DOI: 10.1007/s00267-004-0170-2

Toward a Scientifically Rigorous Basis for Developing Mapped Ecological Regions

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ABSTRACT / Despite the wide use of ecological regions in conservation and resource-management evaluations and assessments, a commonly accepted theoretical basis for ecological regionalization does not exist. This fact, along with the paucity of focus on ecological regionalization by professional associations, journals, and faculties, has inhibited the advancement of a broadly acceptable scientific basis for the development, use, and verification of ecological regions. The central contention of this article is that ecological regions should improve our understanding of geographic and ecological phenomena associated with biotic and abiotic processes occurring in individual regions and also of processes characteristic of interactions and dependencies among multiple regions. Research associated with any ecoregional framework should facilitate development of hypotheses about ecological phenomena and dominant landscape elements associated with these phenomena, how these phenomena are structured in space, and how they function in a hierarchy. Success in addressing the research recommendations outlined in this article cannot occur within an ad hoc, largely uncoordinated research environment. Successful implementation of this plan will require activities—coordination, funding, and education—that are both scientific and administrative in nature. Perhaps the most important element of an infrastructure to support the scientific work of ecoregionalization would be a national or international authority similar to the Water and Science Technology Board of the National Academy of Sciences.

Among the most influential scientific advances of the 20th century was the broad interest in and acceptance of the multiple dependencies between biological and physical phenomena and the ecosystems within which these phenomena occur, and the fact that these dependencies occur and can be recognized across a wide range of temporal and spatial scales. One of the most powerful symbols of this evolving understanding is the image of the Earth as viewed from space. Although the image is almost stark in its simplicity, it provides a compelling perspective on the interdependence between biophysical phenomena and environmental media that occur at multiple scales.

An important consequence of this evolving perspective has been that resource-management and protection efforts have become increasingly focused on ecosystems and ecosystem sustainability rather than on the individual resource components, with humans considered an integral part of this ensemble. This evolving conceptual understanding of the nature of resource-management challenges has been accompanied by an evolution in the tools used to support assessment, management, and research tasks, including the development and application of mapped ecological regions. These regions, which are distinct from maps of single or even multiple landscape characteristics, are defined with reference to scale-specific ecological processes and structures that give rise to distinctive spatial patterns.

Ecological region maps classify the landscape into spatial units with characteristic spatial patterns arising from biotic and abiotic processes. These regions are not, however, simply inert containers filled with biophysical attributes arranged in a distinctive spatial pattern; they are physical spaces with meaning and condition dynamically shaped by humans (Cheng and others 2003). Furthermore, these regions are not closed systems. Regional identity is shaped not only by the internal dynamics of the individual region, but also by exchanges of organisms, energy, and matter with adjoining regions that can be recognized at different scales (Bailey and others 1985, Omernik 1987, North

KEY WORDS: Ecological regions; Hypothesis testing; Research

Published online July 8, 2004.

American Ecosystem Working Group 1997, Graf 2001, O'Neill 2001).

Mapped ecological region frameworks have been used for descriptive (i.e., summarizing and presenting information about status, change, sustainability) and understanding-oriented (i.e., interpreting why a condition is the way it is) purposes. For example, the U.S. Forest Service National Hierarchical Framework has been used for legislatively mandated assessment and reporting about forest and watershed capabilities and biodiversity analysis (Keys and others 1995, McMahon and others 2001), while descriptive uses of the U.S. Environmental Protection Agency (USEPA) framework include determination of lake water-quality-management goals (Heiskary and Wilson, 1989) and poststratification and reporting of data developed as part of the USEPA Environmental Monitoring and Assessment Program (EMAP; Larsen and others, 1994). In Canada, ecological regions have been used over the last few decades as the basis of a series of national and provincial state-of-the-environment and state-of-human-activities reports (Wiken, 1997) and for many specialized status reports such as the state of terrestrial and marine wildlife habitats (Wildlife Habitat Canada, 2001) and the state of forests (Canadian Forest Service, 2000). This was done to improve the capabilities of monitoring systems to track changes in an ecological context and to understand why these changes are taking place (Wiken 1995, Wiken and others 1996). The results present a basis for selecting and analyzing indicators on conditions, stressors, and responses. The World Wildlife Fund supported the development of an ecological region classification to support efforts to conserve regions with important biological resources (Olson and others 2001). The Consultative Group on International Agricultural Research (CGIAR), a part of the United Nations Food and Agricultural Organization (FAO), has developed an ecoregional approach to international agricultural research for sustainable agricultural production (Gryseels and Kassam 1994).

Ecological regions have been used to stratify the natural variability of geographical and ecological phenomena in the investigation of ecological processes (Bailey 1996, McMahon and Cuffney 2000). This type of application relies on the assumption that individual ecological regions reflect biotic and abiotic conditions that are relatively homogeneous and distinct from conditions in adjoining regions. The use of regions to stratify the underlying variability in natural conditions may increase the likelihood of detecting and understanding an environmental response generated by human activities.

Despite the wide use of a number of ecological regional frameworks in conservation and resource-management evaluations and assessments, a commonly accepted and clearly articulated theoretical basis for ecoregionalization does not exist in North America. This fact, along with the paucity of focus on ecological regionalization by professional associations, journals, and faculties, has inhibited the advancement of a widely accepted, scientific basis for the development and verification of ecological regions (Bailey and others 1985, Wiken and Gauthier 1997).

The central contention of this article is that ecological regions should improve our understanding of geographical and ecological phenomena that are associated with individual regions and that arise from the interactions and dependencies among multiple regions. If ecological region frameworks are to be more than simply mapped boundaries circumscribing areas with similar biotic and abiotic features, the theoretical basis for ecological regions must be explored, articulated, and critically discussed. Improved ecological understanding must be based on forming and testing hypotheses about the structure and function of both ecological and geographical processes associated with ecological regions.

