FORUM

The Factor of Scale in Ecosystem Mapping

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ABSTRACT / Ecosystems come in many scales or relative sizes. The relationships between an ecosystem at one scale and ecosystems at smaller or larger scales must be examined in order to predict the effects of management prescriptions on resource outputs. A disturbance to an ecosystem may affect smaller component ecosystems, which are encompassed in larger systems that control the operation of the smaller systems. Environmental factors important in controlling ecosystem size change in nature with the scale of observation. This article reviews those environmental factors that are thought to be useful in recognizing and mapping ecosystems at various scales.

Ecological maps are playing an increasing role in forest land management and planning. Their purpose is to display units of land of various size that reflect differences in response to management and resource production capability. Although such maps are widely used, it is apparent that there is still considerable confusion about exactly what is being mapped and why. In the interest of improving understanding and communication, it is desirable to reexamine the basis for the units shown on these maps.

An ecological map shows an area divided into ecosystems—that is, areas within which there are associations of interacting biotic and abiotic features. How these features are associated or integrated can be shown at two general levels. One level shows the integration within the local area, and another shows how the local area is integrated and linked with other areas across the landscape to form larger systems. All of these areas are ecosystems; albeit at different scales or relative sizes. That the ecosystem concept can be applied at any level of spatial scale is suggested by the work of Goff and others (1971), Troll (1971), Isachenko (1973), Odum (1977), Miller (1978), Mil'kov (1979), Walter and Box (1976), Webster (1979), Forman and Godron (1981), and Bailey (1983), among others.

Two fundamental questions face all ecological land mappers: (a) What factors are of particular importance in the recognition of ecosystems? (b) How are the boundaries of different size systems to be determined? Discussions of certain aspects of these questions have been presented in a number of recent papers (Damman 1979, Wiken and Ironside 1977, Bailey and others 1978, Rowe 1980, Gersmehl 1981, Rowe and Sheard 1981, Barnes and others 1982, Lotspeich and Platts 1982, Delcourt and others 1983).

This article reviews environmental factors that are thought to be useful in recognizing and mapping ecosystems at various scales. Its objectives are to synthesize ideas about scale from the literature and provide conclusions based on that literature.

KEY WORDS: Ecosystem; Landscape ecology; Resource surveys; Mapping scale; Maps

This review is concerned with the delineation of natural ecosystems according to factors that control the distribution of systems rather than according to the results (for example, vegetation) that controlling factors produce. In this way ecosystem units can be recognized regardless of present land use or existing vegetation. These controlling factors are indicative of the potential natural vegetation, that is, the vegetation that would exist if nature were allowed to take her course, without human inference.

Scales of Terrestrial Systems

Scale implies a certain level of perceived detail. Suppose, for example, that an area of intermixed grassland and pine forest is examined carefully. At one scale, the grassland and the stand of pine are each spatially homogeneous and look uniform. Yet, linkages of energy and material exist between these systems. Having determined these linkages, we intellectually combine the locationally separate systems into a new entity of higher order and greater size. These larger systems represent patterns or associations of linked smaller ecosystems.

A scheme for recognizing linkages among ecosystems at three scales of perception has been proposed by Miller (1978). Rowe and Sheard (1981), while using different terminology, advanced a similar scheme (Table 1). The smallest, or local, ecosystems (microecosystems) are the homogeneous *sites* commonly recognized by foresters and range scientists. They are of the size of hectares.

Linked sites create a *landscape mosaic* (mesoecosystem) that, seen from above, looks like patchwork. A landscape mosaic is made up of spatially contiguous sites distinguished by material and energy exchange. They range in size from 10 km^2 to several thousand km^2.

A classic example of a landscape mosaic would be a

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Table 1. Levels of generalization in a spatial hierarchy of ecosystems.

Scheme: Miller (1978)	Scheme: Rowe and Sheard (1981)	Approximate size (km^2)	Map scale for analysis
Region	Macroecosystem	10^5	1:3M
Landscape mosaic	Mesoecosystem	10^3	1:250,000–1:1M
Ecosystem (site)	Microecosystem	10^0	1:10,000–1:80,000

mountain landscape. Between the component systems of a mountain range there is a lively exchange of materials: water and products of erosion move down the mountains; updrafts carry dust and pieces of organic matter upward, downdrafts carry them downward; animals can move from one system into the next; seeds are easily scattered by the wind or propagated by birds.

