Research Applications of Ecosystem Patterns

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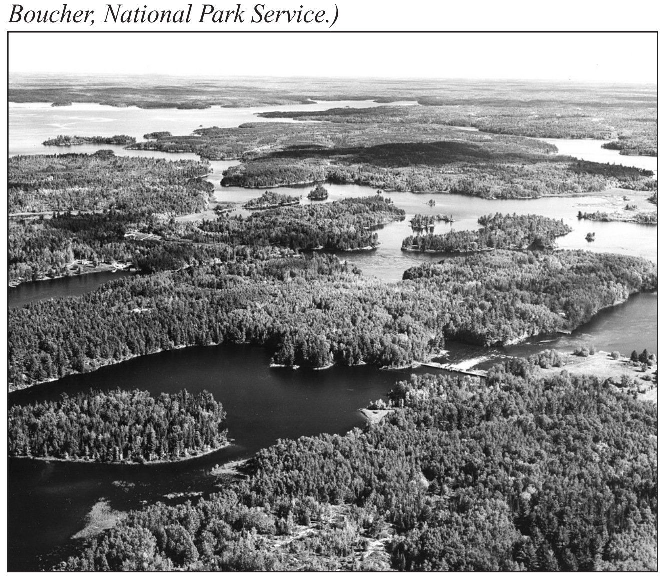
Abstract.—This article discusses the origins of natural ecosystem patterns from global to local scales. It describes how understanding these patterns can help scientists and managers in two ways. First, the local systems are shown within the context of larger systems. This perspective can be applied in assessing the connections between action at one scale and effect at another, the spatial transferability of models, and the links between terrestrial and aquatic systems. Second, scientists and managers can benefit because they gain information about the geographic patterns in ecosystems. Consequently, they are in a better position to design sampling networks, transfer knowledge, and analyze ecosystem diversity. The usefulness of multiscale analysis of ecosystem patterns suggests new scientific directions for research and points the way for restructuring the Forest Service, U.S. Department of Agriculture research programs.

Introduction

The public land-management agencies have been phasing in a new approach to land management. They are shifting from their focus on individual resources to a more holistic approach of managing *whole ecosystems*. This newer approach examines the vertical structure, which is how the ecosystem components (e.g., climate, biota, soil) are integrated at a site. The current reductionist, phenomena-based research is replaced by a *synthesis* approach (cf. Silbernagel 2005).

Ecosystems come in different scales that are nested within each other. The boundaries are open and permeable, leading to interaction, or linkages, between systems. These fluid boundaries can cause identification problems because ecosystems related by geography are not necessarily related by taxonomic properties (Bailey 1996). For example, an area of spruce forests and glacially scoured lakes in Voyageurs National Park, Minnesota constitutes a single system, linked by flows of water and nutrients through podzolized soils toward oligotropic lakes (fig. 1). These are not solely terrestrial or aquatic systems, but geographical ecosystem units. Because of these linkages, modification of one system affects surrounding systems, sometime adversely. Most research provides only data on the vertical structure of the components. There is, however, a need to consider horizontal structure, or connections between systems, because systems are linked to form larger systems. Altering larger systems may affect smaller ones. We must examine these relationships between systems of different scales to analyze the effects of management.

Figure 1.—*A landscape of spruce forests and glacially scoured lakes in Voyageurs National Park, MN.(Photograph by Jack Boucher, National Park Service.)*



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Scale of Patterns

Repeated relationships or patterns emerge at varying scales. For example, in the Boulder, CO area, the rocky, forested Front Range slopes of the Rocky Mountains that rise abruptly from the grassy plains are the most prevalent patterns in that region. In the mountains, trees that respond to additional moisture are seen on north-facing slopes. Numerous rocky outcrops appear on the nearby Great Plains grasslands, which act as reservoirs to support islands of trees and shrubs.

Causes of Ecosystem Pattern at Varying Scales

To delineate these patterns and to understand how and why they are distributed, we must understand the processes of how they form, which is important in understanding their dynamics and how they respond to management.[2] Although the ecosystem concept implies equality among all the components of the system, all the components are not equally significant. Climate largely determines ecosystem boundaries. As it changes, the other components change in response.

Controls over the climatic effect change with scale. At the macroscale, ecosystem patterns are controlled by the macroclimate (i.e., the climate that lies just beyond the local modifying irregularities of landform and vegetation). The effects of latitude, continental position, and elevation combine to form the world's ecoclimatic zones, also know as *ecoregions*.