In this paper we present a plan for strengthening the theoretical basis for the development and use of mapped ecological region frameworks. The plan is organized to accomplish two major objectives. First, we present a conceptual framework intended to provide a systematic discussion of the identity and development of mapped ecological regions. Each of these topics is treated in a major subsection of the paper, with the presentation organized around a series of conceptual propositions that we hope will provide a useful starting point for future discussion and research about ecological regions. Second, the plan includes a synthesis and critical review of information about the state of the science of ecological regionalization. This synthesis draws on our conceptual framework, discussions at the Sioux Falls, SD ecoregionalization symposium (Loveland and McMahon, 2004), and other articles in this special issue of *Environmental Management* associated with the symposium. The major product of this synthesis is a set of research questions that suggest future scientific endeavors in the area of ecological regionalization.

The Identity of Ecological Regions

Most definitions of ecological regions refer to ecosystems as the basic components that are being grouped or classified. Although there is general agreement that ecological regions represent a mosaic of ecosystems that are relatively homogeneous compared to adjacent regions, there is no clear consensus on a conceptual basis for recognizing and understanding the identity of ecological regions (Omernik 1995). A conceptual framework for understanding the identity of ecological regions should proceed from the assumption that the purpose of any geographic region is to improve the understanding of phenomena that show spatial and temporal correlation (Hart 1982). Ecological regions must not be construed as merely descriptive constructs for spatial patterns in one or more biophysical characteristics that are apparent at a particular scale. Levin (1992) suggests that once ecological patterns have been detected and described, the challenge is to discover the determinants of pattern and the mechanisms that generate and maintain ecosystem patterns. It is not unusual in a classification effort, such as ecological regionalization, for the development of a theory-based set of hypotheses that justify or explain the classification system to follow the application of a classification methodology (Sokal 1974). Although the act of defining or classifying a set of ecological regions does not necessarily have to be based on an a priori set of hypotheses or theories, ultimately, for both geographers and ecologists, a regional framework is likely to give rise to hypotheses about how a perceived region has occurred and how it is maintained. Testing hypotheses about large-scale ecological regions will be complicated. No widely agreed upon design for measuring ecological conditions in large-scale regions exists; existing data that might be used to test hypotheses often will come from descriptive surveys not designed to test hypotheses about large-scale areas (Olsen and Schreuder 1997).

We propose four sets of conceptual issues that provide a focus for research designed to improve the understanding of ecological region identity, including the boundaries and stability of ecosystems, the role of humans in defining ecological region identity, the role of pattern and scale in defining ecological regions, and the hierarchical nature of ecological regions. One or more propositions are presented for each issue; together these propositions define key elements of a conceptual framework for understanding ecological region identity. Specific research questions associated with these issues are presented in accompanying tables.

The Boundaries and Stability of Ecosystems

Most discussions of ecological region identity begin with the proposition that any region in an ecoregional framework is composed of an association of ecosystems that is distinct from the association of ecosystems in other regions; ecosystem associations are expressed in a characteristic spatial pattern across the region. O'Neill (2001), however, notes that E. P. Odum's classic definition of an ecosystem as a "natural unit that includes living and nonliving parts interacting to produce a stable system in which the exchange of materials between the living and nonliving parts follows circular paths ... ." has ambiguities related to the assumptions of spatial closure and system stability.

Proposition: Because the boundaries of ecosystems at all spatial and temporal scales are to some extent open, the exchange of energy, materials, and biota with adjoining ecosystems, including ecosystems in other regions, is a critical element in the identity of an ecological region at any scale. The identity of a region cannot be explained by an ecosystem concept that only considers dynamics occurring within the region's boundaries.

Although the ecosystem concept assumes that the interactions and feedback loops needed to explain ecosystem dynamics occur within the boundaries of an ecosystem (O'Neill 2001), the behavior and processes of any individual ecosystem are, in fact, influenced by adjoining ecosystems of a similar spatial and temporal scale and by ecosystems that operate at different scales but with processes that intersect, in some way, with the individual ecosystem. Bailey (1996), for example, notes that ecosystems function as interdependent systems at a variety of scales. For example, a floodplain along a river segment composed of a mix of poorly and well-drained soils, a variety of flora and fauna, and areas with distinct local slope and solar aspect can be considered a local ecosystem. This local ecosystem, however, also functions in the context of a set of larger ecosystems, the variability of which, in time and space, shape the identity of the local floodplain ecosystem. The local floodplain may interact with a river that periodically floods, introducing the floodplain to a distinct set of physical, chemical, and biological conditions; local and frontal weather conditions; and the direct and indirect consequences of human activities.

Ecological boundaries may differ in their origin and maintenance, spatial structure, function, and temporal dynamics; these boundary concepts can be applied when comparing boundaries used in various ecological region systems and testing hypotheses related to regional identity (Strayer and others 2003). For example, directional imbalances in fluxes or disturbances across regional boundaries may lead to boundary shifts (Wiens and others 1985).

Proposition: Ecological region identity is tied to stability in the ecosystems that make up the region. Ecosystem stability, in turn, depends on both internal ecosystem processes, including spatial heterogeneity, and external environmental variability and the spatial extent of the ecosystems. The stability of ecosys-

tem response to small-scale disturbances depends on the system's ability to recover with resilience. The flexibility in ecosystem response that is necessary for long-term stability or sustainability depends on an environment that is heterogeneous in space and time (O'Neill 2001).

Omernik (1995) hypothesizes that ecological regions gain their identity through spatial differences in a combination of ecosystem characteristics expressed at a landscape scale. Ecological region identity, in this hypothesis, is dependent on some degree of ecosystem stability and predictability. Furthermore, although it is assumed that the complex of ecosystem components within an ecological region are homogeneous enough to be distinct from the complex of ecosystem components in adjoining regions, it also is recognized that the spatial association of ecosystems give rise to distinct spatial patterns that arise from a mosaic of heterogeneity and not homogeneity.

O'Neill (2001) claims that heterogeneity within an ecosystem or even within a larger spatial context, such as an ecological region, is necessary to maintain the full range of populations needed to maintain ecosystem stability. Without heterogeneity, for example, pioneer species are not maintained, and recovery from disturbance is either impossible or highly unpredictable. Conversely, a homogeneous ecosystem cannot respond to change and disturbance and is inherently unstable.