At broader scales, landscapes are connected to form larger units (macroecosystems). Mountains and plains are a case in point (Figure 1). For example, the lowland plains of the western United States as a mosaic contrasts with steep landscapes in adjacent mountain ranges. As water from the mountains flows to the valley, and as the mountains affect the climate of the valley through sheltering, two large-scale linkages are evident. Such linkages create real economic and ecologic units. This unit is called a *region*. Regions are in many scales (Bailey 1983). Like landscapes, they stand in contrast with one another, and also are connected through long-distance linkages. Finally, this progression reaches the scale of the planet.

Need for a Spatial Hierarchy

There are several reasons for recognizing ecosystems at various scales. Because of the linkages between systems, a modification of one system may affect the operation of surrounding systems. Furthermore, how a system will respond to management is partially determined by relationships with surrounding systems linked in terms of runoff, groundwater movement, microclimate influences, and sediment transport.

A disturbance to a large ecosystem may affect smaller component systems. For example, logging on upper slopes of an ecological unit may affect downslope smaller systems, such as streams or riparian habitats. The conversion of chaparral to grass also affects stream systems through increased debris production and discharge rates (Orme and Bailey 1971).

Since ecosystems are spatial systems, they are consistently inserted, or nested, into each other. Each level subsumes the environment of the system at the level below it, and therefore conditions or controls the behavior of the system at the level below it. At each level, new processes emerge that were not present or evident at the next level. As Odum (1977) noted, research results at any one level aid the study of the next higher level but never completely explain the phenomena occurring at that level, which itself must be studied to complete the picture.

The processes of a landscape mosaic are more than those of its separate ecosystems because it internalizes exchanges among component parts. For example, a snow-forest landscape includes dark pines that convert solar radiation into sensible heat that moves to the snow cover and melts it faster than would happen in either a wholly snow-covered or a wholly forested basin. The pines are the intermediaries that speed up the process and affect the timing of the water runoff. Watershed managers attempt to produce the same effects by strip-cutting extensive forests. Other examples are given by Miller (1978) and Mil'kov (1979).

Smaller systems are encompassed in larger systems which control the operation of the smaller system. A meadow embedded in a forest operates differently from a large expanse of grassland. The forest affects the microclimate and the plant cover of the meadow, sheltering the meadow from drying winds or from hail. Many bird species that nest in the forest feed in the meadow, and meadow rodents like to hibernate at the edge of the forest or in the interior.

At the zones of contact, or ecotones, between forest and meadow, the greatest concentration of animal life, mostly insects and birds, occurs at the edge of the forest. This accounts for the higher density of animal populations in a forest-meadow landscape than in a forest landscape or a grassland landscape (Odum 1971).

In summary, the relationships between an ecosystem at one scale and ecosystems at smaller or larger scales must be examined in order to predict the effects of management. Because management occurs at various levels from national to site-specific, one of the prerequisites for rational environmental management is to delin-

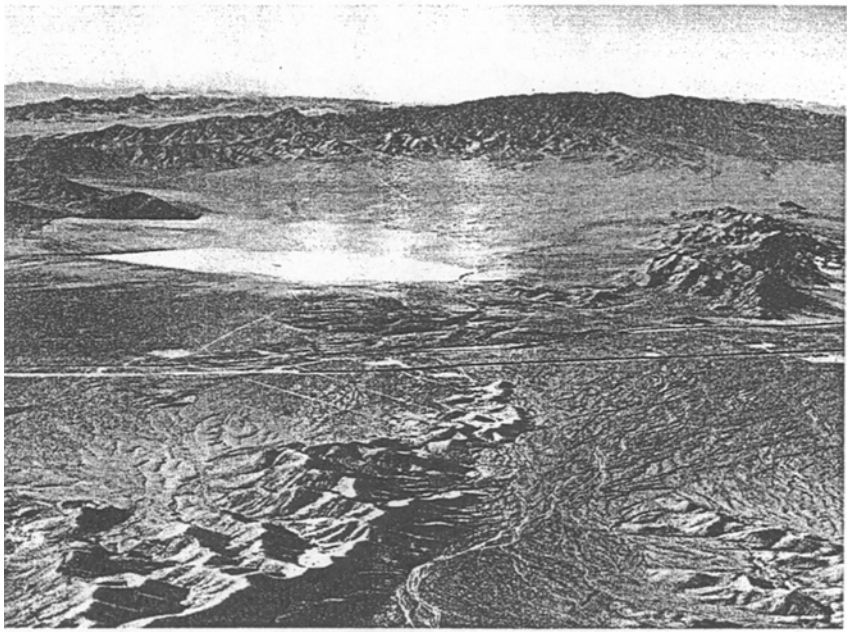

Figure 1. Ecosystems can be considered at various scales. In this view of the Mojave Desert of southern Nevada, the *macroscale* is represented by the mosaic of deeply eroded ranges and smooth basin floors. The *mesoscale* is represented by the two components of the mosaic—ranges or basins. The *microscale* is represented by individual slopes within the mountain ranges. Photograph by John S. Shelton.

eate ecosystems at a level and a scale and intensity appropriate to management levels. A hierarchical system is therefore needed which permits a choice of the degree of detail that suits the management objectives and proposed use.

