ECOLOGY, IMPACT ASSESSMENT, AND ENVIRONMENTAL PLANNING

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A Wiley-Interscience Publication
JOHN WILEY & SONS
New York Chichester Brisbane Toronto Singapore

Library of Congress Cataloging in Publication Data:

Westman, Walter E., 1945–
Ecology, impact assessment, and environmental planning.
(Environmental science and technology, ISSN 0194-0287)

"A Wiley-Interscience publication."
Includes bibliographical references and index.
1. Ecology. 2. Environmental impact analysis. 3. Land use—Planning. I. Title. II. Series.

QH541.W43 1984 333.7 84-11867
ISBN 0-471-89621-7
ISBN 0-471-80895-4 (pbk.)

Printed in the United States of America

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LAND

A landscape segment is typically composed of patches that are discontinuous in some physical or biological sense. Topographic variation, for example, through its effect on air and water flow and sun angle, can induce differences in species composition and soil development at a continuum of scales of patchiness (Table 6.1). These landscape patches may be observed by using soil, vegetation, landform, or other attributes as indicators. Land planners and impact analysts have often used the distinguishing characteristics of a landscape to predict the effect of actions on landscape patches and ultimately, on the entire landscape.

Observation of a landscape at one point in time is much like observing a single frame of a movie. Processes of change become apparent only by observing the landscape periodically or by noting clues to the past that may be present (e.g., floodplain banks, tree growth rings, geological strata). Processes of landscape change occur in a continuum from high frequency or *continual* (e.g., surface soil, coastal erosion) to low frequency or *episodic* (e.g., flooding, earthquake, volcanic eruption, landslide, subsidence).

In this chapter we examine static attributes of landscapes which may be used both as indicators of landscape processes (dynamics) and of likely response to human action. For example, a soil type may indicate both vulnerability to the erosion process and suitability for agriculture development. We also consider how such landscape characteristic can be mapped, using field and remotely sensed data, computerized data storage and retrieval, and graphical presentation. Finally, we examine how the predicted landscape alterations from development proposals can be evaluated using economic, ecological, or aesthetic criteria.

LANDSCAPE CHARACTERISTICS AS INDICATORS OF LAND SUITABILITY AND VULNERABILITY

Vegetation, soil, landform, or combinations of these have been used as indicators of a larger suite of land characteristics in the different land evaluation systems in use around the world (see, e.g., Stewart 1968, McRae and Burnham 1981, McEntyre 1978, Whyte 1976). These initial pieces of land-

Table 6.1. Terms Associated with Increasing Spatial Scales of Analysis of Biological Components of the Landscape

Spatial Unit of Habitat	Order of Magnitude of Typical Spatial Scale	Unit of Biological Assemblage	Distinguishing Characteristics of Biological Unit
Microhabitat	1–10 m^2	Microcommunity	Distinct species composition
Ecosystem	10^2–10^5 m^2	Community	Significant interaction among component species; self-contained flow of energy and materials
Region to subcontinent	10^6+ m^2	Biome	Distinct vegetative physiognomy (external form, e.g., height of canopy, number of strata of vegetation)

scape information may be used in predicting a variety of landscape responses. Thus soil attributes may indicate vulnerability of the landscape to impact from septic tank leachate, using soil porosity and texture as indicators. Soil porosity and texture may also serve to indicate potential of the soil for growing a crop. When considering the development potential of the land, it is useful to distinguish between suitability (immediate potential of the current state of the land), capability (full potential after development) and feasibility (likely potential, considering socioeconomic and political constraints on development) (Belknap and Furtado 1967). Thus a patch of marshland is currently suitable as a wildlife habitat, is capable of being developed for a marina, and may only be feasible for modest development as a recreation area for fishing and bird watching. The vulnerability of a landscape to impact will depend on the nature of the disturbance, the initial resistance of its ecosystems to change, and the rate and manner of recovery of the ecosystems following disturbance (see Chapter 12).

We consider here how landscape attributes can serve as indicators of response to purposeful development or as indicators of vulnerability to inadvertent impact.

Soils

Soils have been widely used as indicators of agricultural capability. Soils are first classified into types based on physical and chemical features. The areal extent of each soil type is mapped (Figure 6.1) using field sampling and some clues (surface color, topography, vegetation) from aerial photographs. The correlation of soil type attributes with potential crop growth is then determined from local agronomic experience, and the soil types are classified into one of several agricultural capability classes. By concentrating on soil attributes relevant to support of built structures (e.g., compaction, drainage, frost heave, expansion potential), soils have also been classified for construction capability in more recent U.S. soil surveys (see, e.g., Golden et al. 1979, Table 9-5). Table 6.2 shows eight capability classes used by the U.S. Soil Conservation Service.

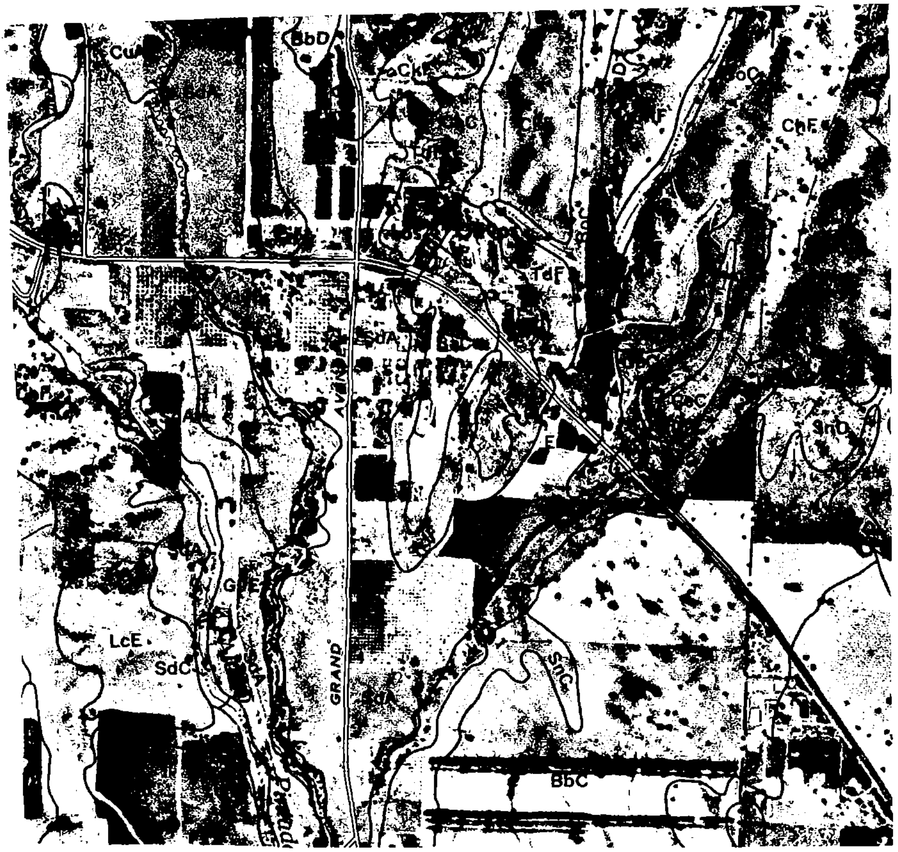

Figure 6.1. Section of a soil survey map overlain upon an aerial photograph, showing soil types in an area near Santa Barbara, California. From Sheet 88 of Shipman (1972).

Figure 6.1 shows soil types for particular portions of a Californian landscape as mapped by the U.S. Soil Conservation Service. Each soil type is classified into a capability classification in the accompanying soil survey document. For example, in Figure 6.1, soil type TdF in the lower middle of the photograph has been classified as capability unit VIIe. The accompanying soil survey document informs us that such soils are found on uplands and terrace escarpments, that they are somewhat excessively to moderately

Table 6.2. Soil Capability Classes for Agricultural Use According to the U.S. Soil Conservation Service

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Class I: Soils that have few limitations that restrict their use. Suitable for cultivation.
    Unit I-4: Deep, well-drained, nearly level, upland soils.
    Unit I-6: Nearly level, well-drained, silty soils on floodplains and low terraces.

Class II: Soils that have some limitations that reduce the choice of plants or require moderate conservation practices. Suitable for cultivation.
    Subclass IIe:[a] Nearly level to gently sloping soils, subject to erosion if tilled.
    Subclass IIw:[b] Moderately wet soils.

Class III: Soils that have severe limitations that reduce the choice of plants, require special conservation practices, or both. Suitable for cultivation.
    Subclass IIIw: Wet soils that require artificial drainage if tilled.
    Subclass IIIs:[c] Soils that are severely limited by stoniness.

Class IV: Soils that have very severe limitations that restrict the choice of plants, require very careful management, or both. Marginal soils.
    Subclass IVe: Soils severely limited by risk of erosion if tilled.
    Subclass IVw: Soils severely limited for use as cropland because of excess water.

Class V: Soils that have little or no erosion hazard but have other limitations that are impractical to remove and that limit their use largely to pasture, woodland, or wildlife food and cover. Level but wet.
    Subclass Vw: Soils limited in use to grazing or woodland because of poor internal drainage.

Class VI: Soils that have severe limitations that make them generally unsuitable for cultivation and limited by steepness, drought, or moisture. Suitable for grazing and forestry uses.

Class VII: Soils with very severe limitations that restrict their use to pasture or trees.
    Subclass VIIe: Hilly, steep, erosive.
    Subclass VIIs: Stony, rolling, steep, shallow to bedrock.

Class VIII: Soils with no agricultural use, mountains.

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[a] The letter "e" indicates the soil is erodible.
[b] The letter "w" indicates wet.
[c] The letter "s" indicates extreme stoniness.

well-drained sandy loams to silty clay loams, of 15–75% slopes, with 15–150 cm depth to bedrock, low to high fertility, moderate to very slow permeability, 3–20 cm of available water capacity, high to very high erosion potential and agricultural capability limited to controlled grazing.

The Canada Land Inventory uses a similar classification on a seven-point scale, primarily by combining classes VI and VII of the U.S. system. Soil surveys are available for many parts of the world primarily for regions with agricultural potential. Useful discussions of the land use capabilities and management problems associated with different soil types may be found in Foth and Schafer (1980) and Steila (1976).

Vegetation

Vegetation maps may record the current nature of the vegetation, indicating such features as dominant species, height of canopy, and extent of canopy closure as well as vegetation at various stages of succession and areas where the vegetation has been cleared. Alternatively, maps may present the *potential* vegetation of the area, that is, the climax vegetation likely to be present in the absence of human interference, given the climate, soil, and topography of the region (Figure 6.2). Potential-vegetation maps (see, e.g., Küchler 1964, USGS 1970) are necessarily more speculative and less accurate but do provide information on vegetation in relation to habitat which are useful as indicators of land capability. The U.S. Forest Service is in the process of developing a National Vegetation Classification system (see, e.g., Paysen et al. 1981, Driscoll et al. 1982), modeled after the proposed international system of vegetation classification (UNESCO 1973).

As with soils, vegetation may serve as an indicator for a wide range of landscape conditions and capabilities. The U.S. Forest Service, for example, uses native vegetation types, or vegetation and soils, as indicators of the potential for growth of commercial timber in plantations or by management (selective cutting) of uneven-aged natural stands (Figure 6.3).

A "site index" system for predicting forest growth capability based on the height of dominant and codominant trees of a specific age on a site is widely used by U.S. foresters and the Soil Conservation Service. Typically the site index is the height of trees at 50 years for shorter-lived species east of the Great Plains, 100 years for longer-lived species more common in the west (see Carmean 1975). For a description of other forest site quality indexes in use worldwide, see McRae and Burnham (1981, Ch. 8).

Ecosystems

A third tradition in land classification has been to use the combined information from various ecosystem components, such as soils, vegetation, land-

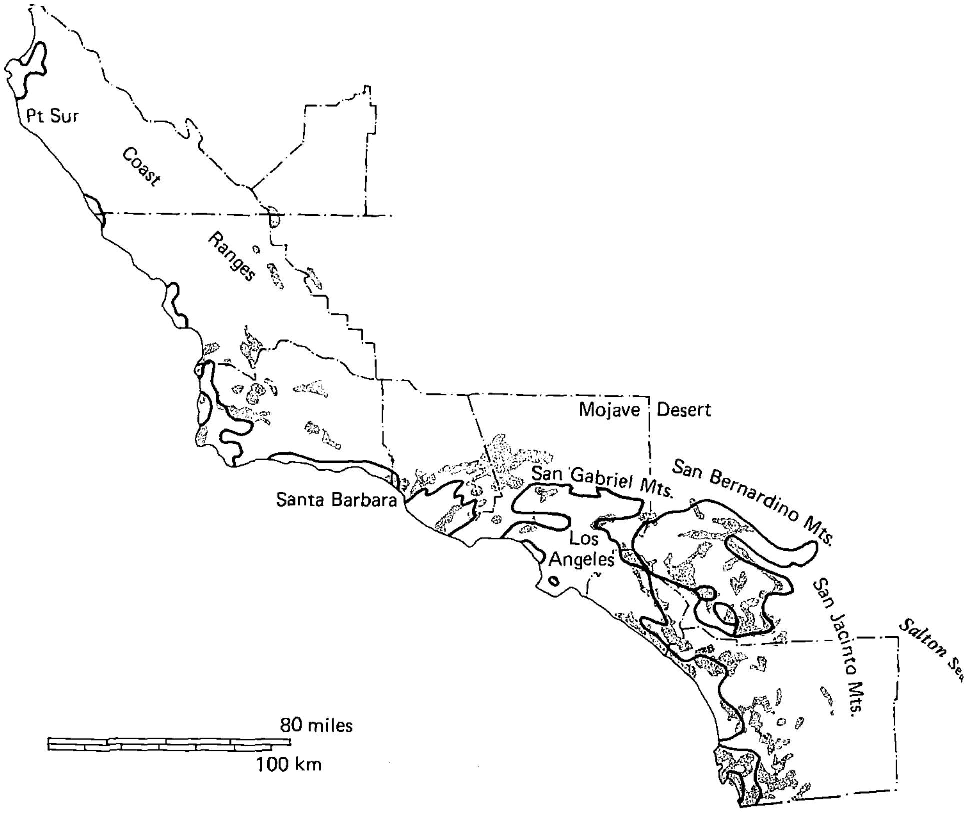


Figure 6.2. Differences between maps of existing and of potential vegetation. Shaded portions show areas of coastal sage scrub ("coastal sagebrush") mapped by the California Forest and Range Experiment Station (Wieslander 1945) from field observations in the 1930s and 1940s in southern California. The outlined areas show the regions potentially supporting coastal sage scrub as the climax vegetation type, as predicted by Küchler (1977).

form, and climate, to map ecological units. The rationale for this approach is that the ecological unit derives from a larger information base and should therefore be a more successful indicator of a range of land capabilities. A difficulty with the approach is that the natural boundaries for soil, vegetation, landform, and climatic differences do not always coincide. Some criteria must be used to establish boundaries. Since this involves judgment by the mapmaker, replication by other mapmakers is more difficult.

In Canada ecological land classification has been performed by a variety of federal provincial and university groups since the 1960s (Rubec 1979, Wiken 1980). The system uses a variety of biological and physical criteria for classification of land into units of increasing size (Table 6.3). Within a given climatic region, landform (including substrate) is often the major influence on vegetation and soil development. As a result at the level of an ecoregion it is possible to generalize about the relationship between soils, vegetation (defined physiognomically), and topography. The series of predictable soil changes with landform, given homogeneous climate and parent material, is called a *catena* and the corresponding vegetation, a *toposequence*. The catena concept has been used both in the Canadian system (e.g., Rowe and Sheard 1981) and the Australian land survey system (Christian and Stewart 1968). A catena and toposequence for the low subarctic ecoregion of the Lockhart River area of Canada is shown in Figure 6.4, and a map of ecoregions and districts for the Lockhart River area in Figure 6.5. At present, ecological land classification in Canada has not been linked with guides to land capability, though the potential is there.

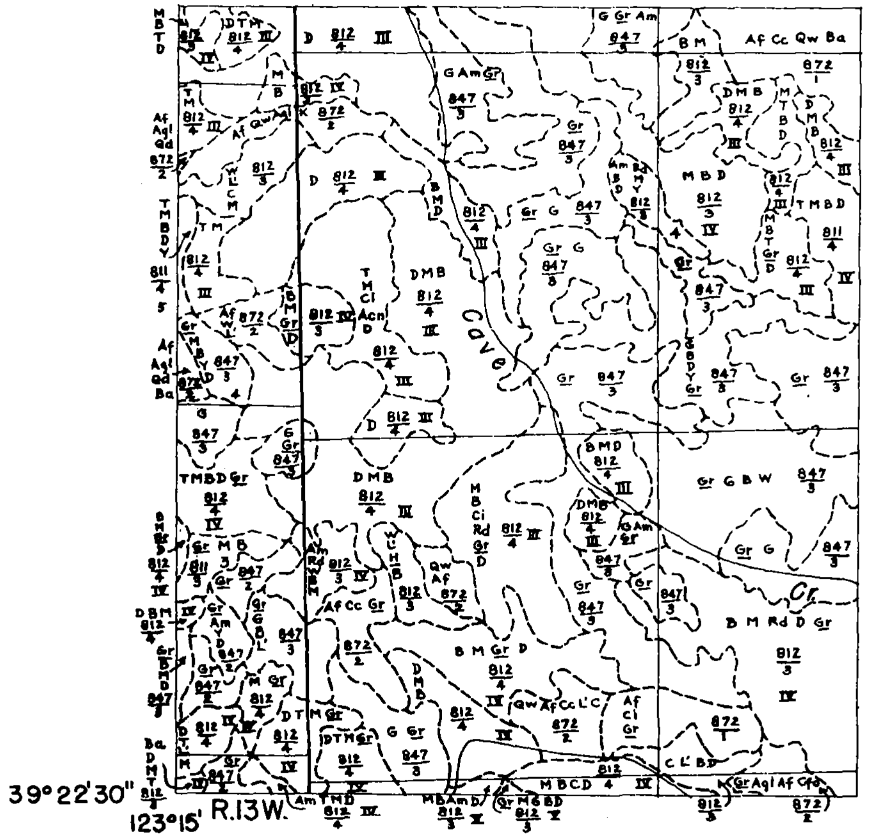


Figure 6.3. A section from a California vegetation-soil map, identifying native vegetation, soil types, and timber growth potential, produced by the U.S. Forest Service and state agencies (Cushman et al. 1948). Three sets of classification symbols are used. Letter groups, like Gr, AvCc, or RDTMCt symbolize names of dominant plant species and other land status elements. Numbers shown as fractions, e.g., 812/4, designate the soil series and average soil depth. Single numbers like 5 or IV rate the capability of the area for growing timber, based on vegetation and soil characteristics of the area.