If ecosystem stability and ecological region identity are a function of ecosystem heterogeneity, they also are influenced by the scale of disturbances to an ecosystem or set of ecosystems. For example, a disturbance to an ecosystem component extending over a large spatial area, such as global climate change (long temporal scale) or a frontal storm system (small area, short temporal scale), can have a large effect on local ecosystems. As O'Neill (2001) suggests, even frequent disturbances that are smaller in spatial scale than the defined ecosystem boundaries can be counteracted by internal feedback mechanisms that aid the system in returning to stability. Ecosystems also can recover from disturbances that are larger than the ecosystem's boundaries by relying on processes, such as dispersal, which are not ordinarily considered part of internal ecosystem processes. Because ecosystem stability depends on the spatial extent of disturbances, the stability of ecosystems (and, perhaps, ecological region identity) is linked to ecosystem size. Large-scale disturbances increase the likelihood that a return to stability will depend on processes external to the ecosystem.

Humans and Ecological Region Identity

Proposition: Humans are an integral part of the ecosystems that define an ecological region, shaping the identity of ecological regions by their choices and actions and the meanings they give to regions. The identity of an ecological region is determined by socially constructed meanings of a region as much as by its biophysical attributes (Cheng and others, 2003).

From a biophysical perspective, humans affect the stability of ecosystems and the identity of ecological regions by fragmenting the spatial structure of the landscape, changing the physical and chemical conditions within which ecological systems operate, creating dispersal barriers and pathways, and changing the frequency distribution of disturbances (O'Neill 2001). From the perspective of human geography, a region's identity depends not only on these biophysical dynamics but on a convergence of social and political processes and social and cultural meanings (Cheng and others 2003). That is, we recognize distinct regions not only by using biophysical indicators we can see in the landscape but also by using other cues—associations, memories, expectations, stereotypes—that are part of the socially conditioned meaning of regions (Taylor and Garcia-Barrios 1995, Turner and Taylor 2003). Just the mention of a regional name—Ozarks, Great Plains, New South, Rust Belt, "Left Coast"—can evoke expectations about the physical appearance of the landscape, resource availability and use patterns, and quality of the environment. These socially constructed meanings can motivate powerful reactions to proposed policies and actions directed at a region. Such proposals and reactions, in turn, can ultimately influence the types of disturbances that occur in ecosystems within the regions and the identities of the regions themselves. For example, people who have never visited the Coastal Plain of the Artic National Wildlife Refuge or old-growth forests of the Pacific Northwest or the site of the World Trade Center in New York can nevertheless have deeply held, culturally conditioned feelings about the wisdom or appropriateness of proposed place-specific policies, thereby shaping the debate about actions that influence both the biophysical and cultural identity of these places and the regions in which they are located.

Pattern and Scale in Defining Ecological Regions

Proposition: The detection of pattern, or the ability to classify, is a function of the scale and variability of information about the component or phenomena to be classified. There is no single correct or proper scale for ecological regionalization.

Wiens (1989) notes in his review of scaling principles that scale is associated with both the extent and the grain of information. *Extent* and *grain* define the upper and lower limits of resolution (i.e., it is not possible to generalize beyond the extent nor can elements of pattern be detected below the grain). *Extent* is the overall area encompassed by a study. For example, in preparing a hydrologic landscape classification map for the State of North Carolina, it would be desirable to have maps of several factors that influence hydrology, such as soils, topography, vegetation, and climate, extending over the entire spatial domain of the State. *Grain* is the size of the individual units of observation. In the North Carolina example, grain refers to the resolution, or minimum mapping unit, of each of the component maps.

The scale of information determines the range of patterns and processes that can be detected. The patterns that emerge from a set of data will change as the scale of the data changes. Holding extent constant, an increase in the grain of measurement generally decreases spatial variance (Wiens 1989). As the grain of a soil map increases, for example, a greater proportion of the spatial heterogeneity of a system is contained within the grain, while between-grain heterogeneity decreases. By holding grain constant, an increase in extent will incorporate greater spatial heterogeneity as a greater variety of landscape elements are included in the area being studied. Between-grain variance increases as extent is increased.

Proposition: Whether or not a proposed region is of interest depends on the degree to which the pattern revealed by the available information at the selected scale addresses a question of interest. Ideally, the scale of information about ecological processes in a regional framework provides a degree of generalization and predictability that matches the level of detail needed by those using the framework.

At very fine scales, stochastic phenomena may dominate, and although statistical patterns may be described, they may be difficult to interpret in terms of broad-scale questions about biological processes (e.g., understanding regional patterns of diversity in a fish community). Somewhat less fine-scaled information may reveal useful information about biological or physical mechanisms or processes, but patterns of interest to managers may still be obscured in detail. In general, viewing ecosystem components at broader scales will reveal collections of components whose behavior is regular enough to allow generalizations to be made (Levin 1992). The loss of detail about process and heterogeneity within a group is compensated for by the gain of predictability. With larger and larger aggregations, higher statistical predictability is attained, although details of variation within an aggregate are lost (Levin 1992).

Wiens (1989) suggests that domains of scale may be associated with classifying particular phenomena. The domain defines a range of resolution in which a particular pattern (or within-group variation) becomes evident when information about various components associated with the phenomena is viewed (Boughton and others 1999). At scales above or below this domain, the pattern becomes unstable or disappears. For example, if the objective is classifying the potential for oak-hickory climax forests, component maps that may be used to classify and map this potential could include soils, climate, topography, solar aspect, and temperature. A domain of scale would exist for mapping regions with a high potential for oak-hickory climax forest if a consistent pattern associated with the objective emerged from maps of the components within a set range of land area only at a given scale range. Studies at a finer scale (e.g., focusing on a spatial domain ranging from 1 to 10 m^2) likely would omit important factors that control the emergence of an oak-hickory pattern, whereas studies restricted to broader scales (e.g., 10,000–100,000 km^2) would fail to reveal relevant finer-scale patterns because important variability characteristics of the pattern would be averaged out (Wiens 1989).