On a mesoscale within the same macroclimate, we commonly find several broad-scale landform patterns that break up the zonal pattern. Hammond's (1954) landform classification (based on surface geometry) is useful in capturing this effect on zonal climate and provides a basis for further differentiation of ecosystems, known as *landscape mosaics*. The automatic classification of maco morphological landforms using geographic information systems (GIS) and digital elevation models has been investigated by Brabyn (1998). He applied a process developed by Dikau *et al*. (1991), which automates Hammond's manual procedure, to the South Island of New Zealand.

A landform unit consists of different ecosystem patterns depending upon the way it breaks up the zonal climate. For example, the Idaho Mountains and Yellowstone Plateau, Wyoming, are both highlands in a temperate steppe climate. The Idaho Mountains are made up of various site-specific ecosystems in a complex pattern, including riparian, forest, and grassland. Deep dissection of the mountain range has resulted in variously oriented slopes with varying local climates. Steep slopes oriented at different angles to the sun add complexity to the otherwise simple arrangement of elevational zones. The Yellowstone Plateau, however, does not have these spotty distribution patterns because its landform is relatively uniform.

At the microscale, local variation in topography will cause small-scale variations in the amount of solar radiation received, create topoclimates, and affect the amount of soil moisture. There are three classes of topoclimate: normal, hotter than normal, and colder than normal. Normal topoclimates occur on flat slopes. In the northern hemisphere, steep, south-facing slopes are hotter than normal, with north-facing slopes colder than normal. In differentiating local sites within topoclimates, soil moisture regimes have been found to be the feature that most significantly segregates plant communities. This feature is the edaphic (related to soil) factor. A common division of the soil moisture gradient is normal, drier, and wetter. Normal soil moisture regimes are found on well-drained uplands. The other regimes occur in topographic positions ranging from drier to wetter, from the top to the bottom of a slope, as well as in bottomlands where the water lies near the surface. These variations subsequently affect the biota, creating ecosystem *sites* as subdivisions of a larger zone (ecoregion). New remote sensing data and GIS analysis methods offer some promise to predicting the distribution of these sites (cf. Franklin 1998).

Ecosystem sites recur in predictable patterns within an ecoregion. The temperate continental zone of southern Ontario, Canada, which also extends south into the northeastern United States, provides a good example of the pattern of sites formed by edaphic-topoclimatic differentiation. On level or moderately rolling areas where the soil is well drained but moist, a maple-

[2] We do not necessarily need more data, which allows an understanding of pattern, because such data cannot generate an understanding of the processes that create these patterns.

beech community is the terminal succession, known as the climatic climax. Where the soil remains wetter or drier than normal, a somewhat different end community occurs. The climatic climax theoretically would occur over the entire ecoregion, but topography leads to different local climates, which partially determine edaphic conditions.

Disturbance and Succession

Disturbance and the subsequent development of vegetation are key contributors to pattern on the landscape at a variety of spatial and temporal scales. The composition of the vegetation of the ecosystem changes with time in a sequence from pioneer vegetation through successional series of intermediate steps to a relatively stable state called late successional vegetation. The late successional types are used to characterize ecosystems because they tend to be far more site specific than pioneer types, which might occur over a wider range of conditions. Furthermore, they are used as baselines for contending with the temporal variability associated with disturbance regimes and attending successional states of vegetation.

Applications

The study of ecosystem patterns has many applications, such as research and management. Ecosystem patterns must be analyzed at multiple levels: local (site) and groups of geographically related sites know as landscapes or ecoregions. This section describes how understanding these patterns can help scientists and managers in two ways.

Local Systems Within Context

First, local systems (sites) are seen within the context of the larger system.

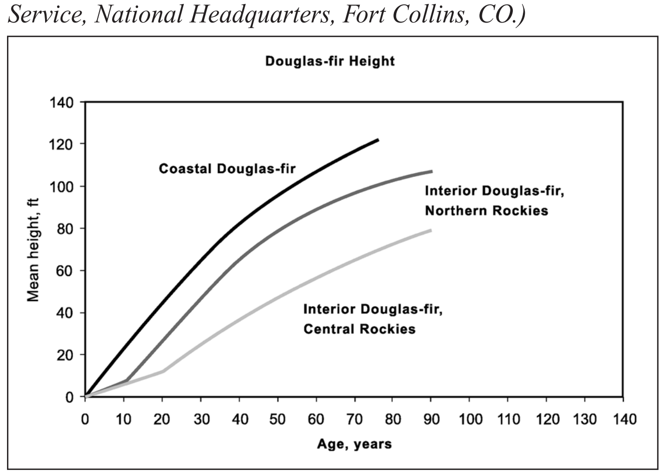
Connections Between Action at One Scale and Effect at Another. The perspective of seeing context can be applied in assessing the connections between action at one scale and effect at another. For example, logging on upper slopes of an ecological unit may affect downstream riparian and meadow habitats.