Factors Controlling Ecosystem Size

The operation of ecosystems of all sizes is controlled by climatic regime, defined as the diurnal and seasonal fluxes of energy and moisture. Climatic regime, in turn, is channeled, shaped, and transformed by the structural characteristics of ecosystems, that is, by the nature of the earth's surface. In this sense, then, all ecosystems, macro and micro, are responding to climatic influences at different scales. The primary controls over the climatic effects change with the scale of observation. Latitude, continentality, mountains, major physiographic regions (for example, Canadian Shield), all control macroclimate or regional climate, while landforms, and local vegetation on them, control local climate.

How this works has been described by a number of authors. Among the best, Rowe and Sheard's (1981) explanation goes like this: Over large continental areas, macroclimatic units are reflective of those major ecosystems that biogeographers have traditionally recognized as biomes, life-zones, or formations. Examples are tundra, boreal forest, steppe, and desert. The boundaries of these large regions often are delineated by major physiographic discontinuities, where mountains meet plains or where igneous rocks change to sedimentary strata. The magnitude of the change is sufficient to impose a parallel marked change in the exchanges of energy and moisture at the surface (the climatic regime), hence, the kinds and patterns of dominant life forms of plants and animals change, as do the kinds of soils.

Rowe and Sheard (1981) argue that because of the magnitude of such changes, it is apparent that the boundaries of macroecosystems are ecological in the sense that they mark the transition from one major climatic regime to another. Though less well marked, the same is true for the smaller divisions within macroregions. Usually the control over climatic regime in meso- and microecosystems is strongly physiographic, exerted by the geology and topography. Hence, local ecosystems are best delineated by their basal landforms. Surface differences in shape, substrate, and moisture regime dictate that rain and solar energy will be received and processed in quite different ways by a field of sand dunes, a lacustrine plain, or an upland tract of hummocky moraine. Similarly, the much smaller microecosystem units based on topographic facets have their own local climatic regimes, indicated by the matching of particular soils and biotic communities to slope and aspects. Latitudinal position has a greater effect on solar energy received than physiography or substrate, and therefore the magnitude of the influences that physiography/substrate have on microecosystems also vary with latitude.

There are other terms for describing the relationship between ecosystem size and climate. Every feature with a distribution that broadly conforms to macroclimate is termed *zonal.* Macroclimate correlates with zonal vegetation and zonal soil types; local climates correlate with many of the variations from the zonal pattern. The term *azonal* is applied to these variations.

An Example of Application

An example of the application of different factors at various scales is the Canadian ecological land classification system (Wiken and Ironside 1977). In broad outline, the classification is based on the idea that the criteria for recognition can be quite different at each of the four scales of analysis. (While the nomenclature and number of levels outlined here are different from those listed in Table 1, the same kinds of factors are used at roughly the same levels in the hierarchies.)

A broad climatic uniformity distinguishes one large *land region* from others, whereas geologic homogeneity differentiates the smaller *land districts* within a land region.

The still smaller *land system* is a terrain unit that is unified by a common mode of exchange between distinctly different internal subdivisions. Thus, an area of spruce forests and glacially scoured lakes constitutes a single land system, linked internally by downhill flows of water and nutrients through coarse podzolized soils toward clear oligotrophic lakes. The land system corresponds rather closely to the concept of the soil catena, the repetitive mosaic of soil types across the landscape.

The smallest subdivision is the *land type,* an area with a uniform topographic setting as well as climatic, geologic, and potential biotic characteristics. The word "potential" is critical, because some Canadian authors allow a single land type to include different kinds of vegetation and animals as long as they represent different stages of biotic succession from weedy pioneers to "climax" forests or grassland. Others propose another level (provisionally called the *land phase*) to allow the classification to communicate the ages and species composition of existing vegetation rather than the presumed result of succession if given enough time.