A Hierarchical Spatial Association of Ecosystems

Several important concepts related to recognizing spatial patterns in ecosystem composition, structure, and function are provided by landscape ecology (Forman and Godron 1986, Bryce and others 1999). McGarigal and Marks (1995) provide a framework for considering a hierarchical spatial association of ecosystems that can be used to understand important principles related to the identity of ecological regions. The most basic spatial unit in this framework is a *patch,* defined as a discrete area of relatively homogeneous ecosystem conditions. An analogous unit, the *site,* is found in Bailey's (1996) typology of spatial units, in which sites are relatively small areas where ecosystems have spatial associations and characteristic spatial structure. Sites have areas ranging from 1 to 10 km^2. Although it is possible that the perspective used to define a patch may be that of an individual organism, it is more likely that the perspective is provided by a broader set of ecological phenomena, such as community assemblages (e.g., fish or invertebrates) or even broader but probably less well-defined sets of phenomena (e.g., ecosystem health).

Proposition: The question of perspective is central to understanding the identity of a patch or, indeed, a spatial unit at any hierarchical level in an ecological framework. Patches are not self-evident; they are defined relative to a given interest or perspective. Patch boundaries are distinguished by discontinuities in environmental conditions from the surrounding areas that are large enough to be perceived or have an influence on the organism or ecological phenomena of interest (Bailey 2004).

A patch, at any scale, has an internal structure among its ecosystems reflecting heterogeneity at finer scales; that is, although it is viewed as homogeneous from a general vantage point, when viewed from a finer scale, a patch actually has internal variability in its component parts. The mosaic of patches at a given scale provide an internal structure for patches recognized at a broader scale. The smallest scale at which an organism or species (or whatever ensemble of components define the patch) perceives and responds to patch structure determines the grain of the patch. This is a level of resolution at which the patch size is small enough that finer differentiation will not matter. McGarigal and Marks (1995) provide an example that illustrates the relation between scale and perceived patch structure. What constitutes a single habitat patch for an eagle may constitute an entire mosaic of patches for a cardinal. Likewise, a single habitat patch for a cardinal (representing a level of landscape differentiation of no interest to the eagle) may represent a mosaic of habitat patches to a butterfly.

Proposition: Perspective is important in recognizing landscapes; there is no absolute size for a landscape. McGarigal and Marks (1995) *note that every landscape has a regional context into which it is embedded, regardless of scale or how the landscape is defined, and this broader context may influence the processes operating in patches within a landscape.*

At the next broader level in a spatial hierarchy of ecological region spatial units, McGarigal and Marks (1995) identify landscapes, which are areas containing a mosaic of patches. Citing Forman and Godron (1986), McGarigal and Marks define *landscapes* as heterogeneous land areas composed of patterns of interacting ecosystems that are repeated in similar form throughout. From an organism's standpoint, for example, a landscape includes an area between an organism's normal home range and its regional distribution. The area encompassing this range could vary widely, depending on the organism. Each scale will be important for a subset of species, and each species probably will respond to more than one scale. Bailey (1996) suggests that landscapes in an ecological region framework may contain areas ranging from 10 to 1,000 km^2. If a landscape is composed of several types of landscape elements (i.e., patches), then the *landscape matrix* is the most extensive and connected landscape element type and plays a dominant role in the functioning of the landscape (Forman and Godron 1986, McGarigal and Marks 1995). The designation of the matrix element depends on the phenomena that are of interest and the scale of investigation. At a fine scale, mature forest may be the matrix with patches of disturbed areas embedded. At a coarser scale, agricultural land may be the matrix with mature forest patches embedded.

Landscapes can be distinguished by how the component parts fit together. Landscape structure can be distinguished by both its composition (i.e., the presence and amount of each patch type (patch richness)) and its configuration (i.e., the physical distribution or placement of patches within the landscape (mean patch core area over the landscape)). Both of these characteristics of landscape structure can influence ecological processes and organisms, and a substantial number of quantitative metrics can be used to describe various aspects of landscape structure and pattern.

Finally, *ecological regions* are formed from a collection of landscapes. These regions, consisting of areas ranging from 1,000 to 100,000 km^2, are formed based on a characteristic repeated pattern in the component landscapes that reflects an association of ecological properties distinct from adjoining regions at the same scale. Although ecological regions are distinct from each other, they are not independent from each other. Barren-ground caribou are integral parts of arctic and northern forested ecological regions, depending on the season. Millions of waterfowl migrate from northern to southern ecological regions each year. Human activities and land uses in one region may greatly affect neighboring or distant regions through mechanisms such as the long-distance transport of airborne pollutants and climate changes that occur over relatively long spatial and temporal scales.

Research Questions Associated with the Identity of Ecological Regions

A number of potential research questions are presented associated with ecosystem boundaries and stability (Table 1), patterns and scale (Table 2), and hierarchical spatial associations of ecosystems (Table 3). A more complete list of research questions, including questions identified at the Sioux Falls Ecoregionalization Symposium (Loveland and McMahon 2004) can be viewed at We do not present a list of research questions associated with the role of humans in shaping the identity of ecological regions, because such suggestions are beyond the expertise of the authors. Because of the importance of humans in determining the identity of ecological regions, the authors would encourage experts from the disciplines of sociology, anthropology, history, and political science to help shape a more complete set of research questions related to understanding ecoregion identity. A substantial amount of social science literature is available for further study on the interaction of humans with the environment in ways pertinent to understanding the identity of ecological regions (e.g., Taylor and Garcia-Barrios 1995, Drummond and Marsden 1999, Barham 2001, Cheng

Table 1. Research questions related to the boundaries and stability of ecosystems

