Ecological Applications, 6(2), 1996, pp. 608–618

A QUANTITATIVE APPROACH TO DEVELOPING REGIONAL ECOSYSTEM CLASSIFICATIONS[1]

George E. Host and Philip L. Polzer
Natural Resources Research Institute, University of Minnesota, 5013 Miller Trunk Highway, Duluth, Minnesota 55811 USA

David J. Mladenoff
Bureau of Research, Wisconsin Department of Natural Resources and Department of Forestry, University of Wisconsin–Madison, 1630 Linden Drive, Madison, Wisconsin 53706 USA

Mark A. White
The Pacific Forest Trust, P.O. Box 858, Boonville, California 95415 USA

Thomas R. Crow
Forestry Sciences Laboratory, North Central Forest Experiment Station, 5985 Highway K, Rhinelander, Wisconsin 54501 USA

Abstract. Ecological land classification systems have recently been developed at continental, regional, state, and landscape scales. In most cases, the map units of these systems result from subjectively drawn boundaries, often derived by consensus and with unclear choice and weighting of input data. Such classifications are of variable accuracy and are not reliably repeatable. We combined geographic information systems (GIS) with multivariate statistical analyses to integrate climatic, physiographic, and edaphic databases and produce a classification of regional landscape ecosystems on a 29 340-km^2 quadrangle of northwestern Wisconsin. Climatic regions were identified from a high-resolution climatic database consisting of 30-yr mean monthly temperature and precipitation values interpolated over a 1-km^2 grid across the study area. Principal component analysis (PCA) coupled with an isodata clustering algorithm was used to identify regions of similar seasonal climatic trends. Maps of Pleistocene geology and major soil morphosequences were used to identify the major physiographic and soil regions within the landscape. Climatic and physiographic coverages were integrated to identify regional landscape ecosystems, which potentially differ in characteristic forest composition, successional dynamics, potential productivity, and other ecosystem-level processes. Validation analysis indicated strong correspondence between forest cover classes from an independently derived Landsat Thematic Mapper classification and ecological region. The development of more standardized data sets and analytical methods for ecoregional classification provides a basis for sound interpretations of forest management at multiple spatial scales.

Key words: climate; ecological land classification; geographic information systems; landscape ecosystem; physiography; Wisconsin.

INTRODUCTION

Recent interest in the analysis and management of landscapes has required the development of spatial frameworks that stratify landscapes into relatively homogeneous regions. Ecological land classification, a hierarchically structured, multifactor approach for mapping ecological units at multiple scales, has been shown to be helpful in quantifying variation in fundamental ecological processes and response to management (Barnes et al. 1982, Host et al. 1987, 1988, Spies and Barnes 1986, Zak et al. 1986). Ecological classification systems (ECS) are defined by factors appropriate to a particular spatial scale. For example, maps at 1:250 000 are typically defined by mesoclimate and regional physiography, whereas 1:15 000 scale maps are defined in terms of soil texture and local ground flora (Damman 1977, Host and Pregitzer 1992). These fine-scale classifications have been used to develop forest management strategies (Cleland et al. 1992), assess wildlife habitat (Johnson et al. 1991), and plan other management operations. Regional classifications often span numerous land ownerships, and are more appropriate for strategic planning issues, such as developing wolf movement corridors across political boundaries (Mladenoff et al. 1995), managing moose habitat, or designing conservation reserves.

Considerable effort has gone into developing ecological classifications at continental (Bailey 1983, 1987), interregional (Omernick 1987), regional (Albert et al. 1986), and local scales (Jordan 1983, Host et al. 1993, Cleland et al. 1994). These classifications, particularly at large spatial scales, often vary in data sources and factors delineating ecosystems. Bailey (1983) based his classification of the United States on

---

[1] Manuscript received 31 August 1994; revised 8 May 1995; accepted 15 June 1995; final version received 28 July 1995.