Table 6.3. Levels of Ecological Generalization Proposed for Use in Ecological Land Classification by the Canada Committee on Ecological (Bio-physical) Land Classification

Level of Generalization Common map scale[a]	Common Benchmarks for Recognition					
	Geomorphology	Soils[c]	Vegetation[d]	Climate	Water[e]	Fauna
Ecoregion 1 : 3,000,000 to 1 : 1,000,000	Regional landforms or assemblages of regional landforms	Great groups or associations thereof	Plant regions or assemblages of plant regions	Meso or small scale macro	Water regime	High species diversity; may correspond either to a widely distributed species (e.g., deer mouse), or to the habitat of individuals within a species
Ecodistrict 1 : 500,000 to 1 : 125,000	Regional landform or assemblages thereof	Subgroups or associations thereof	Plant districts or assemblages of plant districts	Meso or large scale micro	Drainage pattern; water quality	
Ecosection 1 : 250,000 to 1 : 50,000	Assemblages of local landforms or a local landform	Family or associations thereof	Plant associations or a plant association	Large scale micro to small scale micro	River reaches, lakes and shoreland	Less diverse species complement; habitat requirements of typical species more restricted (e.g., beaver, otters); may coincide with specialized areas of animal total habitat (e.g., wintering area, calving grounds)
Ecosite[b] 1 : 50,000 to 1 : 10,000	A local landform or portion thereof	Soil series or an association of series	Plant association or seral stage	Small scale micro	Subdivision of above	
Ecoelement 1 : 10,000 to 1 : 2,500	Portion of or a local landform	Phases of soil series or a soil series	Parts of a plant assoc. or subassociation	Small scale micro	Sections of small streams	Low species diversity; habitat of smaller mammals, reptiles, and amphibians etc.; specialized areas of some fauna's habitat requirements (e.g., denning areas, local wintering deer yards)

Source: Reprinted, with permission, from Wiken (1980).

Note: Definitions for the levels of generalization.

Ecoprovince—an area of the earth's surface characterized by major structural or surface forms, faunal realms, vegetation, hydrological, soil, and climatic zones.

Ecoregion—a part of an ecoprovince characterized by distinctive ecological responses to climate as expressed by vegetation, soils, water, fauna, etc.

Ecodistrict—a part of an ecoregion characterized by a distinctive pattern of relief, geology, geomorphology, vegetation, soils, water, and fauna.

Ecosection—a part of an ecodistrict throughout which there is a recurring pattern of terrain, soils, vegetation, waterbodies, and fauna.

Ecosite—a part of an ecosection having a relatively uniform parent material, soil and hydrology, and a chronosequence of vegetation.

Ecoelement—a part of an ecosite displaying uniform soil, topographical, vegetative, and hydrological characteristics.

[a] Map scales should not be taken too restrictively, as they will vary with the environment setting and objectives of the survey.

[b] This level is frequently subdivided into phases according to the stage of plant succession.

[c] Canadian System of soil classification, Agriculture Canada, 1979.

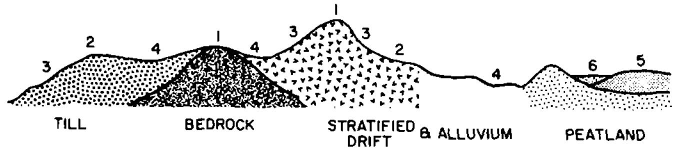
[d] These vegetative groupings are only suggested ones; agreement on a common system is yet to be achieved.

[e] See D. Welch, 1978. *Land/Water Classification*. ELC Series No. 5, Lands Directorate, Ottawa.

LOW SUBARCTIC

Landform-Soil-Vegetation Catenas

	Noncalcareous granitic sandy loam and loamy sand glacial till	Noncalcareous sand and gravel; ice contact and fluvial	Deep peat; medium to high ice content
Soil Assoc.	Porter Lake	Odin Lake	Dymond Lake
	1. Eluviated Dystric Brunisol lithic phase	1. Eluviated Dystric Brunisol	
	2. Eluviated Dystric Brunisol	2. Eluv. Dystric Brunisol	5. Fibric Organic Cryosol
	3. Eluviated Dystric Brunisol	3. Eluv. Dystric Brunisol	
	4. Gleyed Dystric Brunisol; Rego Gleysol, peaty phase	4. Gleyed Dystric Brunisol; Rego Gleysol, peaty phase	6. Mesic Organic Cryosol



Drainage Classes	Symbol	Vegetation
Excessively drained knolls	1	Rock Lichen & Rock-Lichen Woodland
Well-drained flats & convexities	2	Lichen Woodland and Heath-Lichen Woodland
Well-drained side slopes		
- south aspect	3	Shrub-Heath & Shrub-Heath Woodland
- north aspect		Moss-Lichen Woodland
Imperfectly drained		
- toe slopes	4	Moss Forest
- alluvium		Shrub-Herb Forest, Shrub Thicket
Poorly drained flats & concavities	5	Bog Woodland, Heath-Lichen Bog
Saturated lowlands		Sedge Fen, Shrub-Sedge Fen

Figure 6.4. The generalized relationships of soils, physiognomic vegetation types, and the topographic facets of typical landforms in the low subarctic region of the Lockhart River map area of Canada. Reprinted, with permission, from Rowe and Sheard (1981). Copyright Springer-Verlag, New York.

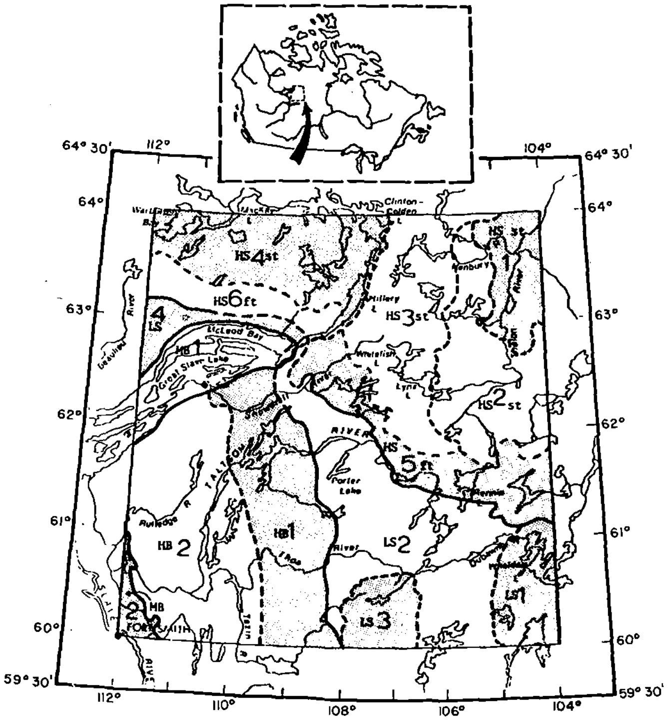


Figure 6.5. Ecological regions and districts of the Lockhart River map area, Northwest Territories, Canada. The regions, separated by solid lines, are designated by letter as MB (midboreal), HB (high boreal), LS (low subarctic), and HS (high subarctic). The latter region includes belts of forest tundra (HSft) and of shrub tundra (HSst). Numbers on the map refer to the districts that, within regions, are separated by broken lines. Reprinted, with permission, from Rowe and Sheard (1981). Copyright Springer-Verlag, New York.

In the Australian land survey system such catenae are being used to map the continent, under the auspices of the federal government (CSIRO, Division of Land Resources Management) (Stewart 1968). Figure 6.6 shows an example of the set of landform-soil units identified for a landscape in western Australia. The current land uses of each landform unit is noted by the surveyors (McArthur et al. 1977). Bennett et al. (1978) have used the units, along with rainfall data, to describe economically feasible land development opportunities for the region.

In the United States the ecoclass and ecoregion (Figure 6.7, Table 6.4) are relatively new classificatory proposals (Crowley 1967, Bailey 1976, 1978). Klopatek et al. (1981) used the ecoregions as one of the spatial scales at which to examine the variety of particular types of vegetation, birds, mammals, and endangered and threatened species. Betters and Rubingh (1978) used the system to classify aspen forest resources in the Central Rockies.

Ellis et al. (1977) summarize vegetation and land use classification systems used in the western United States. The landscape system used in the

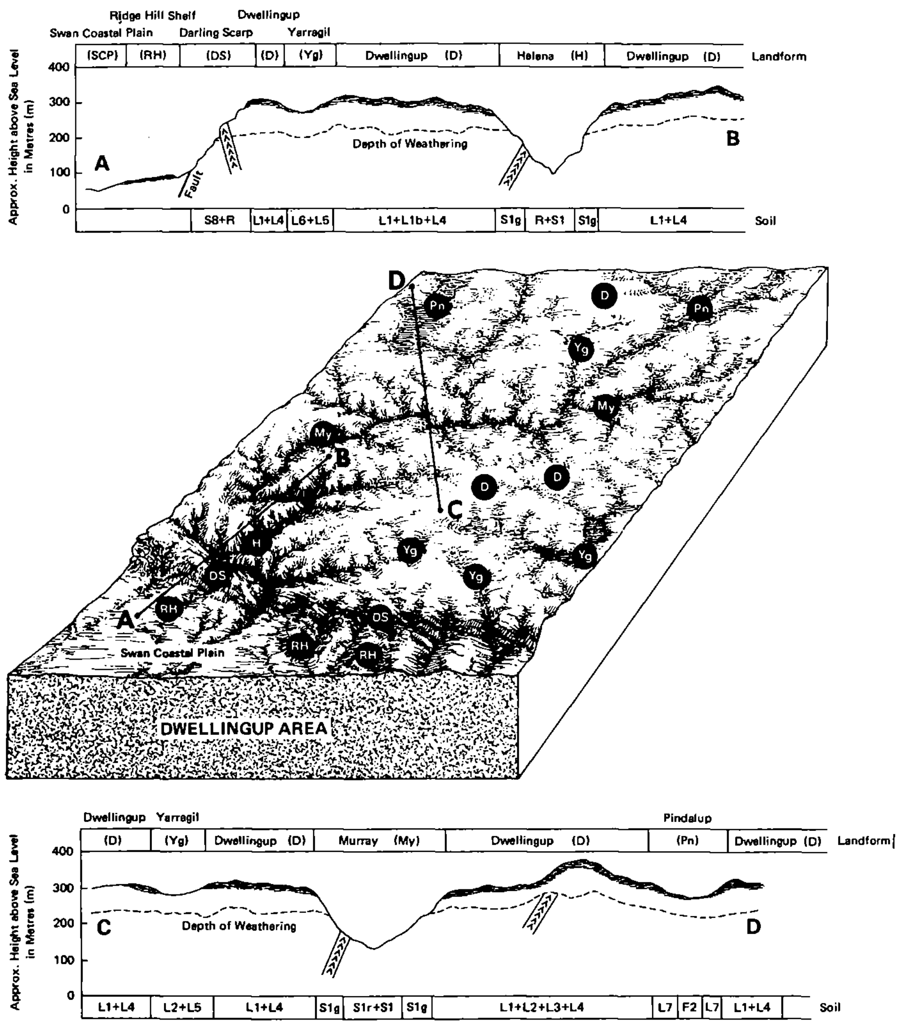


Figure 6.6. Relief diagram and sections of landscapes in the Dwellingup area of the Murray River catchment, western Australia. Abbreviations at the top of the relief diagrams stand for landform types; at bottom, for component soil types. Reprinted from McArthur et al. (1977).

Soviet Union is described by Isachenko (1973). Selman (1982) describes the use of land classification in the United Kingdom to examine the occurrence and value of wildlife for purposes of strategy planning.

Land Use Maps

In classifying land by biological and physical characteristics, one encounters the problem of how to classify land that has already been urbanized. One can

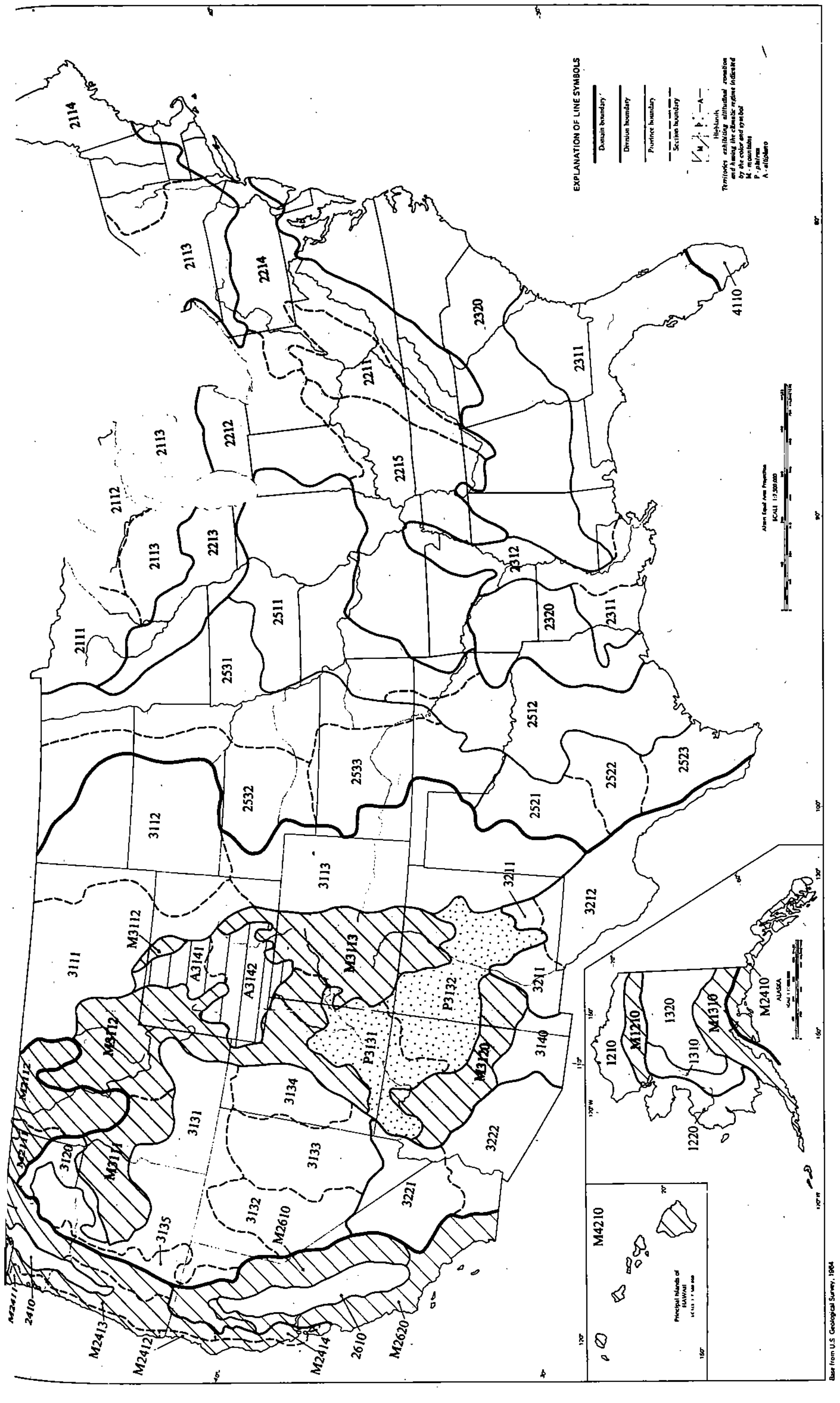
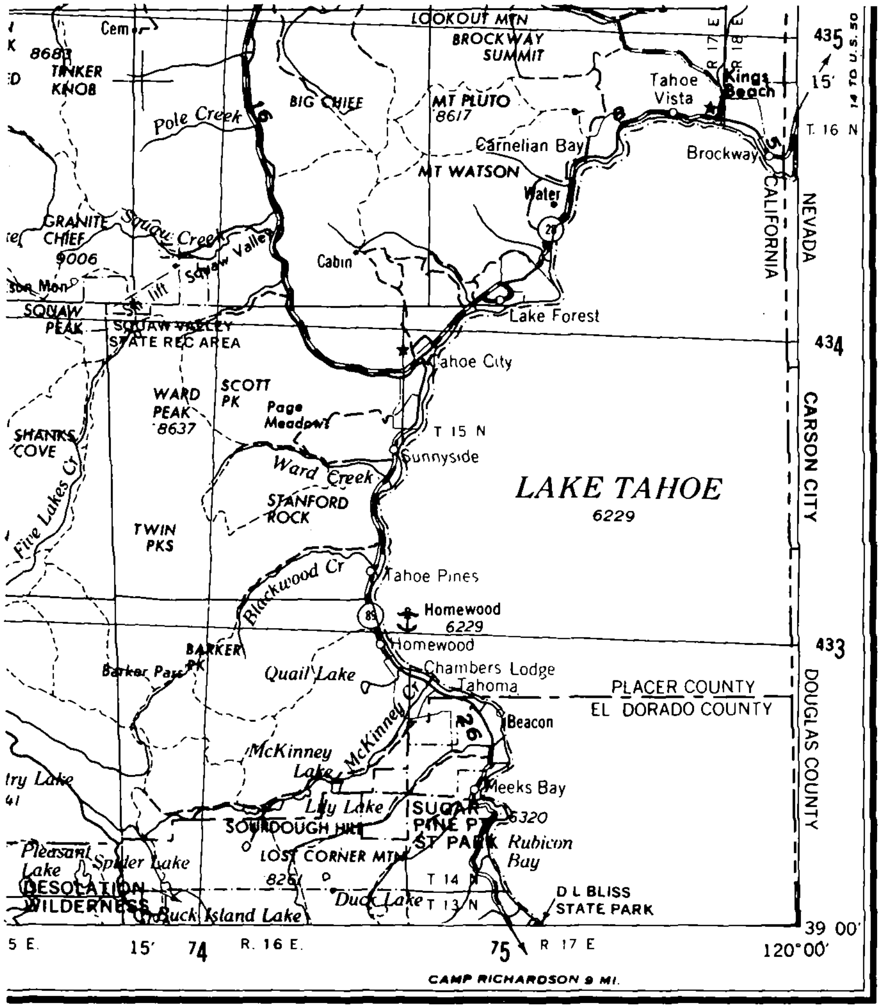


Figure 6.7. A map of the ecoregions of the U.S. based on vegetation, soil, and climate, produced by Bailey (1976). Refer to Table 6.4 for legend.

proceed, as with potential vegetation maps, to determine the ecological category to which the land belongs based on underlying soil, former vegetation and landform, and existing climate. Alternatively, one may limit land classification to relatively undeveloped areas. A third alternative is to map each parcel of land by its existing land use. This is no longer an ecological land classification but rather a record of existing land uses at one point in time. Land use maps exist for urbanized areas in many parts of the world. In the United States both public and private agencies have produced land use maps. Recently the U.S. Geologic Survey has begun to produce land use and land cover (vegetation) maps keyed to 1 : 250,000-scale feature maps. An example is shown in Figure 6.8.