- Is the ability of an ecosystem to return to stable conditions after a disturbance inversely related to the spatial extent of the ecosystem?
- What are the ecosystem processes that are important in controlling the regional factors within and between distinctive regions, given general agreement on the delineation of distinctive regions?
- What are the key ecosystem properties of interest at a particular level (scale) of an ecoregion? What is the characteristic variability of processes at any level of the ecoregion? What ecological and geographic mechanisms and processes are responsible for the patterns observed in ecological regions at various scales?
- How can the development, validation, and use of ecological region maps be more closely driven by ecological theory, either associated with a narrowly conceived set of ecological processes or a more general set of ecological processes and responses?
- Does each region in a framework have a characteristic set of ecological processes that characterize interactions among the ecosystems in the region? If not, what defines the region's identity? When does such a set of ecological processes become an ecological region?
- How does heterogeneity of environmental conditions and ecosystem processes affect the definition of regional boundaries?
- How do the dynamics of exchanges of energy and matter influence the boundaries between ecological regions?
- How do the distinguishing ecological processes and factors that are characteristic of a region at a particular scale maintain a distinct regional identity while interacting with broader-scale processes (e.g., continental climate) that extend over adjoining regions?
- Because ecosystems exhibit dynamic behavior at all spatial and temporal scales, ecosystems can be thought of as nonequilibrium systems (Boughton and others, 1999). Are ecological regions inherently in a nonequilibrium state? At what temporal or spatial scale? What are the implications for predicting ecoregion conditions? Does ecosystem theory explain the stability of ecological regions?
- Should more research be devoted to developing a continuous measure of ecological potential or capability? How would such a spatially continuous index compare with a discrete index? For what purposes could a continuous representation be more suitable than a discrete one, and vice versa?

Table 2. Research questions related to patterns and scale in defining ecological regions

- Is there one "ideal" set of ecological regions at any scale and is each map (e.g., US Forest Service, USEPA) an attempt to capture that ideal? Or, is there no ideal ecoregion framework at a given scale so that any realization is driven by the perspective of the individual creating the map?
- The landscape consists of gradients of various types, some abrupt and some gradual. To what extent is it feasible to accommodate gradients in regionalization?
- What is the relation between the spatial pattern among ecosystems within a region and ecological processes related to the exchange of energy and matter? Is pattern or process generally more determinative of a region's identity?
- Are the patterns and processes of ecosystems characteristic of a region at one level or scale in a hierarchy assumed to occur at the next higher or lower level in the hierarchy? Are ecosystem processes creating patterns at one scale subsumed by distinct processes at different scales? What spatial and (or) ecological processes make a set of ecological regions hierarchical?
- Are there associations of geographic patterning and (or) ecological processes that are characteristic of regions at a particular scale? Is there a relation between these associations across scales, such that associations at one scale can be predicted from knowledge of associations at another scale?
- What scale of ecological region analysis can most effectively assist in predicting landscape change components associated with wildland fires or invasive species?

and others 2003, Turner and Taylor 2003). In general, research is required to better understand the historical relation between people, culture, and the environment and how these relations shape the biophysical characteristics and the cultural identity of ecological regions.

Methods for Defining Ecological Regions

Specialists (Omernik 1995, Bailey 1996, Wiken 1996a) in ecological regionalization have defined two fundamental questions that face those who map ecological regions: (1) what ecological phenomena are important in defining the identity of regions, and (2) how are the boundaries of the regions determined? The previous section of this paper discussed four key issues associated with the identity of ecological regions. In this section of the paper, we discuss important conceptual issues associated with the methods used to define regional boundaries.

Most of the common methods for developing maps of ecological regions rely primarily on combining re-

Table 3. Research questions related to hierarchical spatial associations of ecosystems

- What are the patches or basic units of analysis that underlie a system of ecological regions? From what perspective are these patches recognized? What is the basic ecological phenomenon or phenomena associated with a patch?
- Do different regions, defined at a particular scale, have different landscape matrices; that is, do different landscape elements and components that play a dominant role in the functioning of the landscape differ among or within regions?
- Is a large degree of variability in ecosystem associations at one level in a hierarchy a useful predictor for splitting the ecoregion at a more refined level within the hierarchy?
- The exchange of energy and matter may occur among different regions. Does this imply some sort of zone of influence that extends over multiple regions? Does such a zone imply a basis for defining a hierarchy?
- Does an ecoregion framework need to be hierarchical in a uniform way across the entire framework? That is, where all fine-scale units nest into intermediate-scale units, which nest, in turn, into general-scale units? Could some fine-scale units nest immediately into a general-scale unit, or into several general-scale units? What processes control this?

mote sensing analysis, field studies, and maps of factors (representing biological and physical conditions) that influence and control ecological processes, functions, and structures, either singly (e.g., soil drainage) or as an ensemble (e.g., potential natural vegetation). Two axes can be identified in a typology for understanding the methods used to define ecological regions. Along one axis are the methods for analyzing and combining the biophysical information into a map of ecological regions, which can be classified using either quantitative or qualitative approaches. Both approaches assume that analyzing the spatial association of multiple biological and physical factors that are thought to be associated with ecological phenomena will reveal patterns in the ecological phenomena of interest. Information about these factors may reside in maps, books, tabular data, or in the expertise of those doing the mapping. Neither the quantitative nor the qualitative methods for developing regions can be applied in a way that is independent of the perspective of the analyst. Thus, along a second axis is the perspective (especially related to spatial and temporal scale) associated with the questions that motivate development of a regional framework. Regardless of the method or perspective, regionalization efforts share the overall goal of revealing patterns in factors that characterize ecological regions at a particular scale. The resulting regional boundaries reflect hypotheses about the identity and location of the regions (Whittier and others 1988, Heiskary and Wilson 1989, Hughes 1995).

Classification and the Mapping of Ecological Regions

Proposition: Classification is a fundamental conceptual concern in defining the boundaries of ecological regions. Regional classifications can be monothetic (classes differ by at least one shared distinguishing characteristic) or polythetic (classes share a large proportion of properties but do not necessarily have any one property in common). Because a large number of characteristics typically are used in polythetic classifications, the resulting classification is more likely to be useful for cross-disciplinary questions.

Sokal (1974) has defined classification as the arrangement of components (i.e., the objects or phenomena being classified) into groups or sets on the basis of their relations. These groupings can be determined by very tangible characteristics that are clearly evident in physical space (e.g., the Rocky Mountains or the Great Plains) or by much more abstract concepts (e.g., eigenvector loadings associated with a multivariate ordination of factors thought to be associated with ecological processes). The components of each grouping in a classification have a characteristic pattern in their variability that somehow distinguishes the groups from each other. Whether classification is done statistically or by using an expert-judgement-based heuristic approach, the process is an attempt to maximize between group differences in a set of components being classified to facilitate understanding of complex information.