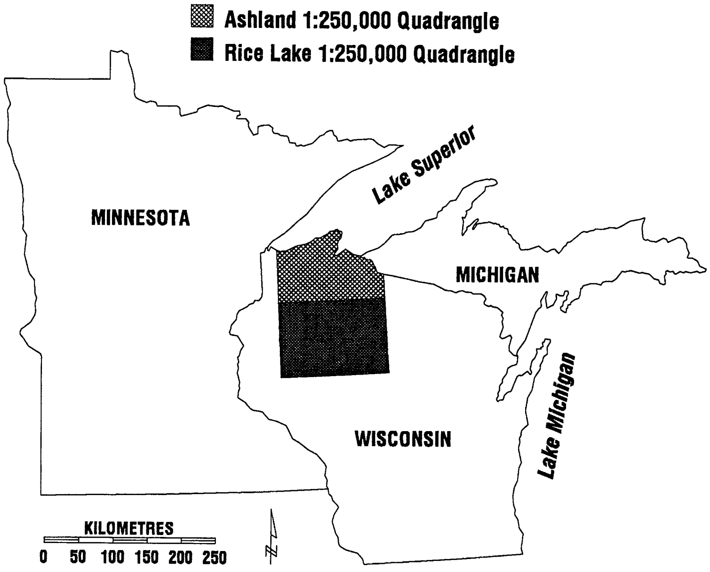

FIG. 1. Location of study area. Rectangles indicate borders of 1:250 000 U.S. Geological Service quadrangles.

Koppen's (1931) climatic classification and Kuchler's (1964) classification of potential natural vegetation. Omernick (1987), in his classification of the conterminous United States, based his delineations on Kuchler's vegetation map in conjunction with physiography (Hammond 1970), land use pattern (Anderson 1976), and soils (USDA 1957). These classifications generally require numerous subjective decisions on the relative importance of different data layers, although the classification units are then treated as objectively defined landscape entities. In addition, such classifications and similar efforts at state and regional scales often contain unit boundaries that are defined by consensus. Because of the methods, the results are often not repeatable.

Albert et al.'s (1986) regional classification of Michigan is based on climate and physiography to identify landscape ecosystems. Denton and Barnes (1988) represent one of the first attempts to employ quantitative methods in the development of a climatic classification. Incorporation of detailed climatic and physiographic information improved the spatial resolution of this classification, but the analytical methods required synthesis and interpolation of statewide weather stations across many years, with the associated problems of weather station density, error screening, and missing data (Denton 1985).

The analysis and integration of climatic and physiographic data are confounded by the subjectivity of boundary criteria, limitations of regional-scale data sources, and analytical problems in dealing with multiple spatial data layers. The increased availability of geographic information systems (GIS) for ecological research (Mladenoff and Host 1994) and the concurrent development of regional-scale spatial databases by government and private industry have resolved some of the problems of regional ecological classification. GIS are readily suited to spatial analysis tasks such as map overlays and the statistical analyses required to integrate different spatial databases. Raster- or pixel-based GIS systems designed for processing remote sensing imagery are capable of analyzing large volumes of data; these techniques can also be adapted to other types of spatial databases. The U.S. Geological Survey (USGS) and the Soil Conservation Service (SCS) have been developing spatial databases related to topography, land use, and soils and making these available in digital format (USGS 1985, Soil Survey Staff 1992). Our primary objective was to develop more objective and repeatable techniques for making regional-scale ecological classifications based on readily available public and private spatial databases.

Ecologically defined maps represent hypotheses about factors that control ecosystem structure and function (Rowe and Sheard 1981). The testing or validation of these maps is thus an important prerequisite to their application. Testing of regional-scale maps is confounded by the difficulty of obtaining independent data and sufficient numbers of samples to characterize regional areas. In this study we used forest composition data independently derived from Landsat Thematic Mapper imagery to test the association of dominant forest types with regional ecosystems.