Conclusions

From the ideas about scale presented in this review, the following conclusions seem warranted:

1) The landscape is conceived as ecosystems, large and small, nested within one another in a hierarchy of spatial sizes. Management objectives and proposed uses determine which sizes are judged important. The aim of useful land classification and mapping is to distinguish appropriately sized ecosystems, that is, land units that differ significantly from one another in respect to management and resource production capability.

2) The relationship between an ecosystem at one scale and ecosystems at smaller or larger scales must be examined in order to predict the effects of management prescriptions on resource outputs. A disturbance to an ecosystem affects smaller component systems. Smaller systems are encompassed in larger systems that control the operation of the smaller systems.

3) All natural ecosystems are recognized by differences in climatic regime. The basic assumption here is that climate, as a source of energy and moisture, acts as the primary control for the ecosystem. As this component changes, the other components change in response. The primary controls over the climatic effects change with scale. Major ecosystems are areas of essentially homogeneous macroclimate that biogeographers have traditionally recognized as biomes, life zones, or formations.

4) Landform is an important criterion for recognizing smaller divisions within macroecosystems. Landform (with its geologic substrate, its surface shape, and relief) modifies climatic regime at all scales within macroclimatic zones. It is the cause of the modification of macroclimate to local climate. Thus, landform provides the best means of identifying local ecosystems.

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Literature Cited

Bailey, R. G. 1983. Delineation of ecosystem regions. *Environmental Management* 7:365–373.

Bailey, R. G., R. D. Pfister, and J. A. Henderson. 1978. Nature of land and resource classification: a review. *Journal of Forestry* 76:650–655.

Barnes, B. V., K. S. Pregitzer, T. A. Spies, and V. H. Spooner. 1982. Ecological forest site classification. *Journal of Forestry* 80:493–498.

Damman, A. W. H. 1979. The role of vegetation analysis in land classification. *Forestry Chronicle* 55:175–182.

Delcourt, H. R., P. A. Delcourt, and T. Webb III. 1983. Dynamic plant ecology: the spectrum of vegetation change in space and time. *Quaternary Science Reviews* 1:153–175.

Forman, R. T. T., and M. Godron. 1981. Patches and structural components for a landscape ecology. *Bioscience* 31:733–740.

Gersmehl, P. J. 1981. Maps in landscape interpretation. *Cartographica* 18:79–115.

Goff, F. G., F. P. Baxter, and H. H. Shugart. 1971. Spatial hierarchy for ecological modeling. US-IBP Eastern Deciduous Forest report 71-41. Oak Ridge National Laboratory, Oak Ridge, TN. 12 pp. (mimeo).

Isachenko, A. G. 1973. Principles of landscape science and physical-geographic regionalization (English translation edited by J. S. Massey). Melbourne University Press, Carlton, Victoria, Australia. 311 pp.

Lotspeich, F. B., and W. S. Platts. 1982. An integrated land-aquatic classification system. *North American Journal of Fisheries Management* 2:138–149.

Mil'kov, F. N. 1979. The contrastivity principle in landscape geography. *Soviet Geography* 20:31–40.

Miller, D. H. 1978. The factor of scale: ecosystem, landscape mosaic, and region. Pages 63–88 *in* K. A. Hammond (ed.), Sourcebook on the environment. University of Chicago Press, Chicago.

Odum, E. P. 1971. Fundamentals of ecology, 3rd edn. W. B. Saunders, Philadelphia. 574 pp.

Odum, E. P. 1977. The emergence of ecology as a new integrative discipline. *Science* 195:1289–1293.

Orme, A. R., and R. G. Bailey. 1971. Vegetation and channel geometry in Monroe Canyon, southern California. *Yearbook of the Association Pacific Coast Geographers* 33:65–82.

Rowe, J. S. 1980. The common denominator of land classification in Canada: an ecological approach to mapping. *Forestry Chronicle* 56:19–20.

Rowe, J. S., and J. W. Sheard. 1981. Ecological land classification: a survey approach. *Environmental Management* 5:451–464.

Troll, C. 1971. Landscape ecology (geoecology) and biogeocenology—a terminology study. *Geoforum* 8:43–46.

Walter, H., and E. Box. 1976. Global classification of natural terrestrial ecosystems. *Vegetatio* 32:75–81.

Webster, J. S. 1979. Hierarchical organization of ecosystems. Pages 119–129 *in* E. Halfon (ed.), Theoretical systems ecology. Academic Press, New York.

Wiken, E. B., and G. Ironside. 1977. The development of ecological (biophysical) land classification in Canada. *Landscape Planning* 4:273–275.