(a)

Figure 6.8. (*a*) A base map of geographic features in the Lake Tahoe area of California, 1 : 250,000 scale.

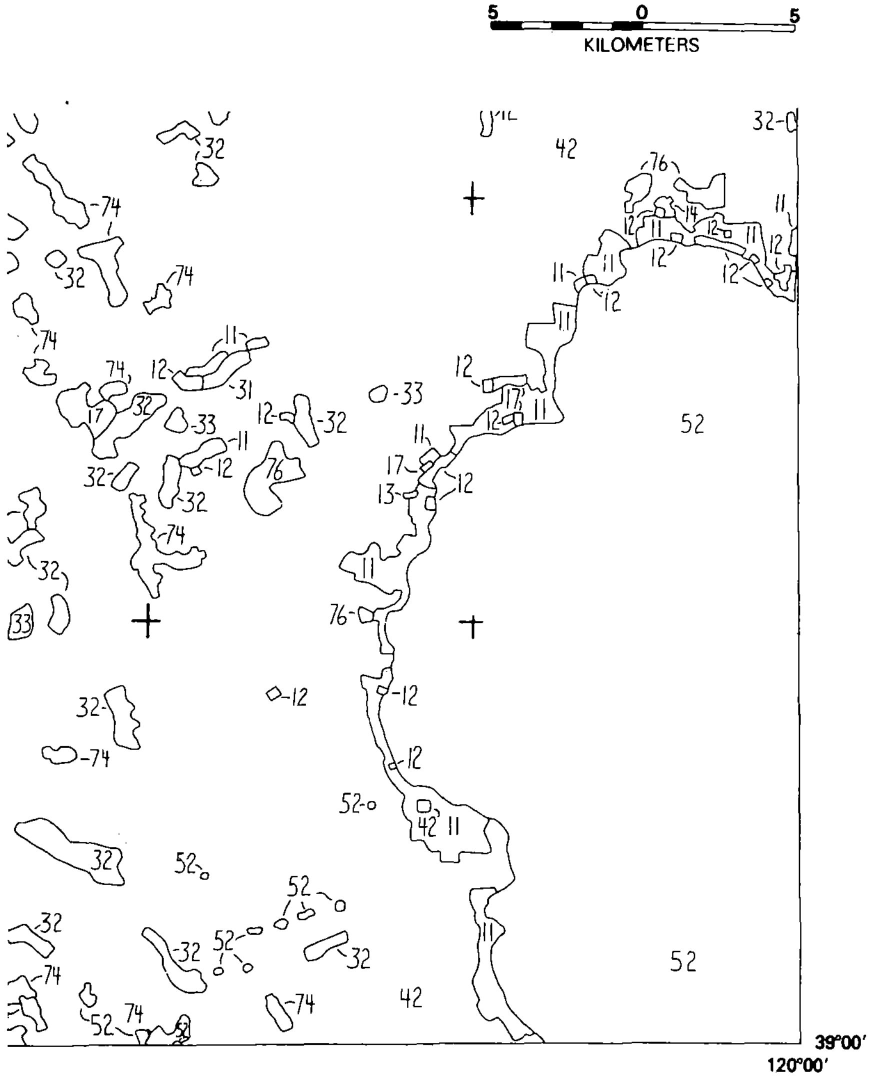


Figure 6.8. (*b*) Land use and land cover units corresponding to the base map in (*a*). Examples of key to units: 11, residential; 12, commercial and services; 32, shrub and brush rangeland; 42, evergreen forest land; 74, bare exposed rock. Section of map "Land Use and Land Cover, 1975–77, Chico, California–Nevada" produced by the U.S. Geological Survey (1979).

Table 6.4. Legend to Accompany the Map of Ecoregions of the United States

		Lowland Ecoregions		Highland Ecoregions	
Domain	Division	Province	Section	Province	Section
1000 Polar	1200 Tundra	1210 Arctic tundra		M1210 Brooks range	
		1220 Bering tundra			
	1300 Subarctic	1310 Yukon parkland		M1310 Alaska range	
		1320 Yukon forest			
2000 Humid temperate	2100 Warm continental	2110 Laurentian mixed forest	2111 Spruce-fir forest 2112 Northern hardwoods–fir forest 2113 Northern hardwoods forest 2114 Northern hardwoods–spruce forest	M2110 Columbia forest (dry summer)	M2111 Douglas-fir forest M2112 Cedar–Hemlock–Douglas-fir Forest
	2200 Hot continental	2210 Eastern deciduous forest	2211 Mixed mesophytic forest 2212 Beech–maple forest 2213 Maple–basswood forest + oak savanna 2214 Appalachian oak forest 2215 Oak–hickory forest		
	2300 Subtropical	2310 Outer coastal plain forest	2311 Beech–sweetgum–magnolia–pine–oak forest 2312 Southern floodplain forest		
		2320 Southeastern mixed			
	2400 Marine	2410 Willamette–Puget forest		M2410 Pacific forest	M2411 Sitka spruce–cedar–hemlock forest M2412 Redwood forest M2413 Cedar–hemlock–Douglas-fir forest M2414 California mixed evergreen forest M2415 Silver fir–Douglas-fir forest
	2500 Prairie	2510 Prairie parkland	2511 Oak-hickory–bluestem parkland 2512 Oak + bluestem parkland		
		2520 Prairie brushland	2521 Mesquite–buffalo grass 2522 Juniper–oak–mesquite 2523 Mesquite–acacia		
		2530 Tall-grass prairie	2531 Bluestem prairie 2532 Wheatgrass–bluestem–needlegrass 2533 Bluestem–grama prairie		
	2600 Mediterranean (dry-summer subtropical)	2610 California grassland		M2610 Sierran forest M2620 California chaparral	
3000 Dry	3100 Steppe	3110 Great Plains shortgrass prairie	3111 Grama–needlegrass–wheatgrass 3112 Wheatgrass–needlegrass 3113 Grama–buffalo grass	M3110 Rocky Mountain forest	M3111 Grand fir–Douglas-fir forest M3112 Douglas-fir forest M3113 Ponderosa pine–Douglas-fir forest
		3120 Palouse grassland		M3120 Upper Gila Mountains forest	

(continued on next page)

Table 6.4. (*Continued*)

Domain	Division	Lowland Ecoregions		Highland Ecoregions	
		Province	Section	Province	Section
		3130 Intermountain sagebrush	3131 Sagebrush–wheatgrass 3132 Lahontan saltbush–greasewood 3133 Great Basin sagebrush 3134 Bonneville saltbush–greasewood 3135 Ponderosa shrub forest	P3130 Colorado Plateau	P3131 Juniper–Pinyon woodland + sagebrush–saltbush mosaic P3132 Grama–Galleta steppe + Juniper–Pinyon woodland mosaic
		3140 Mexican highlands shrub steppe		A3140 Wyoming Basin	A3141 Wheatgrass–needlegrass–sagebrush A3142 Sagebrush–wheatgrass
	3200 Desert	3210 Chihuahuan desert	3211 Grama–tobosa 3212 Tarbush–Creosote bush		
		3220 American desert (Mojave–Colorado–Sonoran)	3221 Creosote bush 3222 Creosote bush–Bur sage		
4000 Humid Tropical	4100 Savanna	4110 Everglades			
	4200 Rainforest			M4210 Hawaiian Islands	

Source: Bailey (1976).
Note: Key to letter symbols: M–mountains, P–plateau, A–altiplano.

LANDSCAPE CHARACTERISTICS AS INDICATORS OF LANDSCAPE PROCESSES

Continual Processes

Continual processes like soil erosion are highly correlated with underlying structural features of the landscape. This correlation can serve as a basis for prediction. For example, Wischmeier and Smith (1965) have suggested that average annual soil loss (A) (tonnes km^{-2} yr^{-1}) from agricultural soils in the United States is a function of six variables:

$$A = 88.27\,(R \times K \times L \times S \times C \times P) \tag{6.1}$$

where

R = a measure of rainfall intensity; an index value related to the maximum 30 minute rainfall intensity per storm (in cm hr^{-1}), averaged over all storms in a given period (obtainable from Golden et al. 1979, Figures 9-4, 9-5; and from the U.S. Soil Conservation Service).

K = a measure of soil erodibility; an index from 0.001 (nonerodible) to 1 (erodible) based on soil texture, structure, organic matter content, permeability (available for U.S. soils from the Soil Conservation Service, or in Golden et al. 1979, Table 9.7).

$L \times S$ = effect of slope on erodibility; S is slope angle (% of 45°), L is slope length (m). The factor $L \times S$ is expressed as the ratio of erosion from the slope angle and length under consideration to that experienced on a slope of 9% and length 22 m. The latter data were obtained from extensive field trials on experimental plots (Wischmeier and Smith 1965). Ratios are obtainable from slope-effect charts (e.g., Golden et al. 1979, Fig. 9-6) for the agricultural soils studied, or by the following formula (Wischmeier and Smith 1965):

$$S \times L = \frac{(0.52 + 0.36s + 0.052s^2)\,\sqrt{L}}{30.862} \tag{6.2}$$

C = Plant cover and management factor; ranges from 0.001 for well-managed woodland to 1.0 for no cover. Values can be computed from procedures in Wischmeier and Smith (1965) or in Golden et al. (1979, Table 9-9).

P = Management practice factor; ranges from .001 for effective contour plowing, terracing and other erosion control for tilled land, to 1.0 for absence of erosion control factors on tilled land. Values obtainable from Golden et al. (1979, Table 9-10).

This equation is known as the universal soil loss equation. Each variable is an equally weighted scalar (see Chapter 4); the variables are multiplied together, rather than summed, to reflect their interdependence. The 88.27 in Eq. 6.1 is a factor to convert the soil loss (A) from tons $\text{acre}^{-1}\ \text{yr}^{-1}$ to tonnes $\text{km}^{-2}\ \text{yr}^{-1}$. Although values were derived for U.S. agricultural soils, the equation has been applied to a wide variety of soils in the United States and elsewhere; Wischmeier (1976), however, cautions against undue extrapolation.

Miller et al. (1979) have written a flexible computer program to calculate soil loss from an area divided into grid units, using the universal soil loss equation. The effect of different management practices and cover values on predicted soil loss can readily be computed in this manner (see, e.g., Briggs and France 1982a; Figure 6.9). An analogous approach has been used to compute predicted soil erosion by wind (Briggs and France 1982b), using a five-variable wind erosion equation developed by Chepil and Woodruff (1963). The variables used are climate, soil erodibility, surface roughness, effective field length, and vegetation.

The likely rates of change for other continual processes, such as coastal erosion or groundwater movement, can also be predicted based on structural features of the landscape. Coastal erosion is dependent on both the geological structure of sea walls and the manner of exposure to wave action; groundwater movement depends on such factors as the depth and angle of impermeable rock layers, water inputs and losses, and the porosity of the rock layers. Maps of average depth to groundwater are typically available from water resource or flood control agencies. For a discussion of these processes, readers may consult environmental geology texts such as Coates (1981), Griggs and Gilchrist (1983), Keller (1979), and Tank (1976).

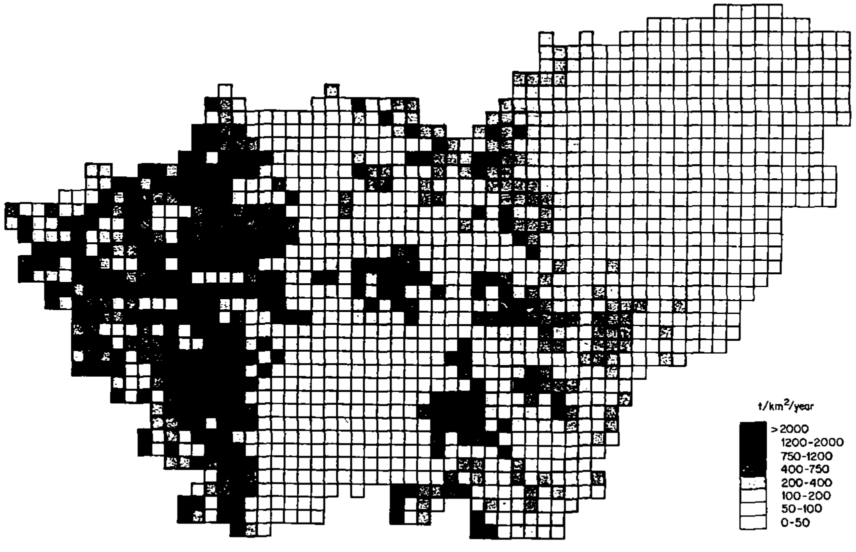


Figure 6.9. Soil erosion by rainfall in South Yorkshire, U.K., mapped on a 1 km² unit grid using the universal soil loss equation (Eq. 6.1). Reprinted with permission from D. J. Briggs and J. France (1982), Mapping soil erosion by rainfall for regional environmental planning. *Journal of Environmental Management* **14**:219–227. Copyright: Academic Press, Inc. (London) Ltd.

Episodic Processes

Natural processes of landscape change are more difficult to predict the more infrequently they occur. This is partly because there have been fewer such events within a monitoring period from which to develop predictive regressions. It is partly also because low frequency, high impact events (major earthquakes, volcanic eruptions) tend to attract less sustained social concern, and support for research and management, than higher frequency, lower impact events (floods, fires) that may be of equal social risk (frequency × damage). Thus our ability to predict, manage, and prepare for fires, floods, and storms is greater than for avalanches and mudslides, and greater still than for earthquakes or volcanoes. The study of natural hazards, and possible social responses to them, is broadly reviewed in such recent books as Botkin and Keller (1982), Heathcote and Thom (1979), and Kates (1978), as well as in the environmental geology texts cited earlier.

Static landscape characteristics may be used as predictors of vulnerability to natural hazards of an episodic, catastrophic nature. We will consider wildfires and large earthquakes as examples of frequent and infrequent hazards, respectively.

Fire

Vegetative mass (fuel loads) and climate (wind, air temperature, relative humidity) are important predictors of fire hazards, and such factors as slope help predict rate and pattern of fire spread. Aspect also serves as a predictor because of its influence on fuel moisture. Based on earlier work of Rothermel (1972), Albini (1976) has developed a computer model (FIREMOD) to predict the intensity and rate of spread of fire in wildlands based on the vegetative and climatic parameters noted above as well as terrain slope (see Figure 6.10). The model is also available for use with a programmable calculator. The U.S. Forest Service is now working to incorporate FIREMOD into a larger set of computer models (FIRESCOPE; Albini and Anderson 1982) which will predict the probability of successful containment and control of a wildfire using a given level of fire suppression effort, and the expected fire perimeter location over a fire period. Kessell (Kessell 1979, Kessell and Catelino 1978, Kessell 1981) has developed computer programs to predict pattern of fire spread across major landscape segments which can be readily updated by incorporating information on recent fires. The model itself accounts for successional changes in fuel load and changes in vegeta-

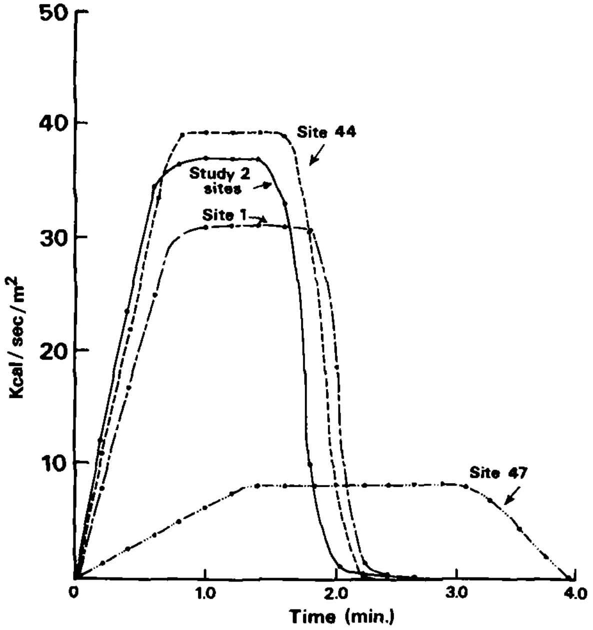


Figure 6.10. Fire intensity as a flame front passes through two coastal (Site 1, Study 2 sites) and two inland sites (Sites 44, 47) of California coastal sage scrub. The figure shows rate of heat release from dead fuels after they have been ignited, as calculated using Albini's (1976) computer model. Reprinted, with permission, from Westman et al. (1981). Copyright Dr. W. Junk, The Hague.

tive composition along environmental gradients. This "gradient modeling" system relies for its survey of vegetation and fuel load on gradient analysis techniques discussed in Chapter 10. For a general review of fire ecology and management techniques, see Wright and Bailey (1982). Green (1981) discusses prescribed burning techniques in greater detail.

A variety of systems have evolved to rate fire hazard. The U.S. Fire Danger Rating System (Deeming et al. 1972) is useful for tracking the changing probability of fire in wildlands as weather and fuel moisture changes over a season. Of greater use for long-range planning is the Australian Fire Hazard Mapping System (Morris and Barber 1980, Barber 1982) which allows mapping of fire hazard to built structures in rural areas on a map of scale 1 : 50,000. Fire "hazard" here reflects both the likelihood of fire occurrence and the extent of likely damage. Each of 10 factors (Table 6.5) is rated on a 1–5 ordinal scale with built-in weighting factor (i.e., nonlinear scalar), and the ratings summed and mapped. Because the ordinal ratings have been internally scaled to be equivalent between criteria, they can be considered interval scales and therefore summed.

A more quantitative approach to rating fire hazard was applied to the Angeles National Forest in southern California by Omi et al. (1979). Because

Table 6.5. Australian Fire Hazard Rating System

Frequency of fire season
Length of fire season
Slope aspect
Slope steepness
Vegetation—ground cover
Vegetation—average annual driest state
Fire history
Amount of existing development or use
Egress from area
Fire services available

Source: Morris and Barber (1980).

