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SUGGESTED HIERARCHY OF CRITERIA FOR MULTI-SCALE ECOSYSTEM MAPPING

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ABSTRACT

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Ecological units of different size suited to the kinds of questions being asked at different levels of management decisions need to be identified and mapped. A set of criteria for sub-dividing a landscape into ecosystems of different size is presented, based on differences in factors important in controlling ecosystem size at varying scales in a hierarchy.

INTRODUCTION

A fundamental consideration in evaluating the land's potential response to management and resource production capability is the nature of the land's biological and physical components and their combination (or integration) to form ecological units, also referred to as ecosystems, or land systems, among others. Ecosystem is used here.

Ecosystems come in different scales which are nested within each other in a hierarchy of spatial sizes (Allen and Starr, 1982). Because of linkages that exist between systems, modification of one system may affect the operation of surrounding systems. A disturbance to a larger system may affect smaller component systems. For example, logging in upper slopes of an ecological unit may affect downstream smaller systems such as stream and riparian habitats.

The relationship between systems at different scales must be examined in order to analyze the effects of management. Since management occurs at varying levels from national to site-specific, a hierarchical system of units, defined according to criteria that make them relevant to the kinds of questions being asked at different levels of management decisions, is needed. Ecosystem analysis is the subdivision of a landscape for this purpose.

The USDA Forest Service has recently issued an interim direction for ecosystem

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classification (USDA Forest Service, 1982). The classification has subsequently been described by Driscoll et al. (1984). However, a standard to be used for identifying and mapping the ecosystems to be classified is not specified.

In the absence of a uniform nation-wide standard, different sets of criteria have been used to partition the national forests in the United States into ecosystem units (also called capability areas on forest planning maps) of various size. Lack of uniformity creates two problems. First, it is difficult to compare experience and information between areas. Second, when data from different forests are aggregated for national assessments of productivity, it is difficult to interpret the results. These problems have led to interest in uniform methods.

This interest is not limited to the United States. Various government agencies and international organizations have discovered the value of, and the need for, ecosystem maps, and hence are sponsoring the mapping of large areas; even whole nations. The recently published FAO guidelines on *Land Evaluation for Forestry* (FAO, 1984) highlight the need for greater international standardization in ecosystem analysis to improve communication and understanding. The FAO guidelines, like the Forest Service classification, do not specify a method for identifying units for evaluation.

A universal system for ecosystem analysis will only develop if agreement is reached on concepts as to the nature of ecosystems, and on criteria which are important in setting the boundaries of different size systems. The purpose of this article is to review those factors which are thought to control ecosystem size so that we can reach a common understanding of their effects. Such an understanding will be likely to reveal the direction along which the formulation of appropriate criteria should proceed.

The basic concepts about scale and ecosystems are discussed in recent books on landscape ecology (such as Isachenko, 1973; Leser, 1976). A synthesis of these concepts has been presented elsewhere (Bailey, 1985). This article reviews the literature and draws conclusions based on that literature to suggest possible criteria to make the concepts operational through mapping.

SCALES OF ECOSYSTEM UNITS

Scale implies a certain level of perceived detail. Schemes for recognizing such scale levels have been proposed and implemented in a number of countries (e.g. Zonneveld, 1972). The nomenclature and number of levels in these schemes vary. One scheme, proposed by Miller (1978), recognizes linkages at three scales of perception. While not definitive, it illustrates the nature of these schemes. The smallest, or microscale, ecosystems are the homogeneous *sites* commonly recognized by foresters and range scientists. They can be delineated at scales ranging from 1:10K to 1:80K. At the mesoscale, linked sites create a *landscape mosaic* that looks like a patchwork. The mapping scale is 1:250K–1:1M. At macroscales, mosaics are connected to form larger systems. This unit with connected mosaics is called a *region*. The mapping scale is in order of 1:3M.

THE QUESTION OF BOUNDARY CRITERIA

The fundamental question facing all ecological land mappers is therefore, how are the boundaries of the different size systems to be determined?

One approach to this question is to analyze factors important in controlling ecosystem size at varying scales in a hierarchy. By this approach, we come naturally to climate. 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 and elevation, all control regional climate, while landforms and the local vegetation on them control local climate. The question of boundary criteria involves the understanding of these factors on a scale-related basis.

CONTROLLING FACTORS AND SCALE

A possible way to describe the factors which are thought to control eco-climatic units, and the scale at which they operate, is given below.

At the macroscale

At the macroscale, the ecosystem patterns are controlled by latitude (irregular solar energy), distance from the sea (continentality or oceanic influences), or elevation. These systems correspond with macroclimatic units, i.e. the climate that lies just beyond the local modifying irregularities of landform and vegetation, generally at the level of the broad climatic regions shown on the maps of Köppen (1931) Troll (1964) or Walter et al. (1975). Maps such as these outline eco-climatic *zones* within which major ecosystems might be expected to occur and which appear to be important to the climatologist and can be used to help determine ecosystem boundaries at the regional scale.