With the ecosystem approach, the interaction between sites can be understood. Processes emerge that are not evident at the site level. An example is a snow-forest landscape that includes dark conifers that cause snow to melt faster than either a wholly snow-covered or a wholly forested basin. Landscapes function differently as a whole than would have been predicted by analysis of the individual elements (cf. Marston 2006).

Spatial Transferability of Models. Predictive models differ between larger systems. The same type of forest growing in different ecoregions will occur in a different position in the landscape and have different productivity. For example, figure 2 shows that the height-age ratio of Douglas-fir (*Pseudotsuga mensiesii*) varies in different climatically defined ecoregions. The ecoregion determines which ratio to apply to predict forest yield. This is important, because if a planner selects the wrong ratio, yield predictions and the forest plans upon which they are based will be wrong. The ecoregion map is helpful in identifying the geographic extent over which results from site-specific studies (such as growth and yield models) can be reliably extended. Thus the map identifies areas for the spatial transferability of models.

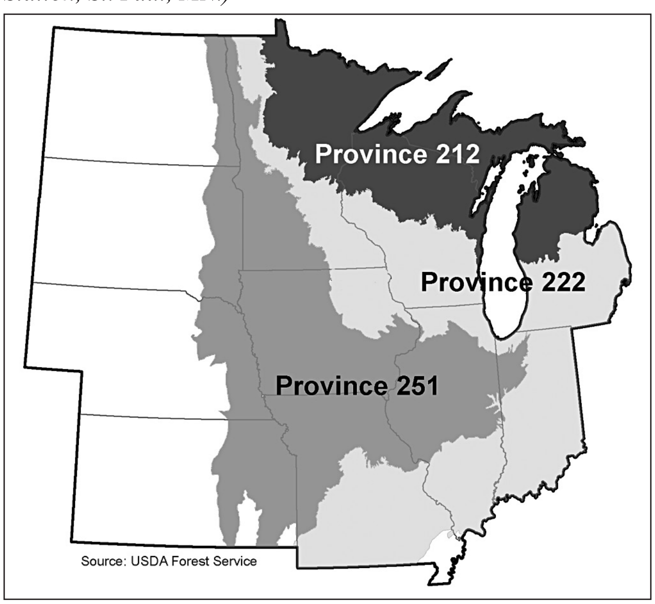
In Canada, studies have found that the height-diameter models of white spruce (*Picea glauca*) were different among different ecoregions (Huang *et al*. 2000). Incorrectly applying a height-diameter model fitted from one ecoregion to different ecoregions resulted in overestimation between 1 and 29 percent, or underestimation between 2 and 22 percent.

Figure 2.—*Height-age ratio of Douglas-fir varies in different climate-defined ecoregions. (Source: Chad Keyser, Forest Service, National Headquarters, Fort Collins, CO.)*



There is another, even more compelling, example. Each of five previous regional Forest Inventory and Analysis (FIA) programs has developed its own set of volume models, and the models have been calibrated for regions defined by political boundaries corresponding to groups of States rather than ecological boundaries. Further, the regional models sometime bear little resemblance to each other. The same tree shifted a mile in various directions to move from southwest Ohio (previous Northeastern FIA) to southeast Indiana (previous North Central FIA) to northern Kentucky (Southern FIA) could have quite different model-based estimates of volume. Growth estimates are likely improved if growth models are calibrated by ecoregions rather than States or FIA regions.[3] Figure 3 shows the ecoregions within the former North Central FIA Region, which were used for the application of volume and biomass equations (Hansen 2002). Statistical analysis of additional FIA data could further test the value of this approach.