Note: Factors rated on a 1–5 ordinal scale and summed to obtain a fire hazard rating of landscape units suitable for mapping.

the nature of the substrate and the intensity of storms makes this area prone to severe erosion and mudslides after vegetation is burned, the rating system includes criteria for sediment loss hazard as well. The several watersheds in this forest were divided into 71 land units of differing aspect or drainage. Each land unit was characterized by a range of landscape characteristics (Table 6.6). Urban and recreation potential, based on criteria established by the U.S. Forest Service (1972a), were included in the rating system as a guide to the human significance of fire and flood damage in different areas, even though this results in mixing analysis and evaluation functions in a single index.

The 71 units were next classified into groups based on similarity in the attributes listed (see Chapter 10 for discussion of multivariate classification methods). By this means, four classes of land with differing potential for fire and flood damage were recognized. Upon mapping, the classes occurred in distinct zones geographically and, with a few exceptions ("outliers"), were reclassified into these geographic zones for purposes of simplification (Figure 6.11). These zones serve as a basis for applying different management procedures to mitigate fire or erosion hazard. This system differs from the Australian one in requiring interval or ratio rather than ordinal data, and it does not use information on fire hazard due to vegetation amount and condition.

Earthquakes

By contrast to fire prediction, the static landscape indicators for earthquake prediction are less helpful, because the periodicity of earthquake activity is

Table 6.6. An American Fire Hazard Assessment System Incorporating Hazard From Mudslides and Sediment Loss Following Fire

Attribute	Measured Variable
Location	Latitude and longitude (degrees)
Elevation-aspect	% of unit in each of five strata: 1. Upper slopes with prevailing north exposure 2. Lower slopes with prevailing north exposure 3. Principal canyon bottoms 4. Lower slopes with prevailing south exposures 5. Upper slopes with prevailing south exposures
Available sediment area	Total area less reservoir area (ha)
Steepness	Relief ratio (Strahler 1957): gradient in elevation/longest dimension
Major drainage density	Sum of drainage lengths/unit area (km/ha × 10^2)
Annual precipitation	Average and range (cm yr^{-1})
Geology and soil dispersion	Erosion hazard index based on soil erodibility and substrate type (1–5 ordinal scale)
Earthquake fault density	Sum of fault lengths/unit area (km/ha × 10^4)
Unimproved road density	Sum of road lengths/unit area (km/ha × 10^4)
Urban and recreational	% of unit area in the highest of seven resource potential classes established for this forest by the U.S. Forest Service

Sources: Information from Table 1 of Omi et al. (1979), An application of multivariate statistics to land-use planning: classifying land units into homogeneous zones. *Forest Science* **25**(3):399–414; adapted with permission of the Society of American Foresters.

Note: Each of 71 land units in the Angeles National Forest were characterized by each of the criteria listed, and these used to classify the units by fire erosion damage potential.

so much longer. Earthquake fault lines can be identified by topographic features in aerial photos (e.g., fault valleys, saddles, scarps, linear ridges, landslides, offset streams, sag ponds), from geologic features (juxtaposition of different rock types and ages, crushed and deformed rocks); and from dramatic vegetation changes (Griggs and Gilchrist 1983). Geologists attempt to distinguish between *active* faults, along which movement has occurred within "recent" times (the last 11,000 years), *potentially active* faults, in which evidence of movement is dated from 11,000–2.5 million years, and older and *inactive,* faults. The inactivity along fault lines in the last several hundred years is not a sufficient indication of its potential for further movement; records in Kansu and northern China regions, where historic records of earthquake activity exist for a 3000 year period, indicate that the region experienced an 800 year period without large shocks, preceded and followed by periods of major earthquakes (Allen 1975).

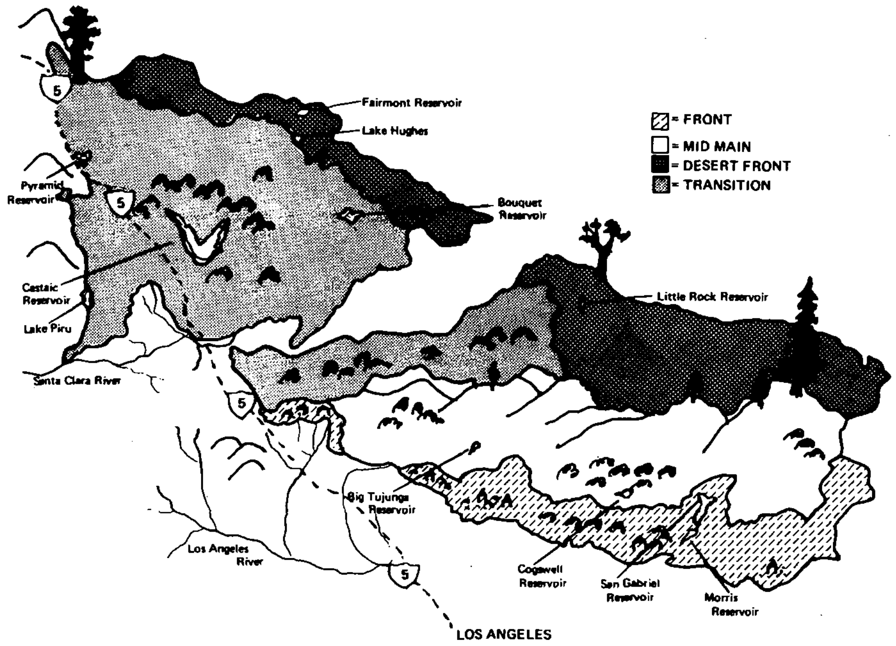


Figure 6.11. Fire damage potential zones, Angeles National Forest, California. Reprinted from Figure 3 of Omi et al. (1979), An application of multivariate statistics to land use planning: classifying land units into homogeneous zones, *Forest Science* **25**(3):399–414, with permission of the Society of American Foresters.

Earthquake fault lines are more accurately considered fault *zones,* since the width of the region in which active ground shaking may occur is wide (on the order of a kilometer or more). The area affected by post-earthquake fires, rupture of water, sewerage, gas, and electrical lines, and damage to roads, bridges, and dams is of course much larger.

Apart from the location of earthquake fault zones, land use planners recognize that certain substrates reverberate in a way that increases damage to built structures during earthquakes. Thus buildings on wet, marshy, or unconsolidated ground suffer more damage than buildings on bedrock. Hence bayfill, sediments, landfill sites and cut-and-fill pads are particularly inappropriate places to build in earthquake-prone regions. Earthquake fault maps, of the type shown in Figure 6.12, can be very useful in land use planning.

Injection of wastes into deep wells can also induce earthquake activity by increasing strain of surrounding rock structures; this phenomenon has prompted the suggestion that purposeful deep-well injection could be used to alleviate earth strain and dissipate the strength of potentially large earthquakes, but too little is known to experiment with such technology in urbanized areas (see Griggs and Gilchrist 1983, Healy et al. 1968).

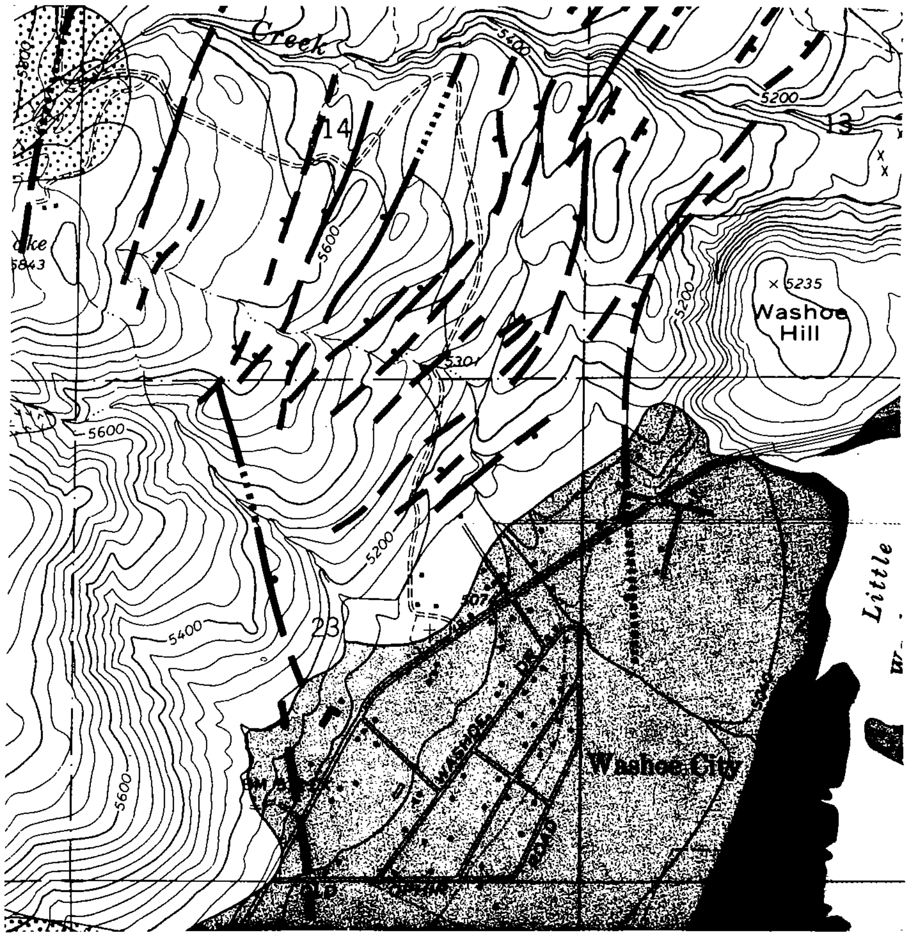


Figure 6.12. Section of the Natural Hazards Map of the U.S. Geological Survey, Washoe City, Nevada, 7½′ quadrangle (Tabor et al. 1978). Dashed lines show locations of earthquake faults; these lines are color coded on the map original to indicate how recently the last known movement along the fault occurred (six categories from <10,000 years to up to 12 million years ago). Shaded areas indicate zones subject to different severities of shaking during an earthquake (six categories mapped). Dotted area at upper left indicates maximum expectable inundation by rockfall avalanches and associated debris flows during an earthquake. Areas of potential landslide during earthquakes were also mapped (not shown).

Certain signs of impending major earthquake activity have been used as a basis for earthquake prediction. One may measure "creep" or small changes in earth position on either side of a fault trace, with theodolites, lasers, or wires strung between poles across the fault line. Small changes in earth rock angles can be measured with tiltmeters. Increases in electrical conductivity of the ground, apparently due to infiltration of water into pores and cracks (Hammond 1973), can be measured with a conductivity meter. Other indicators include patterns of change in the velocity of transmission of small seismic waves through the earth, changes in local magnetic fields, increased emission of radon gas into well water, and changes in behavior of ground-dwelling animals, including the increased appearance of snakes, jumpy behavior in dogs and cats, and the refusal of chickens, hogs, and cows to enter their pens (see Asada 1982, Griggs and Gilchrist 1983, Office of Earthquake Studies 1976, Tributsch 1982).

Earthquake prediction presents as yet unresolved social problems. Because predictions are statements of likelihood rather than certainty, they may cause an alarm in the public which later proves unwarranted. When a seismologist in Los Angeles predicted an earthquake in a portion of the county in 1976, local political officials talked of suing him for any loss of property tax revenue resulting from declines in property values in the region due to the prediction. On the other hand, failure to inform the public of imminent earthquake danger may also result in legal suits.

Long-term plans to reduce earthquake hazard include reinforcing of buildings, enforcing zoning restrictions in fault zones, using flexible piping for underground utility supply lines and developing emergency response capacities (see, e.g., Los Angeles, Department of City Planning 1975; California Office of Emergency Services 1975). Discussions of earthquake prediction and its problems include those of Griggs and Gilchrist (1983), National Research Council (1975), and Press (1975).

Wildfires and earthquakes are only two of the many natural hazards which land planners must consider, but these examples illustrate the fact that planning for natural hazards requires consideration of the complex interplay between physical features, built structures, and social attitudes toward natural phenomena.

MAPPING LANDSCAPE CHARACTERISTICS

Principles of Land Capability Mapping

A common set of landscape characteristics may be used, alone or in combination, to predict the suitability or vulnerability of the land for various uses. Land resource analysts have thus developed flexible systems for data storage and retrieval for use in a variety of land-planning tasks. Typically each landscape attribute is separately mapped, and relevant maps overlaid to determine land units that contain the combination of landscape attributes of interest for particular land uses. Since the 1960s such approaches have rapidly evolved from hand-drawn transparency maps suitable for overlay to elaborate, computerized mapping systems, sometimes attached to automatic systems of data input from satellite photos. Collections of spatial data on landscape attributes, organized for flexible automated use, are termed *geographic information systems* (see, e.g., Calkins and Tomlinson 1977).

Gestalt Method

Hopkins (1977) has summarized major approaches to land suitability mapping; the discussion that follows owes much to his lucid article. The two major mapping tasks are to identify homogeneous units of land with respect to the mapped attribute and to rate the suitability of land units for a particular use. The *gestalt* method of land suitability mapping determines homogeneous land units by direct field observation, implicitly using clues from such characteristics as topography, vegetation, and substrate to establish the distinct units. The homogeneous regions (e.g., valley floors, north-facing slopes) are then rated for suitability for a particular land use (e.g., suited for dense vs. sparse housing), and the units are mapped with a different color or symbol for each suitability class (Figure 6.13). Such an approach suffers from the implicit, hence subjective, nature of judgments regarding land homogeneity and suitability.

Parametric Systems

The gestalt method is also called the "landscape approach" (Fabos et al. 1978), since its first step is the identification of homogeneous landscape units whose suitability for particular land uses is to be judged. The alternative approach, which is now more widely used, is the *parametric* one, in which individual landscape parameters or attributes (soils, vegetation, landform, etc.) are separately mapped and rated for suitability, and these ratings are combined into a grand index of suitability.

Mathematical Combination of Factors

In the *ordinal combination* method, ordinal ratings for suitability for a particular land use (e.g., housing) assigned to each separate landscape characteristic (soil, vegetation, etc) are summed to produce ratings on a composite land use suitability map (Figure 6.13). This approach was used by Ian McHarg (1969) in the Richmond Parkway study and elsewhere. As Hopkins (1977) notes, because an ordinal scale is used, ratings cannot meaningfully be summed between maps (see Chapter 4). The intervals between rating scores may not be the same for different landscape attributes (e.g., a "3" rating on soils may be equivalently suitable to a "2.3" for vegetation). Summation is also inappropriate because the landscape attributes are often not independent in their effect on land use suitability. Thus a particular vegetation may indicate high suitability for housing, and so may its underlying soil type, but the vegetation may be growing there only because the appropriate soil is there. To sum these two suitability ratings therefore results in "double counting."

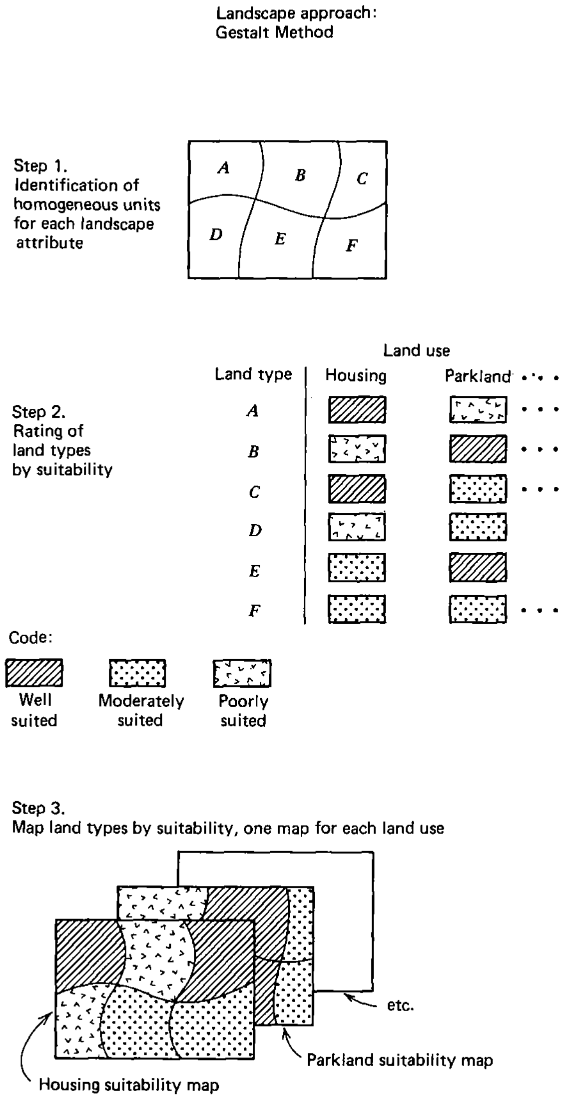
The factors may not only be dependent (vegetation on soils, in the preceding example) but interdependent and multiplicative in interrelation. For example a 25% slope on well-drained soil over clay may result in a mudslide, but a 25% slope with well-drained soil over granite could be quite suitable for housing, as could well-drained soil over clay on a 5% slope (Hopkins 1977). Hence overlaying ordinally rated suitability maps (e.g., slope, soil drainage, subsoil type) is inappropriate both because of the nonadditivity of ordinal scales and the interdependence of landscape factors contributing to suitability.

An ordinal scale can be converted to a common interval scale (in which addition of ratings is meaningful) by transforming the ordinal scale so that the intervals between units are equal to those of the second scale with which it is being compared. If vegetation is rated on a 1–10 scale of suitability in which a "10" is equally suitable to a "5" on a 1–5 scale used for soil suitability and an "8" to a "4", the soil scale might be made equal to the vegetation scale by multiplying all soil ratings by a factor of 2. This transformation between the two scales is a nonlinear function. Hence we would need curvilinear scalars for weighting the different ordinal suitability scales (Figure 6.14).

The Battelle scalar EES system described in Chapter 4 is an example of such an approach, in which weighted scores for separate impact (rather than suitability) categories are added together, after scalar transformation of raw data, to obtain interval ratings. While the EES system uses nonlinear transformation based on expert judgment or empirical data, other planning systems assume linear transformations in the absence of additional data on which to base the scalars.