MATERIALS AND METHODS

Study area

The 29 340-km² study area encompasses the Ashland and Rice Lake 1:250 000 quadrangles in northwestern Wisconsin (43° N, 90° W to 45° N, 92° W; Fig. 1). The area includes the Apostle Islands of Lake Superior, much of the Chequamegon National Forest, and extends into the more agricultural areas of the southern Rice Lake quadrangle. The study area is on the northern edge of the "tension zone" (Potzger 1949, Curtis

TABLE 1. Aggregation of Pleistocene geologic units (Clayton 1985) into geomorphic classes.

Geomorphic class	% of total area	Pleistocene geologic unit
Red clay till	25*	Unmodified glacial topography Lake-modified glacial topography Wave-planed topography Valley side
Till-capped outwash	29	Hummocky stream sediment overlain by silty material Subglacially molded topography
Copper Falls outwash	17	Collapsed proglacial stream sediments Uncollapsed proglacial stream sediments
Copper Falls moraine	15	Thick mass movement till Thin mass movement till
Bedrock	6	PrePleistocene rock (occasional rock outcrops, but often covered with several metres of till or outwash materials)
Peat	3	Postglacial organic sediments
Sediments	4	Wind-blown sediments Spillway sediments Shoreline sediments

* Values do not sum to 100 due to rounding.

TABLE 2. Aggregation of STATSGO map units into physiographic regions.

Physiographic region	Soil texture and drainage classes	STATSGO map unit ID
EX-WD-SAND	Excessively well-drained sands	WI005, WI009, WI016, WI048, WI095
WD-SL/L	Well-drained sandy loams over loam	WI013, WI046
WD-L	Well-drained loams	WI018, WI020, WI032, WI049
WD-SiL/L	Well-drained silt loams over loam	WI014, WI024, WI027, WI031
WD-SiL/Si	Well-drained silt loams over silt	WI007, WI035, WI050
WD-FSL/Shallow to bedrock	Well-drained fine sandy loams, shallow to bedrock	WI010
MWD-FSL	Moderately well-drained fine sandy loams	WI002, WI006, WI022
MWD-SiL	Moderately well-drained silt loams	WI004
MWD-SiCL	Moderately well-drained silty clay loams	WI001
SPD-SiL/L	Somewhat poorly drained silt loams over loam	WI008, WI015, WI023, WI021, WI026
SPD-SiL/Si	Somewhat poorly drained silt loams over silt	WI019, WI025
PEAT/MUCK	Peat and muck soils	WI003, WI033, WI064

1959), and is transitional between the boreal forests of Canada and the central deciduous forests to the south (Pastor and Mladenoff 1992). Originally the region was largely dominated by pine (*Pinus strobus, P. resinosa*) on sandy soils and sugar maple (*Acer saccharum*) with yellow birch (*Betula alleghaniensis*), eastern hemlock (*Tsuga canadensis*), and pine on better soils. Spruce–fir (*Picea glauca–Abies balsamea*) and paper birch (*B. papyrifera*) forests, also often with pine, were more common in the northern portion along Lake Superior (Curtis 1959). Today the region is largely covered by second-growth sugar maple and aspen forest, following destructive logging and fires in the late 19th and early 20th centuries (Mladenoff and Pastor 1993). White pine is greatly reduced and hemlock, a former dominant, is largely eliminated from the landscape (Mladenoff and Stearns 1993).

Climatic analyses

We identified climatic regions based on a high-resolution climatic database consisting of temperature and precipitation values interpolated over a 1-km^2 grid across the study area (Russo et al. 1993). Source data were monthly averages of minimum and maximum temperatures and precipitation derived from 30-yr (1951–1980) climatological station summaries published by the National Climatic Data Center. Multiple regressions were developed to model climatic variables as a function of latitude, longitude, and elevation; the model was then used to predict values over the 1-km^2 grid (Williams and Liebhold 1995). The temperature and precipitation models were based on 126 and 162 weather stations in Wisconsin, respectively. The accuracy of the interpolations was evaluated by comparing model predictions with actual station values. The average absolute difference between predicted and observed minimum and maximum temperatures was 0.56° and 0.72°C, respectively; the average absolute difference for monthly precipitation was 0.70 cm (ZedX 1995). The 36 climatic data layers were incorporated into ARC/INFO, a polygon-based GIS (ESRI 1992), as point coverages and subsequently converted into raster format with Earth Resources Data Analysis System (ERDAS) image processing software (ERDAS 1991).