Figure 3.—*Ecoregion provinces for the North Central Forest Inventory and Analysis Region of the United States: 212 = Laurentian Mixed Forest; 222 = Eastern Broadleaf Forest (Continental); 251 = Prairie Parkland Parkland (Temperate). (Source: Ronald McRoberts, Forest Service, Northern Research Station, St. Paul, MN.)*



Links Between Terrestrial and Aquatic Systems. Streams are dependent on the terrestrial system in which they are embedded. They therefore have many characteristics in common, including biota. Delineating areas with similar climatic characteristics makes it possible to identify areas within watersheds with similar aquatic environments. A good example is the distribution of the northern hog sucker (*Hypentelium nigricans*) in the Ozark Uplands of Missouri, which covers several watersheds. This species of fish is widespread but not uniformly distributed throughout the Mississippi River basin. In Missouri, it is found almost exclusively in the Ozark Uplands ecoregion.

Geographic Patterns in Ecosystems

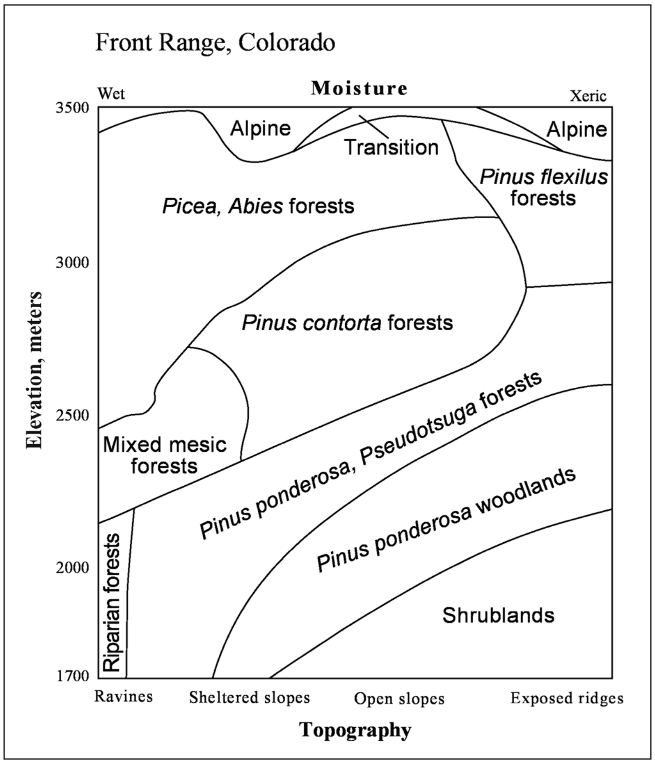
Second, multilevel analysis of ecosystems also provides information about the geographic patterns in ecosystems.

Design of Sampling Networks. Users are thus in a position to design efficient sampling networks. As we have seen, ecosystems recur in predictable patterns within an ecoregion. Data from representative sampled sites can be applied to analogous (unsampled) sites with a high degree of reliability (Bailey 1991). Identification of sites based on ecoregional classification could be used to impute their characteristics from sampled FIA sites, for example, using *k*-Nearest Neighbors or similar techniques (McRoberts *et al*. 2002).

Another example comes from the Rocky Mountains, a temperate steppe mountains ecoregion. This ecoregion, like all ecoregions, is a climatic region within which specific plant successions occur upon specific landform positions. The most likely successional series growing on a site within an ecoregion can be predicted from landform information if the vegetation-landform relationships are known in a particular ecoregion. For example, Douglas-fir forests occur on moist, mid-elevation sites within the Front Range of Colorado. Figure 4 shows the relationships between elevation-topography and climax plant communities. Understanding these relationships, vertically and horizontally, within ecoregion delineations allows the transfer of knowledge from research sites (or inventory plot) to

[3] See McRoberts (2005).

Figure 4.—*Relationships between elevation-topography and climax plant communities, Front Range, CO. (Source: Peet (1981) in Bailey (1996).)*



like sites within the same ecoregion. In fact, O'Brien (1996) found that surveys involving comprehensive sampling efforts will more accurately characterize unmonitored sites (plots) when samples are stratified according to ecologically similar areas such as ecoregions. Unfortunately, we often do not understand the spatial relationships between the FIA plots and the landform-vegetation types within a particular ecoregion. If these were developed, we could likely produce better small-area estimates of vegetation conditions.