An example of a linear weighting system is that described by Lyle and von Wodtke (1974) for use in land suitability mapping in San Diego County, California. In Table 6.7 the effect of using land for citrus production on various environmental processes (including productivity) are assigned relative weights totaling 100 points (bottom row). Each relative weight is then subdivided among vegetation, climate, and land variables according to the role of these landscape or climatic attributes in causing the ecological effect (columns). Thus as the table shows, 10% of the total effect of citrus production is assigned to its effect on sediment transport (by expert judgment). Of these 10 points, 5 are ascribed to slope factors, 2 to the effect of rivers, channels, and other water features, and 3 to the soil runoff potential. Each landscape attribute (e.g., slope class; eight classes in Table 6.8) is then rated as to its relative suitability for inducing all of the ecological effects, up to the maximum weight for the attribute (e.g., total of 19 points for slope; Table 6.7). With this information each land unit is scored for its suitability to citrus production based on vegetation type, slope class, and so on, and these weighted ratings are summed. In the final mapping stage the suitability scores are classed into three categories: low, moderate, or high suitability (Figure 6.15).

In this process the assumption has been made that 40 points for plant productivity are equal in significance for land use suitability to 10 points for erosion or 20 points for pesticide transport. This "weighting" is an evalua-

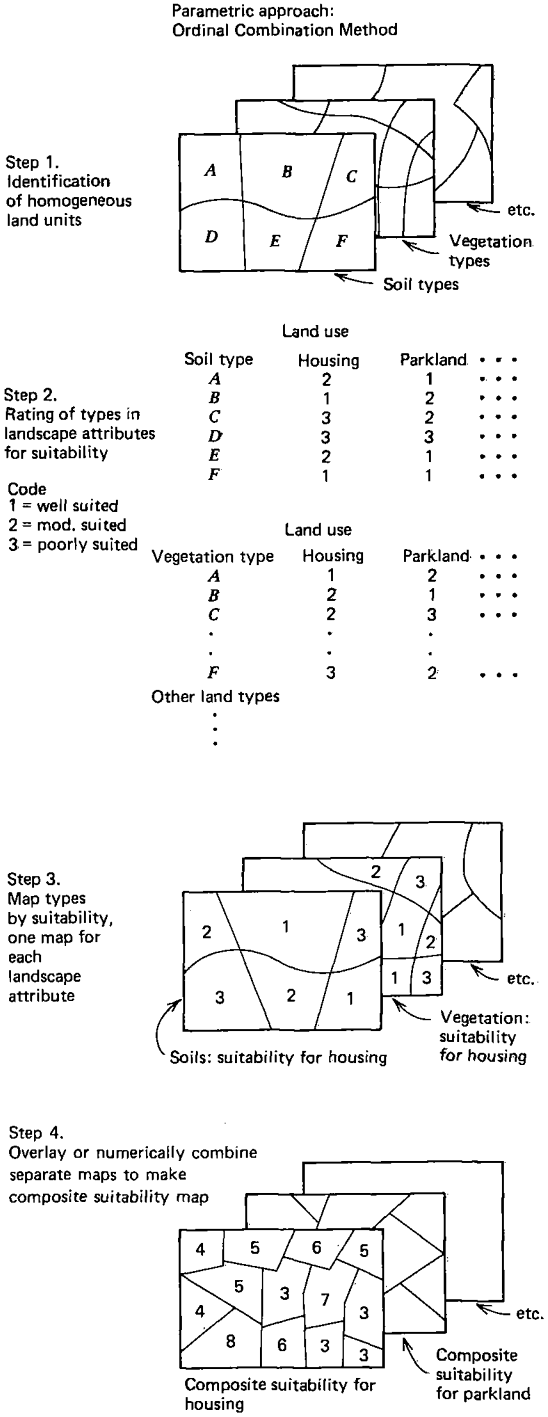


	Land use		
Land type	Housing	Parkland	. . .
A	▨	▒	. . .
B	▒	▨	. . .
C	▨	░	. . .
D	▒	░	
E	░	▨	
F	░	░	. . .

Code:

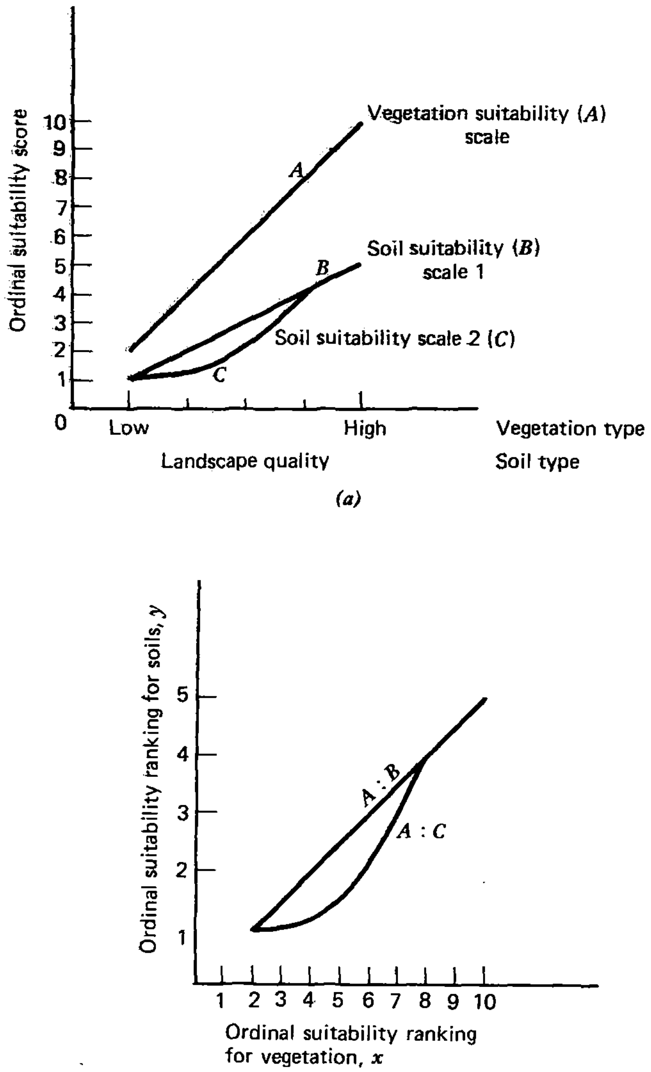
▨ Well suited
░ Moderately suited
▒ Poorly suited

Figure 6.13. Diagrammatic view of alternative land suitability mapping systems. Adapted with permission from Figures 1 and 3 of Hopkins (1977), *Journal of the American Institute of Planners* **43**(4), October issue. Copyright 1977 by the American Institute of Planners (now the American Planning Association). 1313 E. 60th St., Chicago, IL 60637. See next page.



	Land use		
Soil type	Housing	Parkland	. . .
A	2	1	. . .
B	1	2	. . .
C	3	2	. . .
D	3	3	. . .
E	2	1	. . .
F	1	1	. . .

	Land use		
Vegetation type	Housing	Parkland	. . .
A	1	2	. . .
B	2	1	. . .
C	2	3	. . .
.	.	.	
.	.	.	
F	3	2	. . .
Other land types			
.			
.			



(*a*)

(*b*)

Figure 6.14. Examples of scalars to convert ordinal to interval scales. (*a*) The relationship between landscape quality and the ordinal suitability score. *A*, a linear relationship between vegetation quality and the suitability scale. *B*, a linear relationship for the soil scale. *C*, an alternative, nonlinear relationship for the soil scale. (*b*) Line *AB* shows a linear relationship between the vegetation and soil scales, in which the soil scale can be weighted by a constant (0.5, the slope of line *A* of form $y = 0.5x$) to convert it to the vegetation scale. Line *C* bears a linear relationship to *A* only between 8 and 10 on the vegetation scale; its scalar for interconversion to *A* is consequently nonlinear.

Table 6.7. Weights Assigned to the Relative Importance of Each Ecological Effect and Landscape Attribute in Influencing the Suitability of Land for Citrus Production in Southern California

Citrus Suitability	Ecological Effect							
	Sediment Transport	Nutrient Transport	Pesticide Transport	Erosion	Productivity	Disruption of Wildlife Habitats		Total Weight
Vegetation types						5	=	5
Slope	5	4	5	5			=	19
Soil					30		=	30
Water features	2	3	5	2			=	12
Rainfall					10		=	10
Runoff potential	3	8	10	3			=	24
Total Weight	10	15	20	10	40	5	=	100

Source: Reprinted from Lyle and von Wodtke (1974, Fig. 8), with permission of the American Planning Association, 1313 E. 60th St., Chicago IL 60637.

Note: The weights are assigned subjectively by expert judgment.

Table 6.8. Each Landscape Attribute as Divided into Numbered Classes ("Attribute Code") and Assigned a Score ("Model Value") on the Extent of Its Suitability for Promoting Plant Productivity or Reducing Negative Ecological Effects if Land is Used for Citrus Production

Vegetation types	Attribute code	0	2	3	4	5	6	7	8	9	10	11	12	13	14
	Model value	0	1	0	2	3	2	3	3	5	5	0	1	4	4
Slope	Attribute code	0	1	2	3	4	5	6	7	8					
	Model value	0	1	3	5	8	11	13	15	19					
Soil	Attribute code	1	2	3											
	Model value	1	10	30											
Water features	Attribute code	0	2	3	4	5	6	7	8	9	10				
	Model value	0	6	12	6	12	12	6	12	12	12				
Rainfall	Attribute code	1	2	3	4	5	6								
	Model value	10	10	10	5	5	1								
Runoff potential	Attribute code	1	2	3	4										
	Model value	1	8	16	24										

Source: Reprinted from Lyle and von Wodtke (1974, Fig. 8), with permission of the American Planning Association, 1313 E. 60th St., Chicago, IL 60637.

Note: The maximum possible score is equal to the total weight assigned to the landscape attribute (right-hand column of Table 6.7).

tive and arbitrary process. It is a form of linear scaling since points within these weights are assumed of equal value (i.e., are on an interval scale); hence the weighted scores can be added. In the Lyle and von Wodtke example all weightings were assigned by subjective "expert judgment." Thus there is no guarantee that these are truly interval scales. Roberts et al. (1979) have constructed a land suitability model (WIRES) that permits the user to modify the weights in a user-interactive computer system. This feature not only makes such a system more flexible but permits a sensitivity analysis of the choice of weights.

A second problem concerns interdependence of landscape attributes. The EES and Lyle and von Wodtke (1974) weighting schemes (so-called "linear combination" methods) convert different attributes to linear scales for addition into a grand index, hence assuming independence of landscape factors (e.g., slope effects are independent of vegetation effects). As noted earlier, this is usually not a valid assumption. Other systems attempt to represent the interdependence between landscape factors by multiplying, rather than adding, the separate attributes ("nonlinear combination methods"). The universal soil loss equation exemplifies this multiplicative combination of separate landscape attributes. The main problem with the multiplicative approach is that the interdependencies may not be simple multiplicative functions. The dependence of vegetation on slope may be a sine, log, or other complex mathematical function of which simple multiplication is a better approximation than addition, though still not necessarily accurate. Other examples of multiplicative indexes are Storie's (1978) index of soil factors for agricultural production in California and the FAO index of soil productivity (Riquier et al. 1970). Rarely is the ecological information available with which to determine the exact nonlinear relationship between parameters. For further discussion on additive, multiplicative, and more complex systems, see McRae and Burnham (1981, Ch. 6).

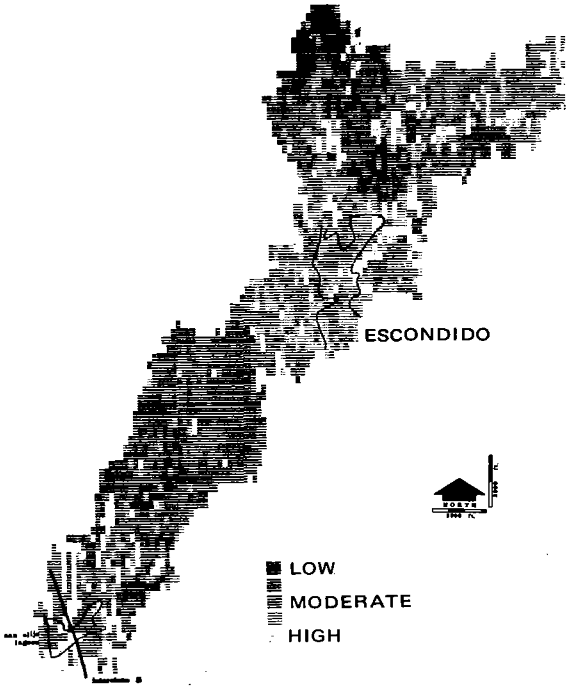


Figure 6.15. A unitized map indicating suitability of land units for citrus production in a portion of San Diego County, California, based on landscape attributes and ecological effects as weighted in Tables 6.7 and 6.8. Reprinted, with permission, from Lyle and von Wodtke (1974), *Journal of the American Institute of Planners* **40**(6), November issue. Copyright 1974 by the American Institute of Planners (now the American Planning Association), 1313 E. 60th St., Chicago, IL 60637.

A third problem, of an ecological rather than statistical nature, exists with all "unitized" mapping procedures which break watersheds or other coherent landscape areas into small grid units for rating and mapping. The ecological interactions between subunits is ignored. Thus in the citrus suitability example each mapped unit was rated separately for effect of slope on pesticide transport, ignoring the transport of pesticide *between* mapped units. The holistic nature of ecosystems is easily lost sight of when interacting landscape segments or ecosystems are subdivided (Westman 1975). This is a problem of the *interdependence of spatial units* and is additional to the problem of interdependence of landscape factors, or the requirement that each mapping unit be homogeneous in relation to some landscape attribute. The problem of ignoring the interdependence of spatial units exists with all unitized mapping approaches. Ecologists have recently become interested in the dynamics of movement of species and materials between "homogeneous" landscape patches. The study of this flow of species, material and energy between landscape patches is part of the emerging discipline of landscape ecology, discussed in Chapter 11.

Identification of Homogeneous Regions

Returning to the problem of interdependence of landscape factors, several other approaches have been used to deal with the problem. One is to identify "homogeneous" land units by overlaying maps for all the separate landscape factors and regarding the resulting landscape units on the composite map as irreducible, homogeneous landscape segments. Such units are then each assigned suitabilities by expert judgment. This procedure ("factor combination" method) differs from the gestalt method in that the process of identifying homogeneous units has been made explicit, though the assignment of suitability rankings remains implicit (Hopkins 1977). In addition to the subjectivity of the ranking process, a major problem with this approach is that the number of landscape units needing to be ranked can be enormous. If, say each of 10 landscape attributes occurred with 10 types in the landscape, 10^{10} or 10 billion separate landscape units would have to be rated.

A possible remedy for this problem is to apply a numerical classification procedure ("cluster analysis") to the units to group them into a manageable number of classes (see Chapter 10). The rating of units of the Angeles National Forest for fire hazard by Omi et al. (1979) cited earlier exemplifies this approach. There factor analysis was used to reduce the initial number of landscape attributes into a smaller number of highly correlated landscape factor combinations. Then land units with similar factor-combination scores were grouped by cluster analysis (Sneath and Sokal 1973), and this classification was further refined by discriminant function analysis (Cooley and Lohnes 1971). The final "homogeneous" fire hazard areas were then mapped (Figure 6.11).

Combination of Ecologically Related Factors

Still another approach for dealing with interdependence of landscape factors is the "rules of combination" method (Hopkins 1977). The combination of landscape attributes (soil, vegetation, etc.) occurring in a landscape unit are considered, and different units are given the same suitability rating if they have certain landscape attribute levels in common. Thus in setting rules for suitability for a golf course, all flat areas with good drainage may be suitable, regardless of vegetation type, since the existing vegetation will be cleared. Thus the units with different vegetation types do not have to be separately considered for ranking. In other words, topography and drainage are interdependent variables, with a certain combination of them acceptable for the land use purpose, whereas vegetation is an independent variable which in this case is insignificant for the land use purpose. Table 6.9 provides another example of rules of combination.

Table 6.9. Illustration of the Nonhierarchical Rules of Combination Approach for Assigning Suitability Ratings to Landscape Units

Landscape Attributes

A.	*Slope, %*	*Surface Soil Drainage*	*Presence of Clay Subsurface Horizon*
Class 1	>30%	Good	Yes
Class 2	<30%	Poor	No

Rules of Combination

B.	*Nonhierarchical (Excluding Consideration of Vegetation). High Suitability*
Rule 1.	<30% slope (2, –, –)
Rule 2.	>30% slope, poor surface drainage (1, 2, –)
Rule 3.	>30% slope, subsurface nonclay (1, –, 2)

C.	*Slope*	*Drainage*	*Claypan*	*Suitability*
Factor combinations in the landscape (number indicates class in part A)	1	1	2	High, rule 3
	1	2	2	High, rule 2 or 3
	1	2	1	High, rule 2
	1	1	1	Low
	2	2	2	High, rule 1
	2	1	1	
	2	1	2	
	2	2	1	

Landscape Attributes

D.	*Hierarchical Combinations. Suitability Based on Slope, Drainage-Claypan*	*Presence of Soil-Binding Vegetation*
Class 1	High	Yes
Class 2	Low	No

E. *Rules of Combination. High Suitability*

Rule 1. All highly suitable units with soil-binding vegetation (1, 1)

F. *Factor Combinations*	*Previous Suitability*	*Vegetation*	*Suitability*
	1	1	High, rule 1
	1	2	Low
	2	1	Low
	2	2	Low

Note: Suitability for housing development (two classes) is rated and varies with the combination of landscape attributes present. The main concern in this example is mudslide hazard. In the hierarchical example, classes established in the nonhierarchical rating are now rated considering the vegetation factor.

Once a group of interdependent attributes that contribute to high or low suitability is identified, it may be considered a single factor combination in the next round of suitability ratings when new landscape attributes are considered. In this way suitability ratings may be accomplished in a hierarchical fashion, with new landscape attributes added to an interaction matrix after smaller combinations of landscape attributes have been grouped into a single suitability class. This "hierarchical rules of combination" approach is also illustrated in Table 6.9. The advantage of the hierarchical approach is that fewer factor combinations ultimately need to be ranked.

Comparison of Methods

Table 6.10 compares the different approaches to land suitability classification. Because of the problems of subjectivity with the gestalt method, and mathematical invalidity with ordinal combination methods, Hopkins (1977) suggests starting with a linear or nonlinear combination method and using rules of combination to deal with interdependence of factors. With the increasing trend for automation of data, the use of multivariate analysis (cluster analysis, hierarchical classification) to reduce the data to a manageable number of units for ranking is likely to increase. An additional advantage of the cluster analysis method is that, by applying appropriate rules of combination, one can begin to deal with the problem of spatial interdependence of units. Thus by screening adjacent cells for certain levels of flow of energy, materials, or species, one can group adjacent units in which this spatial interaction is important.