Mean monthly temperature and precipitation data were subjected to ordination and cluster analyses to identify climatic regions. Temperature and precipitation data from January, March, June, August, and Oc-

TABLE 3. Texture and drainage characteristics of dominant Pleistocene geomorphic classes based on dominant STATSGO map units.

Geomorphic class	Dominant STATSGO map units	Soil texture and drainage classes	Physiographic region
Red clay till	WI001 WI018	Moderately well-drained silty clay loams	MWD-SiCL
Till-capped outwash	WI004 WI008	Moderately well-drained silt loams	MWD-SiL
Copper Falls outwash	WI005 WI006	Excessively well-drained sands	EX-WD-SAND
Copper Falls moraine	WI002	Moderately well-drained fine sandy loams	MWD-FSL
Bedrock	WI010	Well-drained fine sandy loams	WD-FSL

tober were subjected to principal component analysis (PCA) to identify the major sources of variation. We used 5 rather than 12 mo to reduce the strong temporal autocorrelations between months (Briggs and Lemin 1992). PCAs were run on both individual (minimum temperature, maximum temperature, and precipitation) and combined data sets.

Minimum and maximum temperature and precipitation data from each of the 5 mo were the inputs in a 15-band ERDAS iterative clustering algorithm. This analysis assigns a cluster for each pixel based on minimum spectral distance and then iteratively recalculates the means of each cluster until the means no longer shift (Tou and Gonzalez 1974, ERDAS 1991). The number of classes identified in this cluster analysis was user defined; we set an initial cluster size of 10, based on the level of resolution we considered appropriate for the area. Mean values from these 10 classes were subjected to a K-means cluster analysis (Wilkinson 1990) to identify the relationship among the clusters and to aggregate similar clusters.

Physiographic analyses

Numerous studies across the Lake States have shown that at the scale of geomorphic landforms, drainage, surficial and subsurface textures, and topography are primary determinants of forest composition (Curtis 1959, Peet and Loucks 1977, Spies and Barnes 1986, Host and Pregitzer 1992). We were therefore interested in deriving these variables from available geographic databases. Two map sources of similar scale were used to develop this physiographic classification of the region. For the Ashland quadrangle, Clayton's (1984) 1:250 000 map of Pleistocene geology for the Superior Region was digitized into the ARC/INFO GIS (ESRI 1992) as a vector-based map layer. The Pleistocene map is a highly detailed classification in which geologic units are identified by topography, parent materials, mode of deposition, and estimated dates of glacial advances and retreats. This detailed map was simplified by aggregating geologic units into classes of similar origin, topography, and texture, as shown in Table 1. Seven geomorphic classes were derived from the Pleistocene geologic units. The predominant classes were water-worked tills (Red Clay Till), morainal tills, till-capped outwash, and outwash (Table 1). Secondary classes were bedrock, peat, and spillway sediments.