Sokal (1974) distinguishes between monothetic and polythetic classification approaches. Monothetic classifications are those in which the established classes differ by at least one property that is uniform among the members in each class. In ecological regionalization, an example of this type of classification would be a regionalization based on controlling factors. Bailey (1996) describes a hierarchical approach for classifying ecological regions. The partitioning of the landscape into spatial ecological units at any level of the hierarchy is based on the dominance of one particular environmental controlling factor, such as climate, physiography, or vegetation. Regions at each level in the hierarchy differ in terms of this controlling factor. Polythetic classifications, in contrast, are groups of objects that share a large proportion of their properties but do not necessarily agree in any one property. This approach is used in both qualitative and quantitative regionalization systems. Omernik (1995) and Wiken (1996b) note that ecological regions at any scale gain their identity through spatial differences in a combination of landscape characteristics, with the importance of these characteristics for regional identity varying not only among regions but from one place to another within a region. Hargrove and Luxmore (1998) have used quantitative multivariate approaches, including ordination and clustering, to define vegetation ecological regions in a 7.7-million-cell rendering (1-km resolution) of the continental United States. Quantitative and qualitative approaches are based on implicit or explicit multivariate analysis of the variance structure of a set of characteristics thought to be important in defining ecological regions; the resulting classes are inherently polythetic.

A corollary of polythetic classifications is that many properties (or characteristics) are required to classify or group objects (Sokal 1974). An ecological regional classification based on only a few characteristics (e.g., several soil and topography variables) is likely to be modified when additional information about other characteristics (e.g., climate and vegetation) is obtained. Classifications based on many properties are general, because variability in the spatial characteristics of individual variables is likely to be smoothed out when multiple variables are combined into a single mapped classification. Polythetic classification maps are integrated syntheses of information from numerous variables and are most useful in addressing questions that require an integrated analysis of data. The usefulness and versatility of a monothetic or polythetic classification depends on understanding the intended uses of the classifications. A classification based on a few properties may be optimal with respect to these characteristics but may be of little use for a broader set of tasks.

Quantitative and Qualitative Methods for Synthesizing Information into an Ecological Region Map

Proposition: Quantitative and qualitative methods of regionalization are conceptually more similar than sometimes acknowledged in ecological region literature; both are multivariate techniques that rely on analyses of the variance structure of multiple sources of information to identify patterns in the data for a location. The multiple lines of evidence used in both approaches to understand and define regional boundaries help to guard against the overriding influence of any one source map.

In a quantitative approach, patterns emerge from analyzing component data (e.g., digital soil, topography, climate, and geologic maps) largely without reference to any conceptual constraints about the size or connectedness of regions or about the relative importance of the various factors at any point in space. Those favoring a quantitative approach, which may rely on a geographic information system and multivariate techniques for assessing the relation between these multiple factors, argue that quantitative approaches define regions that are reproducible and objective. The use of numerical methods to define class limits enhances reproducibility of the lines that demarcate regions. Although the claim to objectivity rests in the direct lineage between the source maps and resulting regions, discretion may still have to be exercised in a quantitative approach in the choice of input factors, the application of quantitative clustering techniques, and in decisions about boundaries. Proponents of this approach argue that quantitative methods, including eigenanalyses and clustering techniques, can reveal associations among large and complex data sets that may not be evident in a qualitative approach (Zhou 1996, Hargrove and Hoffman 2004). There may or may not be an a priori theoretical construct and associated hypotheses to guide the choice of components used in the analysis. Regardless, ecological expertise must be used to interpret ecological regions produced by quantitative methods (Hargrove and Hoffman 2004) for the resulting regions to be used to test hypotheses about regional identity and what this identity means in terms of specific ecological phenomena.

A qualitative (or weight-of-evidence) approach to defining ecological regions also may be considered a type of multivariate analysis. The information contained in multiple maps is considered synoptically to uncover distinctive patterns in the multidimensional variations among these maps. As is the case with a quantitative effort, the scientific merit of a qualitative approach depends heavily on the knowledge, background, experience, and objectivity of the map compiler in the choice of input factors and knowledge about how these factors interact and are best synthesized (Hudson 1992). In a qualitative approach, expert judgement is assumed to be a valid technique for identifying patterns in multiple geographic phenomena, such as vegetation, climate, physiography, geology, and land use, that are associated with the spatial structure and functioning of ecological characteristics. If quantitative approaches are based on the application of numerically based multivariate data-analysis techniques to assess the variance structure and associated patterns in maps of multiple environmental factors, qualitative approaches depend on the application of expert-judgement-based heuristics, including the often vigorous exchange among those doing the mapping to assess the information contained in multiple maps and determine the rationale for the identity of a region (Omernik 2004).

Although sometimes termed subjective, qualitative approaches are not arbitrary. At least two general approaches to qualitative ecoregionalization can be identified. The environmental controlling system approach is based on the assumption that a single environmental factor associated with ecological processes acts as a primary control for regionalization at a given scale. The regions presented in Bailey (1996) are an example of this approach. An environmental synthesis approach, on the other hand, considers that ecological regions are the net result of the interplay of biophysical components, the importance of which can vary from one location to another; regional identity is tied to the functioning of an ensemble of related components. The regions presented by Omernik (1987, Omernik (1995) and Wiken and others (1996) are an example of this approach. As is the case with quantitative regions, an a priori theoretical construct (and associated hypotheses) may guide the choice of biological and physical factors considered in mapping ecological regions. Regardless, the identity of the resulting regions must be examined after the regionalization, not just to describe the primary distinguishing characteristics but to test the regions, based on clearly defined hypotheses about ecological processes, functions, and structures.