Uses of Remote Sensing

Remote sensing of landscapes, both from airplanes and earth resources satellites (LANDSAT, SKYLAB), has enabled the generation and transmission of spatial data to computers in ways that are revolutionizing land suitability mapping. Whereas the interpretation of aerial photos often still involves a human interpreter of the photograph, who may then encode the information in cells for input to a computer cartographic (map-making) system, it is now common for airplane and most satellite data to be digitized and "interpreted" directly by computers. These machines interpret data from computer-compatible magnetic tapes which record digitized information from a sensor such as a multispectral scanner in the airplane or satellite. A "multispectral scanner" senses light in a series of bands of wavelengths from the visible through the thermal infrared radiating from the earth. Because different earth surfaces (e.g., different crops, air or water of different qualities) reflect or reradiate slightly different amounts of radiation in each of these wavelengths, the sensing of these differences and their interpretation as ground features become possible. Much as a television image can be broken into small units, the information transmitted by radio wave through

Table 6.10. Comparison of Methods for Land Suitability Mapping

Methods	Handles Interdependence of Landscape Factors	Rates Units for Suitability by Explicit Process	Comments	Examples
Gestalt	Yes	No	Has no explicit process for identifying homogeneous landscape units	Hills (1961)
		Mathematical Combination of Factors		
Ordinal combination	No	Yes	Involves invalid mathematical operations	McHarg (1969, pp. 31–41)
Linear combination	No	Yes	Makes often untested assumptions of colinearity of scales used	Ward and Grant (1971); Lyle and von Wodtke (1974)
Nonlinear combination	Yes	Yes	Requires functional relationships generally not known	Voelker (1976, pp. 49ff.)
		Identification of Homogeneous Regions		
Factor combination	Yes	No	Requires very large number of evaluative judgments	Wallace-McHarg (1964)
Cluster analysis	Yes	No	Can be used to deal with spatial interdependence of units	Rice Center (1974); Omi et al. (1979)
		Combination of Ecologically Related Factors		
Rules of combination	Yes	Yes	Requires much time and ecological expertise in establishing rules	Kiefer (1965)

(continued on next page)

Table 6.10. *(Continued)*

Methods	Handles Interdependence of Landscape Factors	Rates Units for Suitability by Explicit Process	Comments	Examples
Hierarchical combination	Yes	Yes	May save time by reducing number of separate evaluations	Murray et al. (1971, pp. 131–174)

Source: Modified from Hopkins (1977) with permission from the American Institute of Planners (now the American Planning Association), 1313 E. 60th St., Chicago, IL 60637.

the air, and reconstituted electronically as cells of an image on a TV screen, so it is with satellite photographs. Antennae on the ground can receive satellite radio waves and record the impulses on magnetic tape. This information can then be used directly for computer-aided mapping.

Because satellites orbit the earth many times a year, temporal changes in land surface features can readily be followed: crop growth, weather features, oil spill movements, progression of disease, insect plagues or air pollution damage in vegetation, coastal erosion, to name a few. Indeed, the amount of information generated is so large that considerable filtering of information is necessary. At the same time, airplane photographs (black and white, color, infrared, multispectral) are useful for smaller-scale studies which can identify individual plants or buildings—a level of resolution not normally possible from satellites.

Remotely sensed data are regularly used in forestry, agriculture, and urban land use studies; mineral prospecting, natural hazard study, and other earth science concerns; studies of movement of water, sediment, and pollutants in lakes, rivers, and the ocean; climatology and weather forecasting; geomorphology, and many other areas. Reviews of principles and applications of remote sensing to environmental sciences include those of Christenson (1979), Lintz and Simonett (1976), Richason (1982), Sabins (1978), and Schanda (1976). Computer-generated maps derived from satellite photographs are shown in Figure 6.16. This example shows how changes in rangeland cover could be followed over time by satellite.

Examples of Computer-Aided Land Resource Analysis: Geographic Information Systems

Three examples of the application of computerized systems to the study of land resources and their utilization are reviewed here to illustrate the range of applications of the techniques discussed in this chapter.

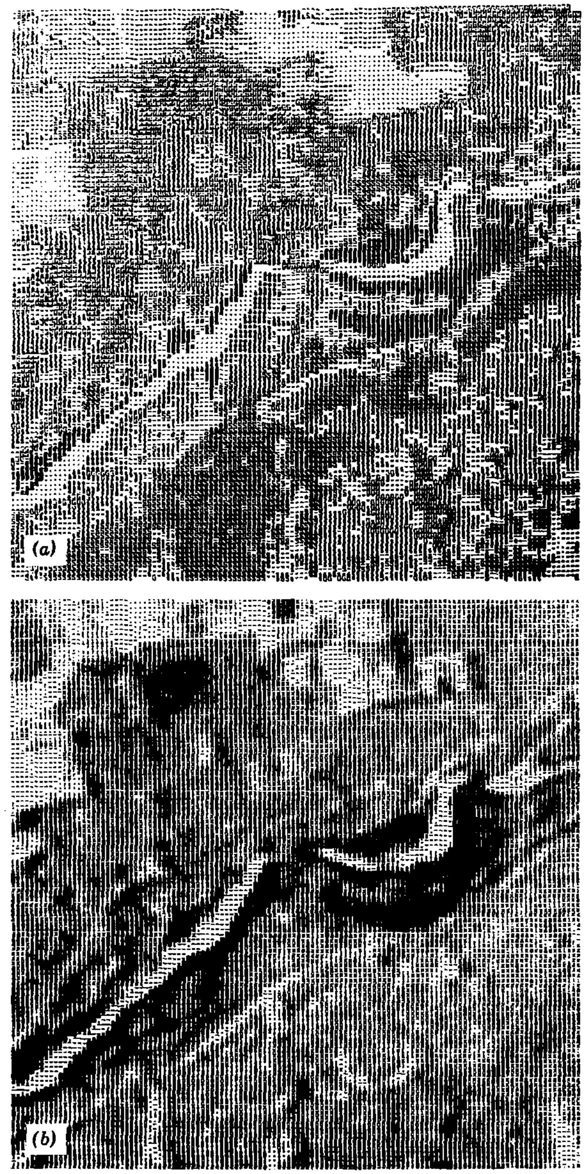


Figure 6.16. (*a*) Land cover classification of Cimarron National Grassland, derived from LANDSAT satellite photo. Each character represents 1.1 acres. Key: *G*, range grasses, >75% cover, no sage; *g*, range grasses, 50–75% cover, no sage; *, range grasses, >75% cover with open tree canopy near river, little or no sage; #, woodland with grass understory, >80% cover, no sage; ~, soil with sparse stubble or weed cover; ·, bare soil; *S*, sagebrush, >75% cover; *s*, sagebrush and yucca, 50–75% cover; -, scattered sagebrush and yucca with grass (<50% sage/yucca, 50–75% ground cover). (*b*) Estimate of vegetative biomass of Cimarron National Grassland, derived from LANDSAT satellite photo. This is a seven-step gray shade print of the LANDSAT multispectral scanner Band 5/Band 7 ratio. Darkest tone (–) represents greatest biomass, lightest tone (–) the least. Each character represents 1.1 acres. Figures *a* and *b* reproduced with permission from "Inventory and evaluation of rangeland in the Cimarron National Grassland," by J. W. Merchant and E. A. Roth, Pecora VII Symposium. Copyright 1982 by the American Society of Photogrammetry.

The METLAND Study

A team of researchers at the University of Massachusetts developed the Metropolitan Landscape Planning Model (METLAND), using the Boston metropolitan region as an example (Fabos and Caswell 1977, Fabos et al. 1978). METLAND is a computer-interactive parametric approach to landscape assessment. Most of the parametric approaches in Table 6.10 are used. In Phase I (Figure 6.17) information on various physical features of the landscape are coded and mapped. Three types of "suitability" judgments are made for each landscape attribute: (1) the value of the landscape attribute as a resource for human use, such as source of water, minerals, or recreational value; (2) degree of hazard: air pollution, noise, or flooding potential; (3) suitability for development (housing, etc.). In order to combine these three suitability ratings into a grand index (the "landscape value") by linear combination, the suitability ratings are converted into dollars (or calories of energy, in a second valuation approach) (Figure 6.18).

"Ecological compatibility" of land units is assessed in two ways. First, landscape units are grouped into five classes based on their plant productivity or on the extent of urban development. The authors intended to use existing biomass and the production (P)/respiration (R) ratio as strict criteria for land classification, based on the suggestions of Odum (1969; see Chapter 8), in which $P/R > 1$ in successional communities, and $P/R = 1$ at climax. Data of this type were scanty for the 104 land use types, so that in practice a combination of available data, extrapolation, and expert judgment were used, and the resulting land use classes were quite conventional (Figure 6.17). Second, "biological potential" is calculated by using the eight crop capability classes derived from U.S. Soil Conservation Service maps, combined with solar radiation input to the land (in three classes) to form a "crop potential index." The U.S. Soil Conservation Service's forest site index is also combined with solar data to form the "forest potential index." These two ratings are then combined in a nonlinear, but nearly additive, way to form a "biological potential" index. An analogous procedure is used to generate "denudation potential" of soil and slope based on Soil Conservation Service's soil-mapping data. Nonlinear scalars are used to convert slope classes into erosion- and runoff-potential interval scales. After the various erosion runoff maps are overlaid, the resulting land units are rated (factor combination approach). The "biological potential" index and the "denudation potential" index are then combined, using nonhierarchical rules of combination, to produce a "substrate profile" index. Finally, the ecological land classes (rated by productivity) and the substrate profile index are combined by nonhierarchical rules of combination to form an "ecological compatibility index."

In a third part of Phase I the potential of the landscape to provide public services (sewerage, water supply, recreation, police and fire protection) is also determined and mapped (not shown in Figure 6.17). For example, for

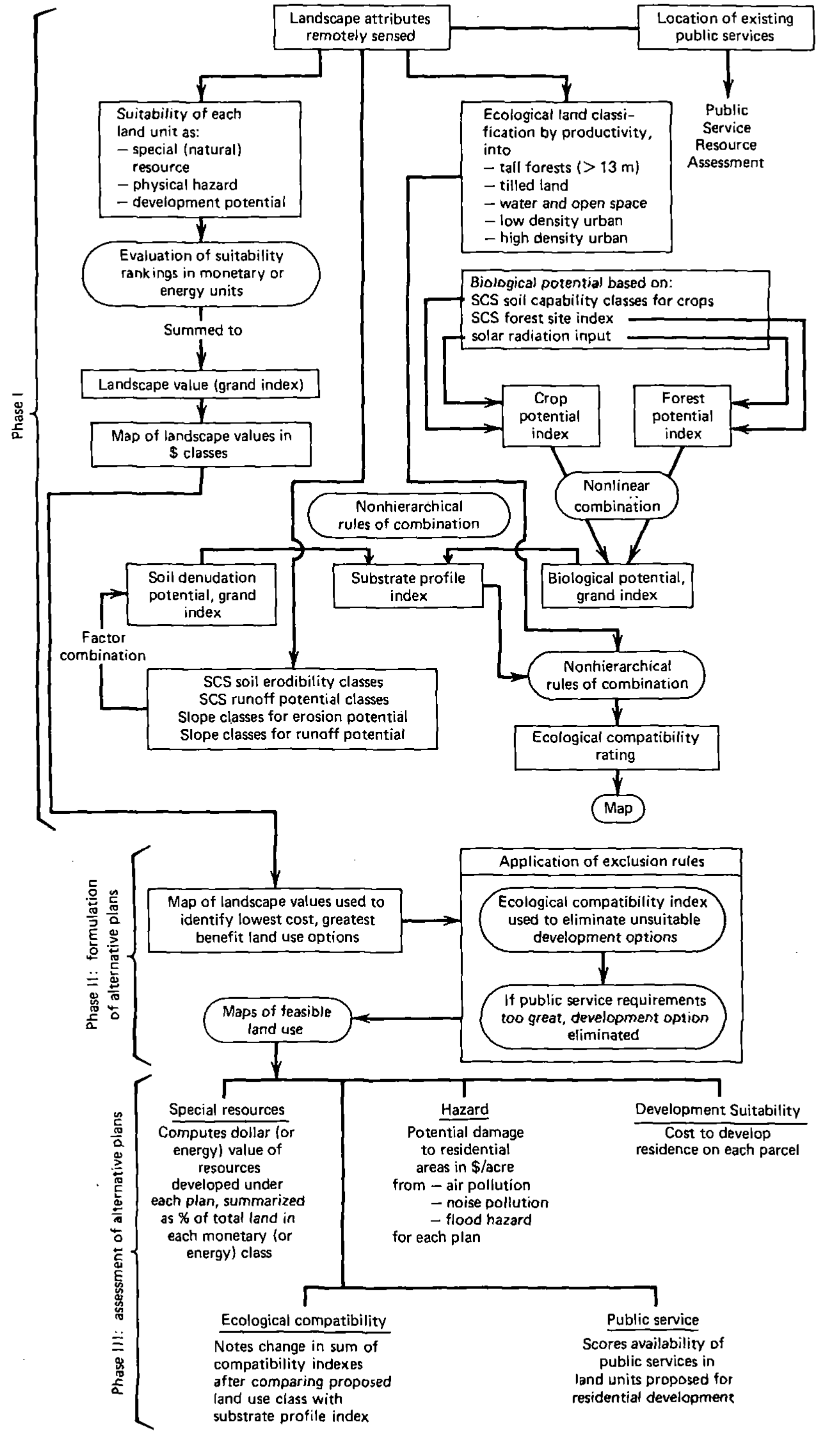


Figure 6.17. Steps in the three phases of the METLAND approach to composite landscape assessment (from information in Fabos et al. 1978).

Figure 6.18. Map of composite resource values for an area along Interstate 91 in Massachusetts, evaluated by the METLAND study. Values are combined worth of agricultural, forest, and wildlife productivity, groundwater, sand and gravel, and visual amenity values. Reprinted from Figure 7.4.1.3 of Fabos et al. (1978) with permission of the author and the Massachusetts Agricultural Experiment Station.

water supply land is classified by distance from the water main and available water pressure.

Because the various landscape indexes are computer encoded, it is possible to generate alternative plan scenarios (Phase II) by computer. For example, land units of high development potential based on landscape value are identified; these are screened for "ecological compatibility," and remaining developable areas analyzed in terms of existing public services. By changing weights assigned to different components of the model, different land use plans will be generated. Community preferences may be incorporated into assignment of weights.

In Phase III alternative plan scenarios are evaluated by their potential for achieving three distinct community goals (landscape values, ecological compatibility, provision of public services; see goals-achievement matrix, Chapter 5). Landscape values are evaluated for net dollar benefit or loss from development of the land. Potentially exploitable natural resources are expressed in dollars per acre, hazard zones are evaluated by potential damage in dollars per acre, and development potential by dollar value of developed resource (e.g., value of house on hill with view) and cost of overcoming physical limitations (e.g., cost of building house, including cut and fill, draining high water table). Ecological compatibility is evaluated by summing the loss in ecological compatibility index scores (ordinal ranking) due to development of land parcels. For example, a house may change the ecological compatibility score from +3 to −3 on a particular site and from +2 to 0 on another site. Public service values of land are ranked on a three-point ordinal scale, and changes in these values similarly noted in the evaluation phase.

While the potential for automating the entire task of land use planning and evaluation is present in the METLAND model, numerous limitations with the model exist. First, data necessary for the mapping tasks are rarely complete, so that much "soft" information is put into the data base. Because we have no way to evaluate statistically our confidence in the accuracy of such data, the resulting output is without bands of confidence. Furthermore the data are compounded with other data in ordinal scales and then summed or combined nonlinearly. None of these mathematical operations are based on empirical relationships or later validated with empirical data. Additional sources of error included errors in mapping boundaries, identifying homogeneous units, and combining overlay boundaries accurately. Also, although many ecological criteria have been included, others have not (e.g., potential for dispersion of pollutants in air, water, or soil); the same could be said for the social concerns. The evaluation of results in dollar terms involves numerous assumptions, especially in relation to nonmarketed goods and services (see Chapter 5), which remain implicit in the valuation procedure. Indeed, despite the opportunity for users to change some weights in the model, so many decisions have been made by the model-builders, and the model calculations themselves are so numerous, that the exact derivation of the final output is not clear to decision makers, the public, or even to any one planner contributing to the model. Although this may be an inevitable feature of any detailed planning process, the use of more and more complex computer models for land use planning does have the effect of alienating the public still further from the assumptions built into the planning process.

The METLAND model was built with the intention that it could be "reparameterized" with new data for use in other parts of the world. Building the model required the work of 40 people for seven years, and hundreds of thousands of dollars.

To date, the model has been reparameterized for use in the Geelong Region, Victoria, Australia; the upper Hussatonic River basin, Massachusetts, and the city of Durban, South Africa, and copies sent to parties in Germany, the Netherlands, and Canada as well as the United States (J. E. Fabos, personal communication, 1983).

The Australian CSIRO South Coast Study

The CSIRO Land Use Research Division, an Australian Federal research organization, developed a computer-aided land use planning program (SIRO-PLAN) during the same period that METLAND was developed (Austin and Cocks 1978). The CSIRO team applied its methodology (Figure 6.19) to the Eurobadalla Shire and environs, on the south coast of New South Wales. The CSIRO methodology also started with an inventory of landscape attributes and identified 3900 homogeneous land units by computerized map overlay. Rather than classify existing land uses by biological productivity, SIRO-PLAN classified land by land tenure (public, private), and current development status (cleared, farmed, forested). Whereas METLAND rated each land parcel for biological and soil denudation potential and rated the compatibility of these with five land use classes, the SIRO-PLAN system coded "raw" information on geology, vegetation, landform, and soils and determined the compatibility of these with eight land uses by a set of subjective "exclusion rules."

An "exclusion rule" states which landscape attributes are incompatible with particular land uses. The eight land uses were agriculture, forestry, urbanization, recreation, beekeeping, conservation, and residue assimilation (landfills, septic tanks). An exclusion rule for forestry took account of slope and potential log volume (see Figure 6.20); for urbanization, one rule excluded land with median slopes >20°.