Detailed Pleistocene geology was not available for the Rice Lake quadrangle. Instead, we used the STATSGO soil database, which is produced by the National Cartographic Center of the SCS (Soil Survey Staff 1992) and maps aggregations of soil series, to identify the major physiographic and soil regions. The STATSGO map units are digitized onto a 1:250 000-scale 1° × 2° USGS quadrangle map base. The STATSGO database consists of generalized soil map units linked to a relational database of soil attributes. This database contains information on map unit area, the proportional areas of component soils within the map unit, and chemical and physical properties of the soils (Lytle et al. 1996). With these data we then generated soil map units with similar drainage, surface and subsurface textures, and particle sizes. The characteristic drainage class for a map unit was calculated as an area-based weighted average of ordinally ranked drainage classes (i.e., 1 = excessively well-drained, 7 = very poorly drained). This weighted rank value was then converted back to the nearest nominal class to determine the dominant drainage class. Texture and particle size, which were less amenable to the weighted average approach, were determined based on characteristics of the dominant soil component (based on proportion of total area) within each map unit. The aggregation of STATSGO map units into texture- and drainage-based physiographic classes is presented in Table 2.

The STATSGO map was considerably more detailed in the Rice Lake quadrangle than in the Ashland quadrangle. The mean polygon size in the Rice Lake quadrangle was 11 740 ha, compared with 17 330 ha for the Ashland quadrangle. Moreover, there was little overlap in STATSGO map units between the two quadrangles; of the 27 STATSGO units that occurred in the Rice Lake quadrangle, only seven occurred in the Ashland quadrangle. Three of these had only minor representation in the Ashland quadrangle (<1.5% of the area), and the remaining four were only minor components of the Rice Lake quadrangle (5% or less). Because the two quadrangles were very different in terms of the

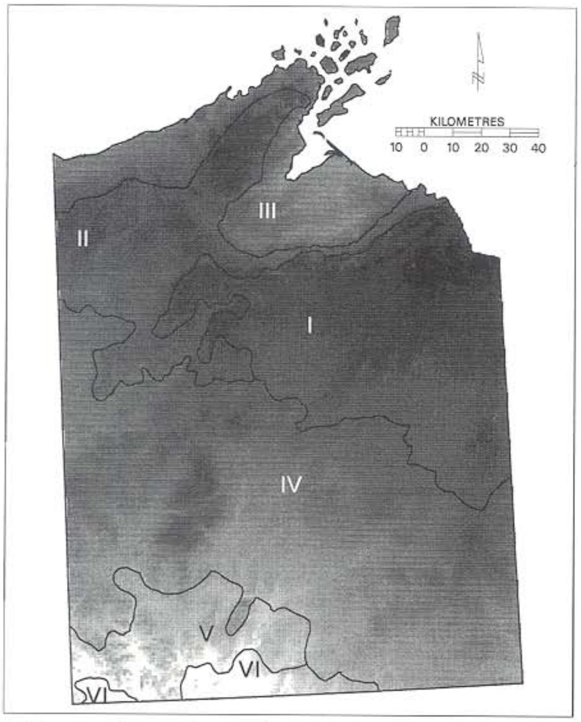

FIG. 2. Scores from principal component axis I plotted for each 1-km² pixel within two 1:250 000 quadrangles in northwestern Wisconsin. Darker pixels denote relatively higher PCA I scores. Lines and symbols represent boundaries and designations for the final climatic regions, respectively. For an explanation of climatic regions see *Results.*

STATSGO soils data, and because of the apparent difference in spatial resolution between the two quadrangles, we used the map derived from Pleistocene geomorphic classes, rather than STATSGO map units, to identify physiographic regions within the Ashland quadrangle.

To place the physiographic region from the Ashland and Rice Lake quadrangles in a common framework, we derived the dominant soil texture and drainage for each geomorphic class from the Ashland quadrangle STATSGO data. A GIS map overlay operation was performed to determine the dominant STATSGO units within each geomorphic class, and texture and drainage for these units were determined to characterize the geomorphic classes (Table 3). For convenience, the physiographic regions derived from these two data sources are hereafter referred to by their dominant drainage and texture categories; however, because of the origins of the data, topography, elevation, and depositional mode are also incorporated into these map unit identifiers.