Each eco-climatic zone is clearly defined by a particular type of climatic regime and, with a few exceptions, the zones largely correspond to zonal soil types and climatic climax vegetation. These zones are reflective of those major ecosystems that biogeographers have traditionally recognized as biomes (Whittaker, 1975).

Highlands differ climatically from the climate of the zone from which they rise and must be considered separately. Two series of eco-climatic units can therefore be established: lowlands and highlands. Such highlands are termed *azonal.*

Since meteorological stations are too sparse in many areas, data are simply not available to map more precisely the distribution of these ecological climates. Thus, we generally substitute other distributions. The composition and distribution of vegetation was used by Köppen (1931) in his search for significant climatic boundaries, and vegetation is a major criterion in the ecosystem region maps of Bailey (1983) and Walter and Box (1976).

Climatic differences useful in recognizing units at this level can be reflected in the vegetation in several ways (Damman, 1979): (1) changes in forest stand structure, dominant life forms, and topography of organic deposits; (2) changes in dominant species and in the toposequence of plant communities; (3) displacement of plant communities, changes in the chronosequence of a habitat and minor changes in the species composition of comparable plant communities. Other differences are given by Küchler (1974) and van der Maarel (1976).

Traditionally, the principal source of such information has been vegetation mapping by ground survey. If large areas are to be surveyed, this approach is not very practical, and satellite remote-sensing data with a synoptic overview can be used to look for zones where vegetation cover is relatively uniform. These zones are especially apparent in low-resolution remote-sensing imagery (Gower et al., 1985; Tucker et al., 1985).

At the mesoscale

Macroclimate accounts for the largest share of systematic environmental variation on the macroscale or regional level. On the mesoscale, the broad patterns are broken up by geology and topography (landform). For example, solar energy will be received and processed differently by a field of sand dunes, lacrustrine plain or an upland hummocky moraine.

Landforms (with their geologic substrate, surface shape and relief) influence place-to-place variation in ecological factors such as water availability and exposure to radiant solar energy. Through varying height and degree of inclination of the ground surface, landforms interact with climate and directly influence hydrologic and soil-forming processes.

In short, the best correlate of vegetation and soil patterns at meso- and microscales is landform, because it controls the intensities of key factors important to plants and to the soils that develop with them (Hack and Goodlet, 1960). Realization of the importance of landform is apparent in a number of approaches to forest land classification (e.g. Barnes et al., 1982).

Landforms come in all scales and in a great array of shapes. On a continental level within the same macroclimate there commonly exist several broad-scale landform patterns that break up the zonal patterns. The landform classification of Hammond (1954), who classified land-surface forms in terms of existing surface geometry, is useful in determining the limits of various landscape mosaics.

According to its physiographic nature, a landform unit consists of a certain set of sites. A delta has differing types of ecosystems from those of a moraine landscape next to it. Within a landscape, the sites are arranged in a specific pattern. Units at this level can be most accurately delineated by considering the toposequence (Major, 1951), or catena of site types, throughout the unit.

At the microscale

Although the distribution of ecological zones is controlled by macroclimate and broad-scale landform patterns, local differences are controlled chiefly by microclimate and ground conditions, especially moisture availability. The latter is the edaphic (related to soil) factor.

Within a landform there exists slight differences in slope and aspect which modify the macroclimate to topoclimate (Thornthwaite, 1953). There are three classes of topoclimate: normal, hotter than normal and colder than normal. The units derived from these classes are referred to as *site classes* (Hills, 1952).

In differentiating local sites within topoclimates, soil moisture regimes have been found to be the feature which provides the most significant segregation of the plant communities. A common division of the soil moisture gradient is: very dry; dry; fresh; moist; wet.

Deviations from normal topoclimate and mesic soil moisture occur in various combinations within a region, and are referred to as *site types* (Hills, 1952). As a result, every regional system — regardless of size of rank — is characterized by the association of three types of local ecosystems or site types.

Zonal site types

These sites are characterized by normal topoclimate, and fresh and moist soil moisture.

Azonal site types

These sites are zonal in a neighboring zone but are confined to an extra-zonal environment in a given zone. For instance, in the northern hemisphere, south-facing slopes receive more solar radiation than north-facing slopes, and thus south-facing slopes tend to be warmer, drier, less thickly vegetated, and covered by thinner soils than north-facing slopes. In arid mountains, the south-facing slopes are commonly covered by grass, while steeper north-facing slopes are forested. Azonal sites are hotter, colder, wetter or drier than zonal sites.

Intrazonal site types

These sites occur in exceptional situations within a zone. They are presented by small areas with extreme types of soil and intrazonal vegetation. Vegetation is influenced to a greater extent by soil than by the climate, and thus the same vegetation forms may occur on similar soil in a number of zones. They are differentiated into four groups.

