Pages 1431–1467 *in* Status of the Sierra Nevada, Volume II: Assessments and scientific basis for management options. Sierra Nevada Ecosystem Project, Final Report to Congress. Wildland Resources Center Report No. 37, Centers for Water and Wildland Resources, University of California, Davis, California, USA.

Stephenson, N. L. 1999. Reference conditions for giant sequoia forest restoration: structure, process, and precision. Ecological Applications **9**:1253–1265.

Swanson, F. J., J. A. Jones, D. O. Wallin, and J. H. Cissel. 1994. Natural variability—implications for ecosystem management. Pages 80–94 *in* M. E. Jensen and P. S. Bourgeron, technical coordinators. Ecosystem management: principles and applications, volume II. Eastside forest ecosystem health assessment. U.S. Forest Service, General Technical Report **PNW-GTR-318**, Pacific Northwest Research Station, Portland, Oregon, USA.

Swetnam, T. W. 1993. Fire history and climate change in giant sequoia groves. Science **262**:885–889.

Swetnam, T. W., and C. H. Baisan. 1996. Historical fire regime patterns in the southwestern United States since AD 1700. Pages 11–32 *in* C. D. Allen, technical editor. Fire effects in southwestern forests. U.S. Forest Service General Technical Report **RM-GTR-286**, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, USA.

Swetnam, T. W., C. D. Allen, and J. L. Betancourt. 1999. Applied historical ecology: using the past to manage for the future. Ecological Applications **9**:1189–1206.

Tausch, R. J., C. L. Nowak, and R. S. Nowak. 1995. Climate change and plant species responses over the Quaternary: implications for ecosystem management. Pages 14–19 *in* R. W. Tinus, technical coordinator. Interior west global change workshop. U.S. Forest Service General Technical Report **RM-GTR-262**, Fort Collins, Colorado, USA.

Turner, M. G., V. H. Dale, and E. H. Everham. 1997. Fires, hurricanes, and volcanoes: comparing large disturbances. BioScience **47**:758–768.

Vale, T. R. 1998. The myth of the humanized landscape: an example from Yosemite National Park. Natural Areas Journal **18**:231–236.

Wallin, D. O., F. J. Swanson, B. Marks, J. H. Cissel, and J. Kertis. 1996. Comparison of managed and pre-settlement landscape dynamics in forests of the Pacific Northwest, USA. Forest Ecology and Management **85**:291–309.

White, P. S. 1979. Pattern, process, and natural disturbance in vegetation. Botanical Review **45**:229–297.

White, P. S., and J. Harrod. 1997. Disturbance and diversity in a landscape context. Pages 128–159 *in* J. A. Bissonette, editor. Wildlife and landscape ecology: effects of pattern and scale. Springer-Verlag, New York, New York, USA.

White, P. S., and J. L. Walker. 1997. Approximating nature's variation: selecting and using reference information in restoration ecology. Restoration Ecology **5**:338–349.

Wright, K. A., L. M. Chapman, and T. M. Jimerson. 1995. Using historic range of vegetation variability to develop desired conditions and model forest plan alternatives. Pages 258–266 *in* J. E. Thompson, compiler. Analysis in support of ecosystem management; Analysis Workshop III. U.S. Forest Service, Ecosystem Management Analysis Center, Washington, D.C., USA.

Wu, J. G., and O. L. Loucks. 1995. From balance of nature to hierarchical patch dynamics: a paradigm shift in ecology. Quarterly Review of Biology **70**:439–466.