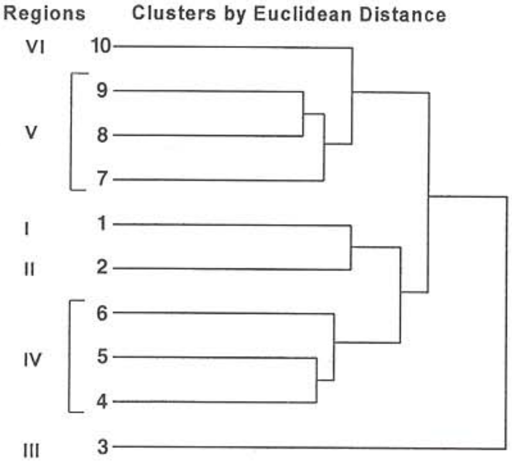

FIG. 3. *K*-means cluster analysis of climatic regions identified with ERDAS clustering routines. Roman numerals identify final groupings of the initial 10 clusters.

Integrating climatic and physiographic data

The final phase of development was to integrate the climatic and physiographic classifications. This was done by performing a GIS overlay operation between the two data sets (ESRI 1992). In the climatic database, elevation was one factor used to extrapolate climatic data, so that climatic boundaries often corresponded to elevational boundaries. Since physiographic boundaries were often related to elevational changes, there was often a strong concordance between the climatic and physiographic boundaries. When climatic and physiographic boundaries were relatively close (within 2–3 km), the two were shifted to coincide. This eliminated the numerous "sliver" polygons that occur when overlaying GIS databases. In cases where climatic and physiographic boundaries obviously diverged, the climatic boundaries were used to divide physiographic regions.

Validation

A fundamental hypothesis of ecological land classification is that the land units differ in forest com-

TABLE 4. Mean climatic data for climatic regions of northwestern Wisconsin; data shown represent variables identified as important in a principal component analysis.

Climatic region	Minimum temperature (°C)				Precipitation (cm)		
	Jan	Mar	Aug	Oct	Mar	Jun	Aug
I	−18.51	−10.37	11.44	1.56	3.35	10.34	10.29
II	−18.53	−9.90	12.11	2.11	3.28	10.08	9.83
III	−17.91	−9.29	12.67	2.78	3.40	9.53	9.27
IV	−17.62	−9.22	12.39	2.28	3.78	8.36	10.03
V	−16.88	−8.22	13.17	2.94	4.17	10.24	9.73
VI	−16.55	−7.98	13.28	3.06	4.27	10.19	9.68