Transfer Information. Ecoregions show areas that are analogous with respect to ecological conditions. This makes it possible to transfer knowledge gained from one part of a continent to another and from one continent for application in another; however, this approach should be used with caution. Because of compensating factors, the same forest type can occur in different ecoregion divisions. It has no regional alliance. For example, ponderosa pine (*Pinus ponderosa*) forest occurs in the northern Rockies and the southwest United States. This distribution does not imply that the climate, topography, soil, and fire regime are necessarily the same. The climate of Williams, AZ, for instance, is characterized by a late spring drought, whereas Colorado Springs is moist throughout the year.

This distinction is important because some ecoregions have a tendency for large wildfires; the ratio of large to small wildfires decreases from east to west (Malamud *et al*. 2005). Also, fire recurrence interval differs markedly between ecoregions with greater frequency in the West. This information suggests that the results of these studies can be used to assess burn probability across the nation to identify areas of high risk. Then government agencies could plan better for wildfire hazards. Ecoregions can also be used as a baseline from which to assess natural fire regimes, which can be used to abate the threat of fire exclusion and restore fire-adapted ecosystems.

Analyze Ecosystem Diversity. Maps of landscape mosaics reveal the relative diversity of ecosystems. For example, maps from the Coastal Plain landscape in North Carolina, which is flat and relatively undissected, show relatively few boundaries between landscape patterns. In contrast, maps from the Piedmont landscape display just the opposite character, reflecting greater ecosystem diversity.

Significance to Forest Service Research

It is important to link the ecosystem hierarchy with the Forest Service research hierarchy (table 1). In so doing, research structures and ecosystem hierarchies correlate such that research information, mapping levels, and research studies work well together. Comparison of research structures and ecosystem levels can identify gaps in the research network.

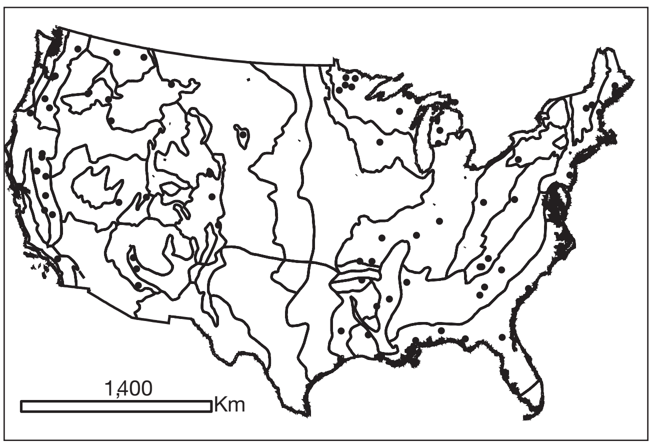
Table 1.—*Relationship between the ecosystem and research hierarchies.*

Ecosystem hierarchy*	Research hierarchy
Ecoregion	Research Station (multi-ecoregions)
Landscape mosaic	Experimental Forest/Range, Watershed
Site	FIA plot, LTER site, Research Natural Area

FIA = Forest Inventory and Analysis. LTER = Long Term Ecological Research.
**Source: Bailey (1988a)*

At the ecoregional scale, existing research locations can be compared with ecoregion maps to identify underrepresented regions or gaps in the network (fig. 5). For example, experimental forests or ranges occur in only 26 of 52 ecoregion provinces (Lugo *et al*. 2006). Several ecoregions have no research facilities while others have more than one. The greatest number (14) falls within the Laurentian mixed forest ecoregion of the Lake States and Northeast. A more comprehensive analysis could include other types of similar research sites, such as Long Term Ecological Research sites, Research Natural Areas, and the like. This analysis could reveal gaps in coverage both across and within ecoregions.

Figure 5.—*Approximate boundaries of ecoregion provinces within the conterminous United States and locations of experimental forests and ranges administrated by the Forest Service. (Source: Olga Ramos, Forest Service, International Institute of Tropical Forestry, San Juan, PR.)*



Restructuring Forest Service Research Programs

The many useful applications of the study of ecosystem patterns suggest new scientific directions for research and point the way for restructuring Forest Service research programs. To address critical ecological issues, it is essential to move from the traditional single-scale management and research on plots and stands to mosaics of ecosystems (landscapes and ecoregions), and from streams and lakes to integrated terrestrial-aquatic systems (i.e., geographical ecosystems). FIA thematic maps (e.g., biomass, forest types) could assist with this.