Application of exclusion rules generates a composite map showing all nonexcluded land uses possible on each land parcel. Whereas METLAND makes greater use of indexes and uses dollars or energy units to rate suitability of land for development, SIRO-PLAN uses a larger number of exclusion rules, in which ecological or economic judgments remain more implicit. The SIRO-PLAN does attempt to deal with the problem of spatial interdependence of land units by establishing exclusion rules for land units that are "incompatible" with uses on adjoining units. In this regard SIRO-PLAN is more sensitive to this problem than METLAND, and research on this aspect continues (Baird 1981).

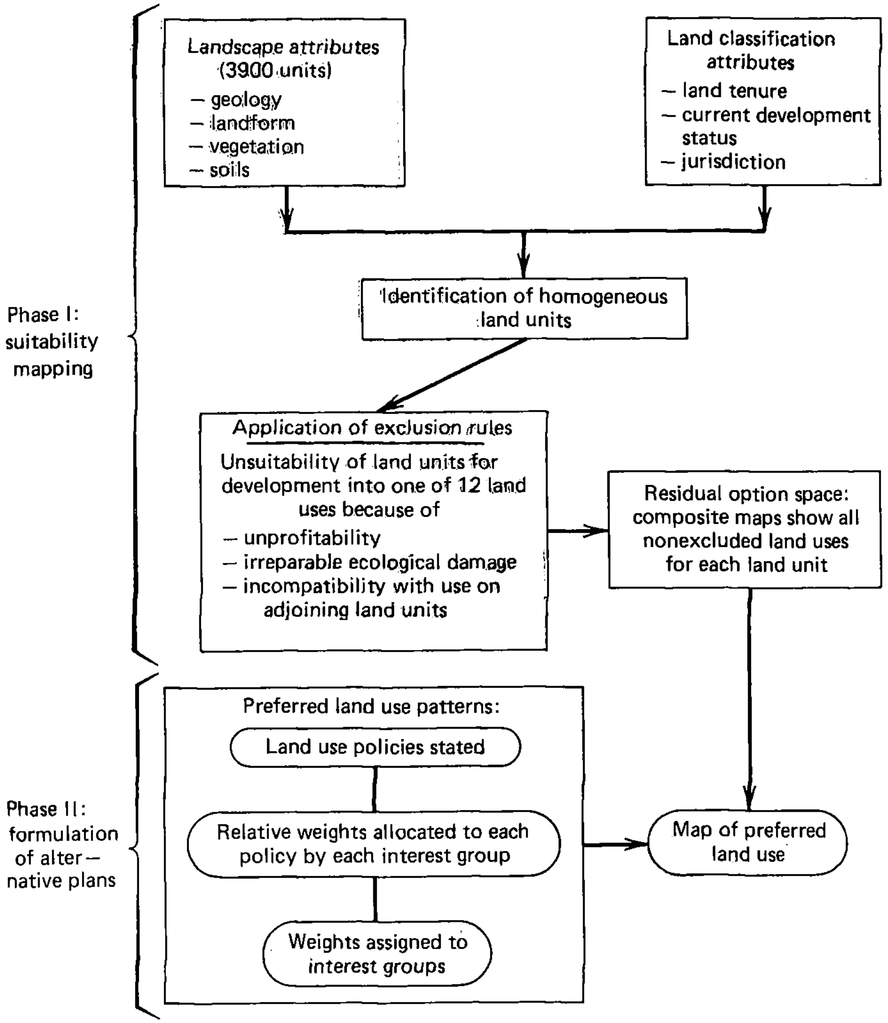


Figure 6.19. Steps in the CSIRO approach to land use planning (SIRO-PLAN), as applied to the south coast of New South Wales, Australia (from information in Austin and Cocks 1978).

In Phase II (formulation of alternative plans) SIRO-PLAN uses explicit policy statements to establish land use priorities. All policy statements are given weights (relativized to 100) by representatives of five public interest groups (agriculture, conservation, forestry, recreation, urbanization). Each interest group is also weighted in importance. The application of the weighted goals to the residual land use option space generates a preferred land use plan by optimization through linear programming (see Chapter 3). For example, policy statements give preference to a use on land most ecologically suited to it, to agriculture on private land, to recreation near cities, and to existing land uses.

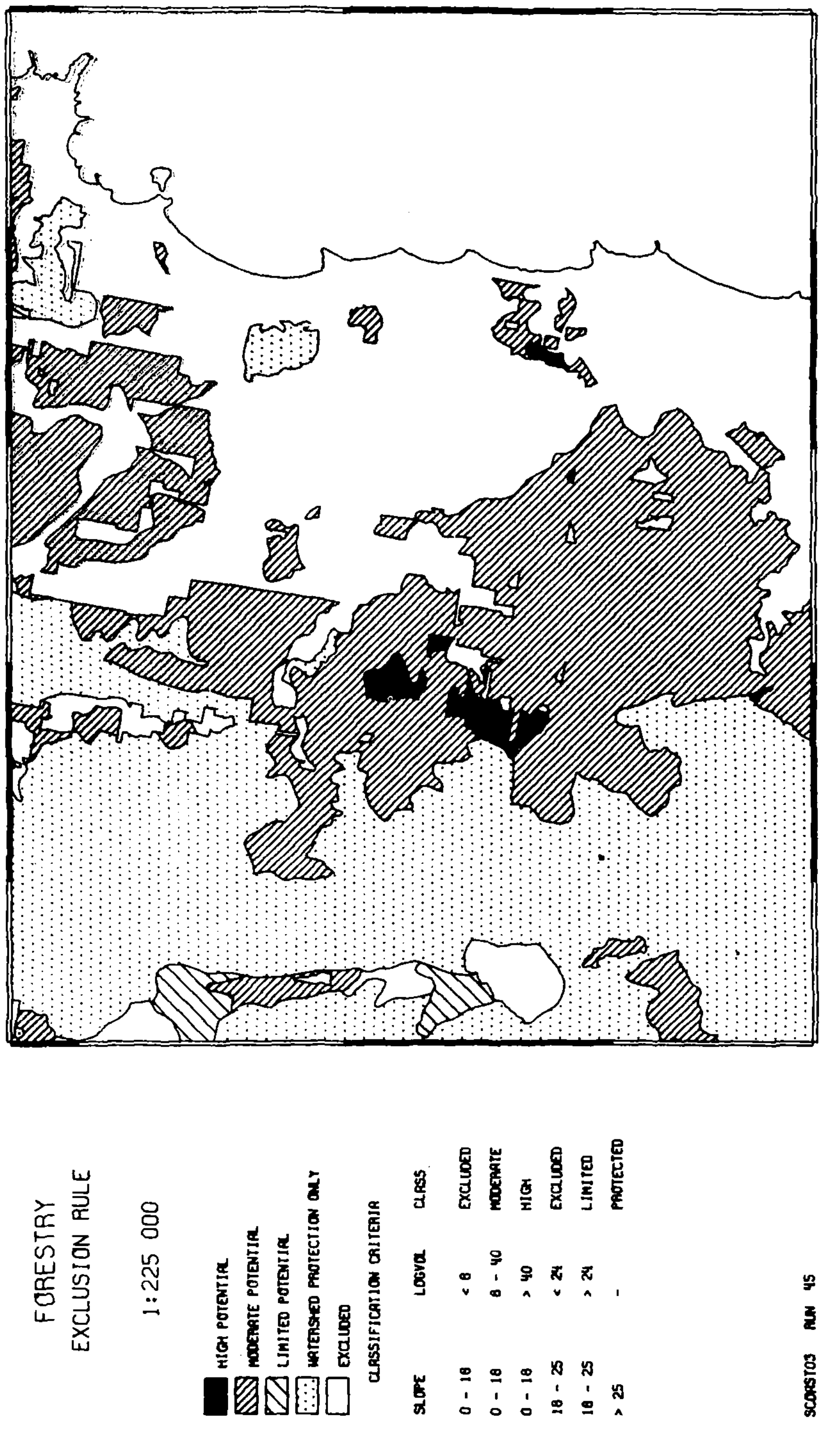


Figure 6.20. Classes of forest growth capability based on landscape attributes, generated by SIRO-PLAN. Reprinted from Austin and Cocks (1977) with permission of the Division of Water and Land Resources, CSIRO.

By contrast, METLAND proposes three plan formulation approaches. The first (Figure 6.17, Phase II) uses an economic criterion: choose land use options with lowest development cost and greatest economic benefit. These possibilities are then screened for ecological compatibility and feasibility of providing public services. This approach has been modeled only for residential development to date. A range of possible plans is thus generated by METLAND. The plans may also be generated by extrapolating existing trends in development, given existing zoning and master plan restrictions, or by inserting community group priorities. The main differences in plan formulation, then, are that SIRO-PLAN provides greater initial flexibility in choosing guiding policies and does not use provision of public services as a suitability criterion.

Although geographic information systems provide the capacity to generate a multitude of alternative land use plans, the choice of a preferred scenario must occur by reference to explicit planning goals. The METLAND approach to plan selection incorporates ecological, economic, and social goals in the initial indexes for land units (Phase I), uses these to derive a small number of land use plans (Phase II), and evaluates each plan by reference to the final grand index scores in dollars or noneconomic units (Phase III), leaving final choice to decision makers. The CSIRO approach uses ecological and economic criteria to filter possibilities to a small number of land use plans (Phase I) and then applies enough policy goals to filter choices to a single option by linear optimization (Phase II). The latter approach more completely specifies the nature of the trade-offs to be made between economic, ecological, and other goals, although by doing so with a computer optimization program, the exact nature of the trade-offs remains obscured. In the CSIRO system "unprofitability" of a land unit for development is made as a qualitative judgment via an exclusion rule, rather than as a quantitative cost/benefit ratio. Such exclusion rules have equal weight to those based on ecological criteria. The METLAND approach to evaluation is more disaggregated, with quantitative economic and semiquantitative index scores not summed; it therefore permits the final trade-offs to be judged more explicitly by the decision maker. Despite their differences in detail the two models are quite similar in broad approach, and many of the same strengths and weaknesses occur.

The CSIRO model took 6 years and 31 professional staff to build at a cost in excess of $500,000. To aid the reparameterization of SIRO-PLAN for use in other parts of Australia, investigators at CSIRO have taken two steps. First, they have designed a somewhat simplified version of SIRO-PLAN, called LUPLAN, for use on microcomputers and line printers owned by most local government planning agencies (Ive 1980). Second, they have compiled a check list of policies or guidelines for use, as a starting point, by local planners (Cocks et al. 1980, Compagnoni and Cocks 1981) and have developed a computerized data bank (ARIS—Australian Resources Information System; Cocks and Walker 1980) containing raw spatial data on resources, bibliographic information, and a mapping capability. With these developments SIRO-PLAN has begun to be used more widely by local agencies (M. Austin, personal communication, 1983). It was also used to prepare a management plan for the Cairns section of the Great Barrier Reef Marine Park (Cocks et al. 1982).

Corridor Siting

A subclass of land use planning problems to which computerized techniques have been applied involves selection of an optimum corridor for such purposes as roads, transmission lines, pipelines, or tanker routes. End points on a map are specified, and search procedures among land units identify contiguous parcels that satisfy specified criteria such as minimum length, cost, or optimization of conflicting economic and environmental goals.

Rasmussen et al. (1980) illustrate a computerized technique for the selection of road paths through forest which would keep construction costs low and scenic quality high. The costs of road building were calculated based on the cost of clearing forest from land units of particular slope and stand density. The economic value of the scenic quality of forest stands was estimated by use of a panel-of-experts technique (Daniel and Boster 1976). Because data on slope, forest density, and scenic quality were available on a coarser grid-cell density than was to be used for path selection, a computer program called SYMAP (Dougenik and Sheehan 1975) was used to interpolate values between available data points, to fill in values for each cell of the map grid. Different weights were applied to the importance of scenic quality or construction costs, and different road routes were generated. Once a desirable corridor is determined by these criteria, other computer programs, such as OPTLOC (Bennett 1973) or FSRDS (George 1975), can be used to locate and align the road within the corridor.

General Comments on Geographic Information Systems

From these three examples we see that geographic information systems offer the potential for finding optimum one- or two-dimensional spaces for particular development purposes based on a range of landscape attributes. Following the mapping of quantitative or economic indexes of landscape value, contiguous cells are chosen that optimize particular weighted objectives or remain as "option spaces" following the elimination of unsuitable areas. In the process of constructing indexes much information is lost, information is extrapolated beyond the empirical data base, and sources of statistical error are compounded.

A question needing further research in unitized land capability mapping is how to account better for the spatial interdependence of landscape units. One approach is to combine individual units into larger, ecologically homogeneous areas using cluster analysis. Typically the landscape attributes used in such a cluster analysis reflect structural rather than dynamic features of ecosystems. One way to isolate areas that act as a functional unit for flow of materials, energy, or species is to start by identifying land classes at an ecosystem, ecoregion, or larger level and devising regional plans that account for these larger units of integration. For example, Cooper and Zedler (1980) mapped natural areas as regional units in southern California, ranked these on a four-point "ecological sensitivity" scale, and recommended avoidance of the most sensitive areas when planning developments such as rights-of-way.

A major issue is how to identify the natural boundaries of the "regional ecological units." As illustrated diagrammatically in Figure 6.21, there is a continuum in the areal extent of the flow of materials (including pollutants), energy, and species in the landscape, punctuated by significant declines in the rate of exchange between landscape units at certain boundaries of scale. Thus as the edge of a forest stand is reached, a number of species reach the boundaries of their likely migration, though the dispersal probability is itself a continuous function within and between species. Some individuals of minimally dispersing species will escape the stand border, just as some species are more likely to emigrate than others (e.g., deer vs. burrowing rodents). Waterborne pollutants are confined within watershed boundaries in certain

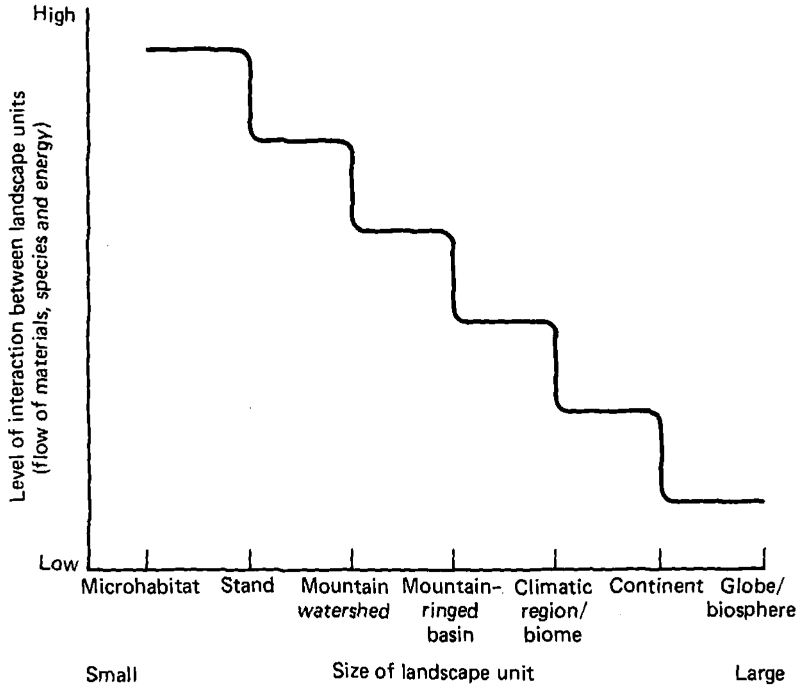


Figure 6.21. Flux of materials and energy between landscape units of increasing scale. The exchange of materials (including pollutants), energy, and species between landscape units is continual across areas of increasing extent, but certain ecological boundaries cause a decline in exchange of these, resulting in a step curve.

directions, but can escape this boundary via river or groundwater flow. Large quantities of pollutants are often confined within "airsheds" defined by basin topography (mountain ranges surrounding flatter areas), but a certain proportion of pollutants will disperse beyond such a basin. For effective land capability mapping, these natural ecological boundaries should be used, but at the same time planners should recognize that the appropriate ecological boundary to use may differ depending on whether one is focusing on species dispersal, water or air pollutant movement, or some other feature. Hence dispersal of air or water pollutants are typically modeled separately (see Chapter 7), as is movement of species between landscape units (see Chapter 11).

EVALUATING ALTERNATIVE LAND USE PLANS

The geographic information systems discussed in the previous section incorporated economic, ecological, and aesthetic criteria into the process of scenario generation. Because final plans are a compromise between conflicting criteria, one may evaluate the final plans by examining how close each comes to achieving specific economic, ecological, or aesthetic goals. The methods of evaluation in relation to economic goals were discussed in Chapter 5. Here we will briefly review methods of evaluation in relation to ecological goals and refer readers to additional work on aesthetic evaluation.

Ecological Criteria

Carrying Capacity Approaches

One approach to evaluating a proposed land use plan in relation to ecological goals is to examine whether the proposed level of resource use will exceed the natural "carrying capacity": the ability of the natural ecosystem to support such levels of use without adverse ecological effect.

The carrying capacity concept derives from the study of population growth in ecology. In the presence of a limitless supply of resources essential for growth, the rate of population growth (the rate of change in number of individuals N present at time t vs. $t + dt$) will be proportional to the initial population size (N_0), and the intrinsic rate of natural increase (r), which is a function of generation time and reproductive biology of the species. Hence the J-shaped exponential growth which results (Figure 6.22*a*) can be expressed in the equation,

$$\frac{dN}{dt} = rN_0 \tag{6.2}$$

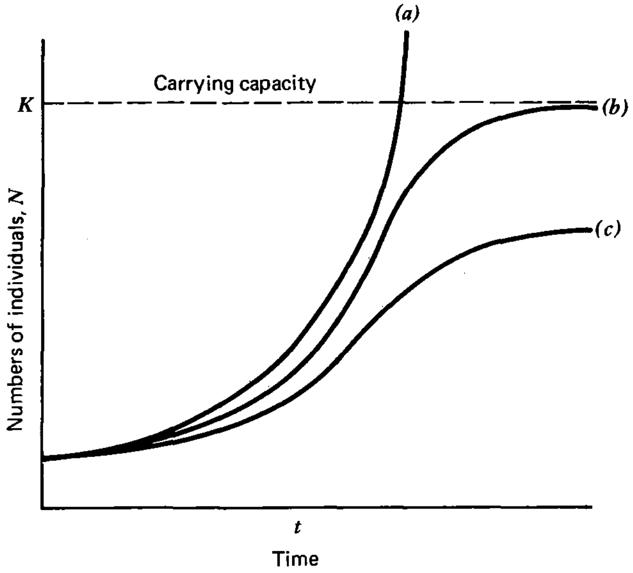


Figure 6.22. Population growth and carrying capacity. (*a*) The exponential curve of population growth; (*b*) the sigmoidal or logistic curve of population growth of a species in the presence of a limiting resource. K is the maximum sustainable population, or "carrying capacity," on this resource base. (*c*) A possible growth curve of a species in the presence of competition from another species for the limiting resource.