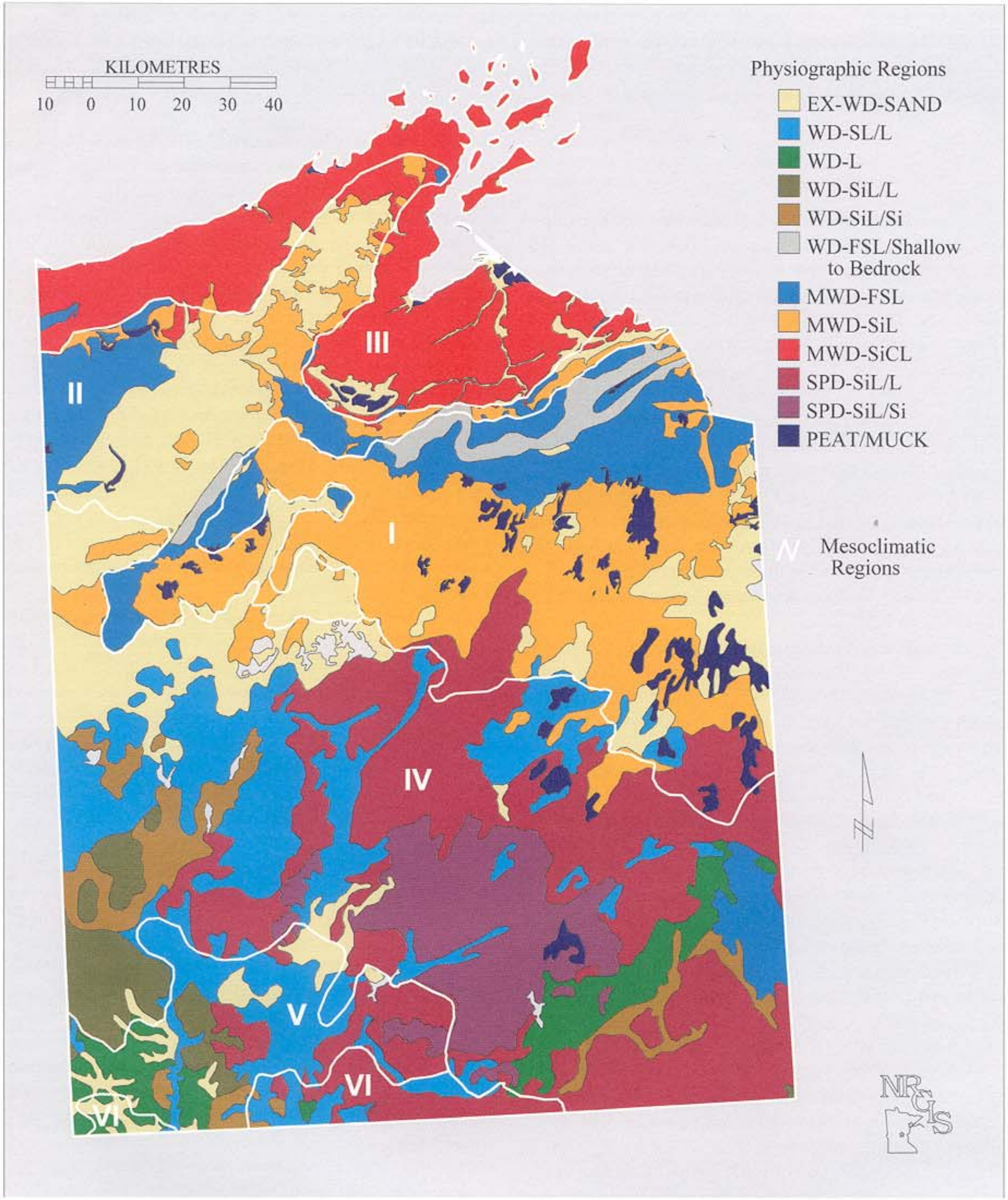

FIG. 4. Map of climatic and physiographic regions in northwestern Wisconsin.

position. While the disturbance and management histories of forest stands contribute to existing forest patterns, climate and landform provide fundamental constraints over forest composition and should be reflected in a regional classification. We used independently classified Landsat imagery to test the hypothesis that forest landscape composition differs among regional ecosystems. The Landsat classification was based on multitemporal imagery, and classified forest cover to genus and, in many cases, to species (Wolter et al. 1995). We determined proportions of cover types within each regional ecosystem and calculated the electivity index (Jacobs 1974, Jenkins 1979, Pastor and Broschart 1990), which indicates a positive or negative association of a cover type with a regional ecosystem. The Landsat classification provides an independent data set to assess species differences among ecosystems.

RESULTS

Climatic analyses

Principal component analysis.—Principal component analysis (PCA) of climatic data indicated that March precipitation and January and March minimum temperatures constituted the greatest source of variation in the data set. This first axis accounted for 87% of the overall variation. The 30-yr average minimum temperatures for January ranged from −19.4° to −16.2°C and March minimum temperatures ranged from −11.5° to −7.5°C. March precipitation across the study area ranged from 2.9 to 4.4 cm. The second axis, which accounted for 9% of the variation, was positively related to June and August precipitation and negatively related to August and October minimum temperatures. June and August precipitation ranged from 8.9 to 10.9 cm. August minimum temperatures ranged from 10.6° to 13.5°C, and October minimum temperatures ranged from 0.8° to 3.3°C.