Perspective and Mapping Ecological Regions

Proposition: The identity of an individual region or set of regions is defined with reference to an individual or collective set of ecological phenomena and to the purposes and the perspective of the person doing the regional mapping. The choice of a method for mapping an ecological framework must be preceded by a statement of the purpose of the framework and the temporal and spatial scales of interest.

Ecological regions and their components—patches/sites, landscapes, landscape matrix—are not self-evident. Hierarchy theory suggests that ecosystems tend to self-organize based on the spatial and temporal scales of observation; that is, once an observer selects the temporal and spatial scales, it is possible to detect patterns in the spatial and temporal characteristics of ecosystems (Boughton and others 1999). As noted earlier, broad-scale patterns (and understanding) of ecological characteristics are relatively general; at finer scales, patterns reflect the variability of more detailed ecological mechanisms. Whether the pattern is noteworthy depends on whether recognition of the patterns allows a question of interest to be addressed more effectively.

A common initial perspective for mapping qualitative ecological regions originates in interest in defining relatively few regions that cover a large area, where any region has relatively similar broad-scale ecological characteristics compared with adjoining regions (e.g., domains and divisions (Bailey 1996); Level I ecological regions (Omernik 1987)). The development of regions with broad spatial and temporal resolution is driven by questions that evolve from an interest in general-scale understanding of ecological characteristics. For Omernik (1987, 1995), the overall question of interest underlying ecological-region mapping efforts is to identify areas in which coincident patterns of natural and human geographic features contained in maps and human expert judgement can define regions where the aggregate of biotic, abiotic, terrestrial, and aquatic characteristics are similar. In Omernik's conceptual framework, broadly drawn (Level I and Level II) regions are based on small-scale maps of biotic and abiotic characteristics thought to exert a composite influence on ecological conditions. More finely scaled regions rely on finer scaled mapped and tabular data, as well as increasing reliance on the expert judgement of regional and local discipline experts. For Bailey (1996), the overall interest is understanding the environmental factors that exert dominant control of ecosystem processes at various scales and using these factors to partition the landscape into regions. The components that exert the most control determine the boundaries at the upper, more general levels of the classification; differentiating criteria at the upper (spatially and temporally broad-scaled) levels exert general control over ecological processes, whereas criteria at lower (finer spatial and temporal scales) exert more narrow and specific control.

The perspective for quantitative ecological region maps may appear arbitrary. In the United States, where a substantial number of relatively large-scale digital maps are available, it is relatively straightforward to create a regional map with the number of regions defined, a priori, by the user. Hargrove and Hoffman (2004) produced maps of as many as 5000 regions in the United States on the basis of 25 mapped environmental factors; at any level within this hierarchy (e.g., a map of 10 regions or a map of 1000 regions), the regions are distinguished by the variance structure of the multivariate data set. Wolock and others (2004) developed a quantitative regional map, with a number of regions designed to approximately match the number of regions in the USEPA Level II ecological region map, to allow for comparison between these frameworks.

Patterns in the variability of the ecological information at a particular scale may suggest boundaries, or groupings of ecosystems, that are not exactly coincident with the boundaries of regions defined to address questions at a different scale using information appropriate at the different scale. Because boundaries are scale dependent, regional boundaries at any scale may or may not nest exactly into a spatially coincident, larger (i.e., smaller-scaled) regional framework.

It should also be noted that a bottom-up, or data-driven, perspective also has been recognized as an approach for identifying ecological region patterns (McMahon and others 2001). Although a data-driven approach could conceivably be used at any scale, the detailed information needed to support process-level understanding of landscape characteristics typically may be available only for relatively small areas. The difficulty in building an ecologically oriented classification system from the bottom up, however, is that it is difficult to perceive the patterns intrinsic to ecological regions from the bottom up (Rowe and Sheard 1981). A floodplain, for example, is represented by a pattern of spatially associated characteristics that include topography, hydrology, vegetation, and aquatic and terrestrial flora and fauna. Classification from below will never arrive at the unit "floodplain" because it represents an illogical pattern of spatially associated components (Bailey 2004).

Complementary Use of Quantitative and Qualitative Methods

Proposition: Proponents of either a quantitative or qualitative ecoregionalization approach have clear ideas of the shortcomings of the alternative approach, yet Hargrove and Hoffman (2004) *and Omernik* (2004) *acknowledge the potentially complementary nature of quantitative and qualitative regionalization approaches. Complementary uses of these methods should be explored collaboratively by researchers with quantitative and qualitative expertise.*

Hargrove and Hoffman (2004) note that "while human experts may be able to rationally defend drawing a particular borderline, it may be difficult for them to describe or elucidate the method that they used to place it at that precise location. An inability to fully circumscribe the model being used means that drawing the last ecological region border does little to help with the placement of the next, particularly if the same human expert is not available." From a different perspective, Omernik (2004) suggests that "by relying completely on reductive [i.e. quantitative] methods, we are unable to gain an understanding of the true nature of ecological regions." Quantitative mapping methods, however, can objectively describe the variance structure of multiple mapped factors within a qualitatively defined region and supplement the understanding associated with qualitative regions defined by using expert judgement (Rowe and Sheard 1981). The degree to which the two methods complement each other is largely unexplored, however, due in part to a lack of familiarity and acceptance by practitioners of either approach with the conceptual basis and strengths of knowledge claims made by using the other approach. One potential research direction is to use quantitative, "reductionistic" ecosystem study approaches (Wiens and others 1985) to dissect regions (derived either quantitatively or qualitatively) into their constituent patterns and processes, in an effort to understand the structure and functions of ecosystems within a given ecological region and of boundary dynamics among regions. Reductionistic approaches could be useful in testing hypotheses related to ecological region frameworks as well as in identifying factors and processes to consider in developing future regional frameworks.

Data and Replicability

Proposition: An important challenge for those mapping ecological regions is to broaden the possibilities for the types of data used to reveal patterns. Because all knowledge about the patterns and functions of ecological systems cannot be reproduced in a map, reproducible approaches must be developed for using the expertise and judgment of scientists and nonscientists.