Some Research Questions

These studies reveal useful applications of ecosystem patterns. Many relevant research questions associated with these patterns still remain, including the following: What are the natural ecosystem patterns in a particular ecoregion? What are the effects of climatic variation on ecoregional patterns and boundaries? And, what are the relationships between vegetation and landform in different ecoregions? While some have suggested that GIS analysis can assist in answering these questions, that approach should be used with caution because it will help identify pattern, but it cannot generate an understanding of the processes that create these patterns (Bailey 1988b).

Natural Ecosystem Patterns

Historically, a high level of landscape heterogeneity was caused by natural disturbance and environmental gradients. Now, however, many forest landscapes appear to have been fragmented due to management activities such as timber harvesting and road construction. To understand the severity of this fragmentation, the nature and causes of the spatial patterns that would have existed in the absence of such activities should be considered. This analysis provides insight into forest conditions that can be attained and perpetuated (Knight and Reiners 2000).

Effects of Climatic Variation

Current climate exerts a very strong effect on ecosystem patterns, and climate change may cause shifts in those patterns (Neilson 1995). Anthropogenic and climatic change could yield ecoregions that are much different, or less useful, after many years; therefore, temporal variability is an important research issue. While several researchers are doing work on the effect of climate change on tree species distribution (cf. Iverson and Prasad 2001), others are working on the impact of climatic change on the geography of ecoregions. For example, Jerry Rehfeldt[4] has predicted the potential distribution of the American (Mojave-Sonoran) Desert ecoregion under the future climate scenario produced by the IS92a[5] scenario of the Global Climate Model, with about 5 °F warming and 50 percent increase in precipitation. He has produced maps that show a greatly

[4] Rehfeldt, J. 2005. Personal communication, retired, USDA Forest Service, Rocky Mountain Research Station, 1221 S. Main Street, Moscow, ID 83843.

[5] This is one of the emissions scenarios developed in 1992 under the sponsorship of the Intergovernmental Panel on Climate Change. IS92a has been widely adopted as a standard scenario for use in impact assessments.

expanding desert under this scenario. Despite the percentage increase in precipitation, the amount of rainfall fails to keep pace with the increase in temperature, so the climate becomes more arid.

There are limits to the number of monitoring sites that can be established for monitoring changes in the global environment. Obviously, sites should be representative. Stations also should be located where they can detect change. The boundaries between climate-controlled ecoregions are suitable for this purpose. FIA has roughly 160,000 forested sample sites. This criterion could identify a subset of these sites that could be more intensively sampled to provide needed monitoring information.

Relationships Between Vegetation and Landform

The relationships between vegetation and landform position changes from ecoregion to ecoregion, reflecting the effect of the macroclimate. A species occupies different positions in the landscape. For the same soil moisture condition but with different topoclimates, tree species change their positions in different regions (table 2). With these changes, related changes occur in the vigor of other tree species, ecosystem productivity, and so on. Knowledge of these differences is important for extending results of research and management experience, and for designing sampling networks. These relationships have been extensively studied in some regions (cf. Odom and McNab 2000) but, unfortunately, not in others. Where sufficient studies have been done, these relationships might be modeled and mapped to improve understanding of these ecosystems.

Table 2.—*Relationships between vegetation and landform in various ecoregions in Ontario, Canada. (From Burger (1976)).*

Ecoregion	Topoclimate		
	Hotter	Normal	Colder
1	P		
2	P		P
3	P		P
4	A	P	P
5	A		A,P
6	C		A,P
7			C,A

P = Picea glauca (white spruce); *A = Acer saccharum* (sugar maple); *C = Carya ovata* (shagbark hickory).

Relationship to Ecomap

The Forest Service Ecomap program (Cleland *et al*. 1997), which was initiated in 1993, follows the same ecosystem hierarchy presented here; however, it recognizes more levels but on the same principles. It has been adopted by the Forest Service as part of an ecological mapping system to support ecosystem management. Note that the finer scale delineations are not generally available beyond the boundaries of the national forests.

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Literature Cited

Bailey, R.G. 1988a. Ecogeographic analysis: a guide to the ecological divisions of land for resource management. Misc. Pub. 1465. Washington, DC: U.S. Department of Agriculture, Forest Service. 16 p.

Bailey, R.G. 1988b. Problems with using overlay mapping for planning and their implications for geographic information systems. Environmental Management 12: 11-17.

Bailey, R.G. 1991. Design of ecological networks for monitoring global change. Environmental Conservation. 18(2): 173-175.