First, there are those which are *unbalanced chemically*. Some examples from the United States are the specialized plant stands on serpentine (magnesium-rich) soils in the California Coast Ranges. Other examples are the belts of grassland on the lime-rich black belts of Alabama, Mississippi and Texas, and the low, mat saltbush (*Atriplex corrugata*) on shale deserts of the Utah desert, which contrasts with the upright shrubs on adjacent sandy ground.

The kind and amount of dissolved matter in ground-water also affects plant distribution. This is especially obvious on coasts and along the edges of desert basins where the water is brackish or saline.

Second, *very wet* sites are where intrazonal plant distributions are controlled by the ground-water table. The plants of these sites are phreatophytes that send roots into the water table.

Third, *very dry* sites with sandy soils, because of limited moisture-holding capacity, are drier than the general climate. At the extreme, sand dunes fail to support any vegetation.

Fourth, there are *very shallow* sites. Soil depth, as a factor in plant distribution, may be controlled by depth to a water table or depth to bedrock. Vegetation growing along a stream or pond differs from that growing some distance away where the depth to the water table is greater. Examples of the influence of depth to bedrock on plant distribution can be seen in mountainous areas where bare rock surfaces that support only lichens are surrounded by distinctive flowering plants growing where thin soil overlaps the rock, and is, in turn, surrounded by forest where the soil deepens.

In summary, topography, even in areas of uniform macroclimate, leads to differences in local climates and soil conditions. The climatic climax would theoretically occur over the entire region but for topography leading to different local climates, which partially determine edaphic or soil conditions. On these areas, different edaphic climaxes occur; climatic climaxes occurring only on mesic soils.

The units at this scale correspond to units with similar soil particle size and mineralogical classes, and soil moisture and temperature regimes. These are generally the same differentiating criteria used to define families of soils in the System of Soil Taxonomy of the National Cooperative Soil Survey (USDA Soil Conservation Service, 1975).

The potential, or climax, vegetation of these units is the plant community with the rank of association, which is the basic unit of phytocenology. Associations (also called habitat types in the western United States by Pfister and Arno, 1980) are named after the dominant species of the overstory and of the understory.

CONCLUSIONS

All natural ecosystems are recognized by differences in climatic regime. The basic idea 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. Regional ecosystems are areas of essentially homogeneous macroclimate. Landform is an important criterion for recognizing smaller divisions within macroclimatic units. Landform modifies the 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. At the mesoscale, the landform and landform pattern form a natural ecological unit. At the microscale, such patterns can be divided topographically into slope and aspects units that are relatively consistent as to soil moisture regime, soil temperature regime and plant association, i.e. the homogeneous "site".

Therefore, the answer to the question of boundary criteria is that climate, as modified

TABLE I

Mapping criteria for ecosystem units at different scales, with examples

Scale	Name of unit	Criteria	Examples of units	
			Lowland series	Highland series
Macro	Region or zone	Eco-climatic zone (Köppen, 1931)	Temperate semi-arid (BSk)	Temperate semi-arid regime highlands (H)
	Landscape mosaic	Land-surface form class (Hammond, 1954)	Nearly flat plains (A1)	High mountains (D6)
	Site	Soil family/plant association	Fine, montmorillonitic frigid-typic soils w/ *Agropyron smithii/ Spartina pectinata* (western wheatgrass/ prairie cordgrass)	Fine, loamy, mixed typic soils w/ *Abies lasiocarpa/ Vaccinium scoparium* (subalpine fir/grouse whortleberry)

by landform, offers the logical basis for delineating ecosystems, both large and small.

Based on the foregoing review, criteria indicative of climatic changes of different magnitude are presented in Table I. They are offered as suggestions to guide the mapping of ecosystems of different sizes. In broad outline, the criteria for delineation are quite different at each of three scales of analysis. The results of this review are not meant to be definitive but rather an attempt to highlight criteria which appear to be important and which can be used to establish ecosystem boundaries.

With reference to the general principles involved in assigning prime importance at the different scale levels to different criteria, it should be noted that Rowe (1980) has raised the need for a caveat. Although the levels can be mapped by reference to single physical and biological features, they must always be checked to ensure that the boundaries have ecological significance. A climatic map showing such key factors as temperature and precipitation is not necessarily an ecological map until its boundaries are shown to correspond to significant biological boundaries. Likewise, maps of landform, vegetation and soils are not necessarily ecological maps until it has been shown that the types co-vary with one another. Before any map is used, it should be thoroughly tested and modified if necessary (Bailey, 1984).

It is important to link the ecosystem with management hierarchies. It is not suggested in the foregoing that three levels of ecological partitioning are everywhere desirable; there could be two or nine, depending on the kind of question being asked and the scale of the study. However, it is advantageous to have a basic framework consisting of a relatively few units to which all ecological land mappers can relate and between which other units can be defined as required.

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