Most methods for mapping ecological regions rely on multiple maps and sources of information of components associated with an ecological characteristic of interest. It is assumed that these maps and information sources, used in conjunction with the expert judgment of those doing the mapping, reveal patterns that suggest the structure and functions of the ecological characteristics. New mapping approaches may use maps and information sources that use emerging technologies to indicate the dynamic nature, in space and time, of many of the processes that may be important in identifying the core identities and boundaries of regions. Examples may include maps that portray the dynamics of change in climate, as well as changes in other ecosystem components (e.g., human-induced land-cover change, hydrologic variability, agricultural productivity and nutrient use, cropping patterns), where changes are driven by socioeconomic factors but have very important consequences for ecosystem structure and function. At a finer scale, newer mapping technologies may allow the portrayal of a spatial gradient of ecosystem (and associations of ecosystems) functions, which may be particularly important at the boundaries of ecological regions.

Proposition: Procedures and decisions in the qualitative process, which are analogous to the clustering rules in a quantitative classification process, should be explicitly recorded and made available for critical scientific discussion.

The replicability of the ecological regions developed by any method represents a basic scientific threshold

Table 4. Research questions related to regionalization methods

- Are there comparative advantages in the regionalization methods related to: realizing particular purposes for ecological region maps; portraying regions of a particular scale; integrating information about both geographic patterning and ecological processes, functions, and structures; using certain types of data; replicating the mapping effort; and considering and representing uncertainty?
- Can quantitative methods be developed that effectively delineate process-related characteristics of ecoregion boundaries, including uncertainty and the existence of regional transition zones?
- Are there inherent differences in the capabilities of qualitative and quantitative methods to make use of information about the geographic patterning and ecological functions, structures, and processes that define a region's identity and boundaries? If so, do these differences provide an advantage relative to either the purposes or uses of ecoregion maps? If these differences do exist, can a complementary use be made of both methods that incorporates their relative strengths?
- What makes input data (e.g., mapped, tabular, etc.) suitable or unsuitable in mapping ecological regions at any scale? Can the requirements for these data be standardized?
- What happens when data for an area to be mapped is of variable quality, either in terms of spatial or temporal scales or in terms of information content?
- How much data are required to understand and represent spatial patterns, structures, and ecological processes?
- What does it mean to say that a qualitative regionalization approach is replicable? In particular, what are the standards that can be used to assess the scientific appropriateness of data, assumptions, judgments, and decisions used in the qualitative mapping effort?
- How effectively can statistical evaluations show similarities or differences among ecoregions based on statistical analysis of particular variables, such as temperature, soils, land cover, and nutrient concentrations, as opposed to status or response indices that integrate multiple ecosystem characteristics?

for the acceptability of a knowledge claim. The question is whether the resources used in the mapping effort could be used by an independent team of similarly qualified mappers to develop a similar map. Many scientists assume that quantitative mapping approaches have an advantage in this regard; that is, quantitative techniques can be more easily used to reproduce a regional map than expert-judgment, weight-of-evidence-based qualitative approaches. However, qualitative approaches may be no less replicable as long as the decision rules and other expertise brought to bear in a qualitative effort are well documented.

Research Questions Related to Methods for Defining Ecological Regions

A number of potential research questions are presented associated with regionalization methods (Table 4). A more complete list of research questions can be viewed at

Conclusions

The importance of a theoretical basis for ecological regions has been long understood. Bailey (1987) notes that a conceptual understanding of the nature of ecosystems is a fundamental prerequisite for establishing ecological regions. Even if there is no theoretical basis for detecting and describing patterns and associations among ecosystems that are essential in identifying an ecological region, once regions have been defined, the determinants of ecosystem patterns and the mechanisms that maintain the patterns must be analyzed and understood (Levin 1992).

A self-evident principle in any plan to improve the scientific basis for developing and using ecological regions is that the scientific validity of ecological regions depends on testing claims or hypotheses about the identity of regions and about the suitability of methods for developing regions. In part, this requires adhering to common scientific practices of articulating methods and assumptions. It also requires posing and testing hypotheses about the structure and functions of geographic and ecological processes at a particular scale within the framework of existing and developing theories in the disciplines of geography and ecology. A theory-based understanding of a region's identity is a necessary condition not only for developing and testing hypotheses about the regional framework, but also for understanding the capabilities and limits of a framework for management and planning purposes.

Presentation of this science plan must acknowledge that successful implementation of this plan will require activities—coordination, funding, and education—that are administrative in nature, involve staff time, and may often require the participation of both scientists and nonscientists. Perhaps the most important element of an infrastructure to support the scientific work of ecoregionalization is a national or international authority (similar to the Water and Science Technology Board of the National Academy of Sciences) that could provide advice and guidance in implementing a national/international science plan for ecological regions. Such a board could support the effective collaboration of researchers operating in a variety of contexts—Federal, State, provincial, local government, universities, and nongovernmental organizations—in the completion of tasks, including the development, use, monitoring, hypothesis testing, and verification and evaluation of regional frameworks. This support could include the development of a business plan outlining funding requirements and the development of a comprehensive funding rationale. Such a board could help ensure the development and adherence to a set of standards or principles that guide ecological region mapping, regardless of mapping methodology. Support could also include development of a communications plan directed to the general public and decisionmakers providing information about important ecological region concepts, geospatial and ecological processes, current applications, and the potential uses of ecological regions. Finally, such a board could have an advantageous position to help focus a well-defined research agenda linked to other important issues, such as ecosystem management, sustainable resources, and biodiversity conservation.

For the past two decades, the use of ecological regions as a basis for describing the status and trends of natural resources has been well established. The widespread use of some type of ecologically based regional framework by governmental and nongovernmental planning and management agencies in North America indicates the appeal and practical usefulness of a concept promoted by researchers in the United States (particularly Robert Bailey and James Omernik) and Canada (particularly Ed Wiken). The authors of this science plan believé an increase in systematic, hypothesis-based research and critical discussions of the basis for and efficacy of a variety of methods for mapping ecological regions should represent the focus of the next generation of scientific effort related to ecological regions. An increased level of effort in this direction will improve our understanding of the fundamental geographical and ecological processes that underlie ecological regions and improve the management activities supported by these ecological frameworks.

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