Bailey, R.G. 1996. Ecosystem geography. New York: Springer. 216 p.

Brabyn, L. 1998. GIS analysis of macro landform. In: Proceedings, spatial information research centre's 10th colloquium. New Zealand: University of Otago: 35-48.

Burger, D. 1976. The concept of ecosystem region in site classification. In: Proceedings, international union of forest research organizations XVI world congress, division 1. Oslo, Norway: Norwegian Forest Research Institute: 213-218.

Cleland, D.T.; Avers, P.E.; McNab, W.H.; Jensen, M.E.; Bailey, R.G.; King, T.; Russell, W.E. 1997. National hierarchical framework of ecological units. In: Boyce, M.S.; Haney, A., eds. Ecosystem management. New Haven, CT: Yale University Press: 181-200.

Dikau, R.; Brabb, E.E.; Mark, R.M. 1991. Landform classification of New Mexico by computer. U.S. Geological Survey open-file rep. 91-634. Denver, CO: U.S. Geological Survey. 26 p.

Franklin, J. 1998. Predicting the distribution of shrub species in California chaparral and coastal sage communities from climate and terrain-derived variables. Journal of Vegetation Science. 9: 733-748.

Hammond, E.H. 1954. Small-scale continental landform maps. Annals Association of American Geographers. 44: 33-42.

Hansen, M. 2002. Volume and biomass estimation in FIA: national consistency vs. regional accuracy. In: McRoberts, R.E.; Reams, G.A.; Van Deusen, P.C.; Moser, J.W., eds. Proceedings, third annual forest inventory and analysis symposium. Gen. Tech. Rep. NC-230. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 109-120.

Huang, S.; Prince, C.; Titus, S.J. 2000. Development of ecoregion-based height-diameter models for white spruce in boreal forests. Forest Ecology and Management. 129: 125-141.

Iverson, L.R.; Prasad, A.M. 2001. Potential changes in tree species richness and forest community types following climate change. Ecosystems. 4: 186-199.

Knight, D.H.; Reiners, W.A. 2000. Natural patterns in southern Rocky Mountain landscapes and their relevance to forest management. In: Knight, D.H.; Smith, F.W.; Buskirk, S.W.; Romme, W.H.; Baker, W.L., eds. Forest fragmentation in the southern Rocky Mountains. Boulder, CO: University Press of Colorado: 15-30.

Lugo, A.E.; Brown, S.L.; Dodson, R.; Smith, T.S.; Shugart, H.H. 2006. Long-term research at the USDA Forest Service's experimental forests and ranges. Bioscience. 56(1): 39-48.

Malamud, B.D.; Millington, J.D.A.; Perry, G.W. 2005. Characterizing wildfire regimes in the United States. Proceedings of the National Academy of Sciences. 102: 4694-4699.

Marston, R.A. 2006. President's column. Ecoregions: a geographic advantage in studying environmental change. AAG Newsletter. 41(3): 3-4.

McRoberts, R. 2005. Personal communication, Mathematical Statistician. U.S. Department of Agriculture, Forest Service, North Central Experimental Station, 1992 Folwell Avenue, St. Paul, MN 55108.

McRoberts, R.E.; Nelson, M.D.; Wendt, D.G. 2002. Stratified estimation of forest area using satellite imagery, inventory data, and the *k*-nearest neighbors technique. Remote Sensing of Environment. 82: 457-468.

Neilson, R.P. 1995. A model for predicting continental-scale vegetation distribution and water balance. Ecological Applications. 5: 362-385.

O'Brien, R.A. 1996. Forest resources of northern Utah ecoregions. Res. Bull. INT-RB-87. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 43 p.

Odom R.H.; McNab, W.H. 2000. Using digital terrain modeling to predict ecological types in the Balsam Mountain of western North Carolina. Res. Note SRS-8. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 11 p.

Peet, R.K. 1988. Forests of the Rocky Mountains. In: Barbour, M.G.; Billings, W.D., eds. North American terrestrial vegetation. Cambridge, England: Cambridge University Press: 63-102.

Silbernagel, J. 2005. Bio-regional patterns and spatial narratives for integrative landscape research and design. In: Tress, B.; Tres, G.; Fry, G.; Opdam, P., eds. From landscape research to landscape planning: aspects of integration, education, and application. Wageningen UR Frontis Series. Vol. 12. Dordrecht, The Netherlands: Wageningen UR: 107-118.