In the presence of a limited supply of some essential resource, the population growth will be slowed due to negative feedback (e.g., competition for the scarce resource), and eventually net population growth will cease at a level equal to the maximum sustainable by the essential resource in least supply (the limiting resource). This maximum sustainable level (K in Figure 6.22*b*) is the carrying capacity of the resource base for the species. The growth curve is S-shaped, sigmoidal or "logistic," and can be modeled as

$$\frac{dN}{dt} = rN\left(\frac{K - N}{K}\right) \tag{6.3}$$

The population growth rate of an organism is further affected by competition with other species, so that the equilibrium population size of a species in the presence of competitors will normally be lower than in the absence of competitors (Figure 6.22*c*). For discussions of population ecology, see such texts as Krebs (1972) and Whittaker (1975).

When the concept of carrying capacity is extended beyond population studies, it quickly becomes evident that defining the natural carrying capacity involves subjective judgment regarding what constitutes "adverse" ecological effects. Whether the trampling of a meadow in a national park, and creating a hiking trail, exceeds the carrying capacity of that environment will depend on the evaluation criteria applied. A preservationist concerned with maintaining the physical environment may argue that such trampling has changed the natural function of that portion of the ecosystem and is therefore a breach of the carrying capacity. A hiker concerned with wilderness appreciation may feel that this level of damage has not ruined his or her ability to experience the meadow, and indeed has enhanced it by improving access. A park official may feel that the park's ability to accommodate the increased number of visitors to the area (parking, sanitation, etc.), resulting from the increased access, has been exceeded. Carrying capacity has thus been judged in at least three different ways: environmental, perceptual, and institutional. Godschalk and Parker (1975) note that the carrying capacity of a region for urban growth is often set by all three of these perspectives. Local water supply may initially be limiting to growth (environmental); as rivers are dammed and channelized to increase water supply, a new limit may be reached as citizens feel the environment is becoming too unnatural (perceptual); if this threshold is passed, the ability of institutions to raise the taxes to supply abundant, unpolluted water to the growing population may finally be exceeded (institutional). In many Mediterranean- and arid-climate urban regions precisely this progression has occurred, and institutions struggle to find socially acceptable means to increase water supply.

Frissell et al. (1980) tried to use a carrying capacity concept to develop a land use plan for Yosemite National Park. Their technique involved mapping the park by level of scenic and biotic value and allocating acceptable levels of visitor use to each zone. This was done first by determining land areas physically unsuitable for extensive campground and facility development due either to natural hazard, susceptibility to soil erosion or compaction, dust buildup, or presence of sensitive wetlands. The amount of remaining area judged suitable for development was 26% less than the area currently developed. The existing and developed land area was then reduced by 26% to obtain a plan considered within carrying capacity limits. Such an approach assumes that the existing ratio of number of visitors to developed area is acceptable and simply reduces both to match the level of development considered ecologically acceptable. In fact, however, there was no empirical evidence that the existing ratio of people to developed land was ecologically, perceptually, or institutionally within acceptable limits.

Gilliland and Clark (1981) also explored use of carrying capacity concepts in planning the future of Lake Tahoe, a recreational lake surrounded by cabins and hotels in the Sierra Nevada bordering California and Nevada. Table 6.11 shows sediment and phosphorus loading rates for the lake under estimated "natural" (predevelopment) and present conditions, as well as under three alternative land use plans or "environmental threshold standards." The urban land use in Table 6.11 is divided into areas adjacent to water ("stream environment zones") and landlocked areas. The "natural conditions" column in Table 6.11 takes a preservationist view and assumes that *any* urban development will exceed the carrying capacity. This assumption does not take into account any natural ecosystem resistance (see "inertia," Chapter 12) or assimilative capacity (Chapter 7), so that any empirical attempt to determine the ecological carrying capacity is forgone. The three alternatives A, B, and C simply attempt to establish levels of use given different perceptual and institutional (cost) constraints. Thus in this example there has been no attempt to determine the true ecological carrying capacity of the lake.

Starting in 1974, the U.S. Fish and Wildlife Service attempted to use detailed ecological data to establish carrying capacity for wildlife habitats. The U.S. Fish and Wildlife Service (1980a, b; 1981) methodology attempts to evaluate changes in the carrying capacity of a habitat for a particular species of wildlife. For each species of interest, ecological field and laboratory studies are conducted or reviewed in an effort to determine the optimum conditions for survival and reproduction of the species. The optimum value for each habitat variable is given a habitat suitability index (HSI) value of 1.0, and habitat values less than (or in some cases, greater than) the optimum are scaled linearly from 1.0 to 0.0 on the HSI scale (see Figure 6.23*a*). In the absence of more detailed information, a linear relationship is assumed between the abundance of a species and the habitat variable, and between HSI and the carrying capacity (modal peak). There is a good theoretical basis for questioning this assumption, since most species show a Gaussian response curve (Figure 6.23*b*) to the habitat variable controlling it most strongly and more complex nonlinear responses to less significant habitat factors (Austin 1976; Westman 1980, Ch. 10).

Once a suitability index scalar is obtained for each habitat variable affecting the species, existing habitat conditions are rated on the scalar as a proportion of the optimum or carrying capacity condition (e.g., HSI = 0.4 for 25% canopy cover in Figure 6.23). The theoretical weakness with this procedure is that if single-species experimental data are used, it assumes that the "optimum" habitat for a species in the absence of competition is equal to its optimum in the field. Due to niche differentiation in a multispecies community, however, habitat optima are typically different for a species in the community setting than in isolation (see, e.g., Whittaker 1975, pp. 77–82).

To combine separate HSI values for different ecological parameters into a single grand index of habitat suitability for the species, any of several methods are proposed (U.S. Fish and Wildlife Service 1981). If the parameters are such that a low suitability in one parameter (e.g., herbaceous cover in which hawk prey lives) is compensated for by a high value of another variable (e.g., high cover of tall, isolated trees used as posts to look out for prey), the two (or more) parameters are to be averaged arithmetically or geometrically. If the relationship between habitat suitability variables is cumulative (e.g., herb cover and tree cover both encourage hawk prey species), then the variables are simply added. If, however, the sum exceeds 1.0,

Table 6.11. Three Alternative Environmental Threshold Standards and Their Carrying Capacity Implications for the Lake Tahoe Basin, California

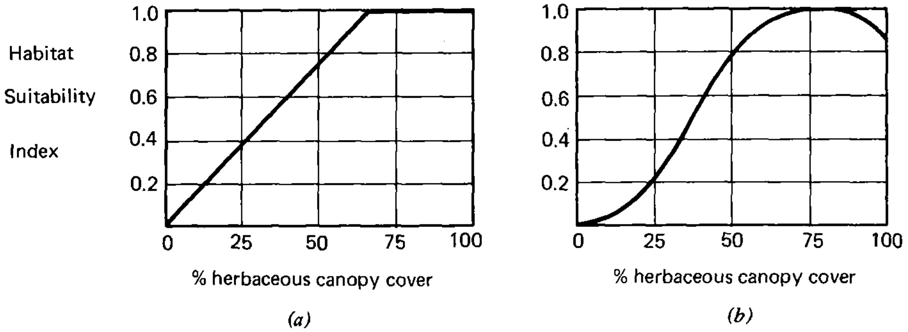
	Natural Conditions	Present Conditions	Alternatives A	B	C
		Desired Environmental Quality			
Water quality of Lake Tahoe	Equilibrium or undetectable degradation	Exponential deterioration	Maintain existing quality by reversing current trend of exponential deterioration with a margin of safety.	Maintain existing quality by reversing current trend of exponential deterioration.	Allows the present exponential deterioration to continue.
	Primary productivity[c] 40 $gC/m^2/yr$	Primary productivity was 80 $gC/m^2/yr$ in 1978; the increase averages 5%/yr.			
	Clarity[c] 29 m (Secchi Disk depth annual average)	Clarity was 26 m in 1978; decline averages 1%/yr.	(It is not possible to determine precisely what reduction in nutrient and sediment loads is required to reverse the current trend toward eutrophication.)		
		Environmental Threshold Standards[a] (Metric Tons/Yr as Runoff)			
Sediment loading rate	3100	61,000	36,000	38,000	82,000
Total nitrogen loading rate					
Dissolved	10	142	84	89	191
Particulate	16	242	143	150	325
Total	26	384	227	239	516
Total phosphorus loading rate					
Dissolved	5	77	45	48	103
Particulate	32	530	313	330	713
Total	37	607	358	378	816
Mitigation cost (million 1979 dollars)	N/A	N/A	95	95	0
		Carrying Capacity			
Urban land use[a] (hectares)					
Stream environment zones	0	1,740	1,740	1,740	3,764
Total	0	9,543	9,543	9,543	14,211
Population[b] (summer peak)					
Residents	0	73,200	73,200	84,400	106,600
Total	0	223,200	223,200	257,500	325,000

Source: Reprinted from M. W. Gilliland and B. D. Clark (1981) The Lake Tahoe Basin: a systems analysis of its characteristics and human carrying capacity, *Environ. Manage.* 5:397–407, with permission of Springer-Verlag, New York.

[a] Based on data from the California State Water Resource Control Board (1980), natural sediment, nitrogen, and phosphorus loading rates are somewhat controversial; land use represents subdivided land.

[b] Assumes that the land use to people ratio under each alternative is the same as in 1978.

[c] Primary productivity measurements began in 1960; clarity measurements in 1968.



(a) (b)

Figure 6.23. U.S. Fish and Wildlife Service HSI scalars. (*a*) Habitat Suitability Index (HSI) in relation to herbaceous cover for the red-tailed hawk, from Figure 3.12 of U.S. Fish and Wildlife Service (1981). (*b*) A Gaussian curve fitted to the same modal optimum as in part *a*. On ecological grounds this is a more likely shape for scalars.

1.0 is taken as the maximum value for the HSI grand index. This introduces an undesirable nonlinearity into the relationship between component HSIs and the grand index. If a single habitat parameter is considered a limiting factor to the welfare of the species, its value is suggested to be used alone for the grand index. (The Fish and Wildlife Service's method actually recommends taking the value of the HSI parameter with the lowest score as the "limiting factor." This procedure has no basis in ecological theory since the limiting factor will not necessarily be the one with the lowest HSI index.)

A major problem with any of these approaches to aggregation is that they require extensive empirical study before the true nature of the relationships between variables can be ascertained. Further, of the many ecological variables being rated by an HSI index, it is unlikely that the relationships between all of them will be cumulative, or all compensatory. Hence to compile a grand index, a more complex formula—involving addition of some variables, averaging of others, and so forth—would have to be derived. The interrelations between sets of variables (e.g., cumulative with compensatory variables) would also have to be determined. Such requirements exceed the current capacity of ecological science. In the U.S. Fish and Wildlife Service system all variables are assumed to be cumulative, compensatory, or part of a "limiting factor" complex. No empirical evidence is used in this determination. The grand index of HSI values is finally multiplied by the area thus assessed (e.g., 10 km^2) to obtain habitat units (HU) in areal units (km^2). Habitat units are later summed for different subareas of a species range of concern. The evaluation of the economic significance of the habitat suitability changes is treated in an additional phase (U.S. Fish and Wildlife Service 1980c).

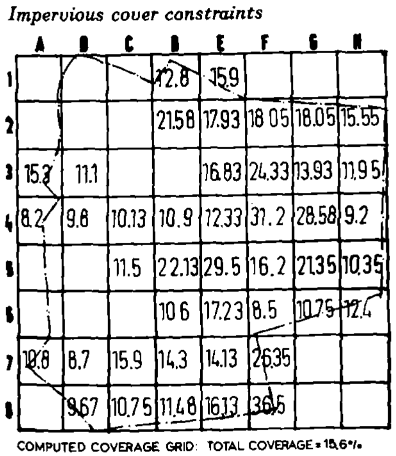
Although the carrying capacity notion is used in the habitat evaluation method, it is applied with disregard to several fundamental ecological concepts, and the mathematical manipulations are not empirically justified. The overall method is therefore theoretically flawed at present. Some features of the method, however, do hold promise for use once refined. The U.S. Fish and Wildlife Service (Fort Collins, Colo.) had prepared HSI models for 77 species of American fish, birds, and mammals by the end of 1983.

The notion of carrying capacity is an important one, but its application in assessment techniques to date has been troubled either by a lack of use of detailed ecological data or by the neglect of ecological theory in the application of those data. The application of the carrying capacity concept is clearly ripe for further research.

Environmental Performance Standards and Impact Zoning

By disaggregating an ecosystem into specific components whose natural functions can be exceeded, one has a somewhat more manageable approach to the carrying capacity concept in ecological land use planning. The "environmental performance standards" discussed in Chapter 2 exemplify this approach. For example, development may be permitted if natural runoff rates do not increase or if they decrease by less than 10% (Rahenkamp et al. 1977). Such a performance standard limits the degree of change from the natural condition, which is assumed to represent a natural carrying capacity. Of course, if a natural site is in a stage of successional change to some other condition, taking the background level as an unchanging standard is of dubious merit.

Nevertheless, a given performance standard can be combined with land suitability maps to indicate the development constraints necessary on a particular land unit to achieve the environmental performance standard. Thus Figure 6.24 shows the percentage of impervious cover (e.g., concrete roofs, roads) allowable on a land unit of given soil, slope, and vegetation, so that a given level of runoff will not be exceeded. Expected runoff was computed using U.S. Soil Conservation Service's equations for calculating runoff from


Impervious cover constraints

	A	B	C	D	E	F	G	H
1				12.8	15.9			
2				21.58	17.93	18.05	18.05	15.55
3	15.7	11.1			16.83	24.33	13.93	11.95
4	8.2	9.8	10.13	10.9	12.33	31.2	28.58	9.2
5			11.5	22.13	29.5	16.2	21.35	10.35
6				10.6	17.23	8.5	10.75	12.4
7	10.8	8.7	15.9	14.3	14.13	26.35		
8		9.67	10.75	11.48	16.13	36.5		

COMPUTED COVERAGE GRID: TOTAL COVERAGE = 15.6%

Figure 6.24. Impact zoning. Map shows the percent impervious cover that can be added to each land unit and still comply with a particular environmental performance standard. In this case the standard was that the direct runoff shall not exceed that created by a land use of one single-family unit per acre. Landscapes with greater natural infiltration capacity can accommodate a larger % of impervious cover and still meet the standard. Reprinted from Figure 10 of Rahenkamp et al. (1977), with permission of *Plan Canada,* Journal of the Canadian Institute of Planners.

climate, slope, vegetation, and soil porosity data (U.S. Soil Conservation Service 1972), modified by the extent of impervious surface. The resulting map is not unlike a SIRO-PLAN map in which a particular performance standard is applied as a policy.

In the present example the map was derived from a Canadian geographic information system (Rahenkamp et al. 1977). The use of environmental performance standards, combined with land suitability maps, to produce acceptable levels of environmental change on particular land units, is termed *impact zoning*. It has been used in two communities in Massachusetts for several years (Kelly 1975, Lynch and Herr 1973).

Although the combining of performance standards with capability maps permits a somewhat more manageable approach to establishing ecological carrying capacity, the problem of the spatial interdependence of units remains. A true ecosystem carrying capacity derives from the interaction of ecological elements (land, air, water, species) in space and time. The unitized "impact zoning" approach does not integrate across these ecosystem elements, or spatially across land units. Perhaps factor analysis of ecological elements and cluster analysis of spatial units can help to reassemble the holistic notion of carrying capacity, starting with impact zoning as a basis. In so doing, we are reassembling parts of a geographic information system. The METLAND or SIRO-PLAN systems have built-in (inflexible) or user-applied performance standards, respectively.

Aesthetic Criteria

In addition to economic or ecological criteria for evaluating the effects of development on a land resource, aesthetic criteria may also be applied. Assessment of the visual or scenic qualities of a landscape is sometimes termed "landscape evaluation." Some analysts have attempted to evaluate the scenic qualities of a landscape by dissecting it into "universally valued" landscape elements (mountains, waterfalls, long vistas, etc), or design elements (color, texture, line, contrast). Others (e.g., Jacques 1980) have declared the process of landscape evaluation totally subjective and have sought, for example, to compare public opinion on vistas before and after changes, using photographic comparisons and other techniques. Dearden (1981) suggests that landscape appreciation derives from some mix of "intrinsic beauty" and individualistic pleasurable responses. He notes that landscapes of superlative beauty are more likely to be judged similarly by a wide variety of groups than landscapes of inferior quality. The field of landscape evaluation is young, but active. While a treatment of issues in this field is beyond the scope of this book, readers may consult comprehensive literature reviews by Dalzell (1978), Daniel and Boster (1976), Dearden (1980), Krutilla and Fisher (1975), Lang and Armour (1980), McAllister (1980, Ch. 11), Moss and Nickling (1980), Penning-Rowsell (1980), and books by U.S. Forest Service (1972b, 1973–75), and Zube et al. (1975).

CONCLUDING REMARKS

The use of landscape characteristics as indicators of land suitability or vulnerability, and the recognition of homogeneous land units in relation to these characteristics, are two of the key steps in computerized land use planning. Many such systems have further assumed that the landscape characteristics are independent both in effect on land suitability (factor independence) and in interaction between spatial units (spatial independence). In both cases interdependence is usually the more realistic assumption. While attempts to deal with factor interdependence are reasonably well developed, attempts to deal with spatial interdependence are less so.

Many geographic information systems tend to combine indexes of suitability or vulnerability in additive, multiplicative, or weighted fashion, without empirical evidence to characterize the true form of interrelationship. The use of nonlinear scalars holds promise in providing more realistic forms of interrelation, but the empirical data needed to develop these are time-consuming and difficult to collect. Data collected on single species under laboratory conditions, furthermore, are not likely to characterize the performance of the same species in a community setting in the field. Yet the use of field data often limits application of the scalar to a particular physical locale. In the short term the solution to these problems would appear to lie in accepting generalization and extrapolation from available data. In the longer term the science of ecology may clarify the attributes of species, communities, and landscapes that serve as the best predictors of ecosystem response to stress and hence permit more effective prediction from a limited data base. The progress in this area is reviewed in Part V.

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