A map of the first principal component shows the highlands of the Bayfield peninsula and inland areas of the Ashland quadrangle receiving high PCA scores, which indicate areas of low winter and spring temperatures (Fig. 2). The ameliorating effect of Lake Superior is evident in the lower scores observed immediately inland from the lake. PCA scores decrease gradually to the south, indicating latitudinal effects on climate.

Cluster analysis.—An analysis of similarity among clusters reduced our number of climatic regions from 10 to 6 (Fig. 3). The regions consisted of a relatively well-defined "lake effect" zone in the northern Ashland quadrangle, and northwest to southeast trending bands defining climatic regions to the south (Fig. 2). Regions I and II generally had the coldest temperatures throughout the year. Temperatures in Region III, which is north of Regions I and II, appeared to be moderated by Lake Superior; this unit was more similar to Region IV in the northern Rice Lake quadrangle than to its adjacent climatic regions (Table 4). There is a steep climatic gradient defined by the Penokee Range in the northeastern study area, where the transition from Region III to Region I occurs over a span of <10 km. The distribution of precipitation across the regions varied by season, with Regions V and VI in the southern Rice Lake quadrangle receiving greater precipitation in the spring and Region I in the northeastern Ashland quadrangle receiving the highest summer precipitation.

Physiographic analysis

The final physiographic classification consisted of 12 classes based on parent materials, topography, soil texture, and drainage class (Fig. 4). Classification units ranged in size from 460 to 4570 km^2. The Ashland quadrangle consisted of two very different landforms: the water-worked red clays along the south shore of Lake Superior and the sandy moraines and uplands of the outwash terraces. The Red Clay Tills (MWD-SiCL) in the northern Ashland quadrangle form a flat-to-undulating topography; this landform continues across northern Wisconsin and into the Upper Peninsula of Michigan. The Copper Falls Outwash (EX-WD-SAND) consists of collapsed and uncollapsed sediments, with topography ranging from level to hummocky (Clayton 1984). These sediments are generally sand-textured and well- to excessively well-drained. In several areas, these outwash sands are overlain by a silt-textured cap one to several metres in thickness; this is defined in the aggregate map as Till-capped Outwash (MWD-SiL). The last major feature of the Ashland quadrangle is the Copper Falls Moraine (MWD-FSL), which consists primarily of mass movement and drumlinized lodgement till (Clayton 1984). Soils of the Copper Falls Moraine are typically sandy or silty loams; drainage varies from well-drained to poorly drained depending on topographic position.

The eastern Rice Lake quadrangle consists primarily of somewhat poorly to poorly drained silt loams, as well as numerous small peat or muck depositions. The western Rice Lake quadrangle consists of well-drained sandy and silt loam, with a small proportion of excessively well-drained sand associated with river drainages. Forty-four percent of the Rice Lake quadrangle is in the somewhat poorly or poorly drained classes, compared with 3% in the Ashland quadrangle.

Validation

The analysis of the classified Landsat imagery showed strong correspondence between forest cover type and regional ecosystem. The pines in particular had strong affinities with more xeric ecosystems; 94% of all jack pine (*Pinus banksiana*) and 51% of red pine (*Pinus resinosa*) occurred on the excessively well-drained sands (Table 5). In terms of electivity, an index which estimates the strength of positive or negative association of species with the ecosystem (Pastor and Broschart 1990), jack pine had a strong positive association with the excessively well-drained sands and strong negative associations with all others (Fig. 5). Red pine was also secondarily associated with the moderately well-drained silts (23% of total cover). Sugar maple (*Acer saccharum*) was primarily associated with somewhat poorly drained silt loams and well-drained sandy and silt loams (Table 5).

Over half the recently cleared forest (56%) occurred on excessively well-drained sands (Table 5). This may be partly because this particular ecosystem is heavily forested relative to the others and much of the land is under U.S. Forest Service and private industrial ownership (White et al. 1993). Conversely, agricultural pro-

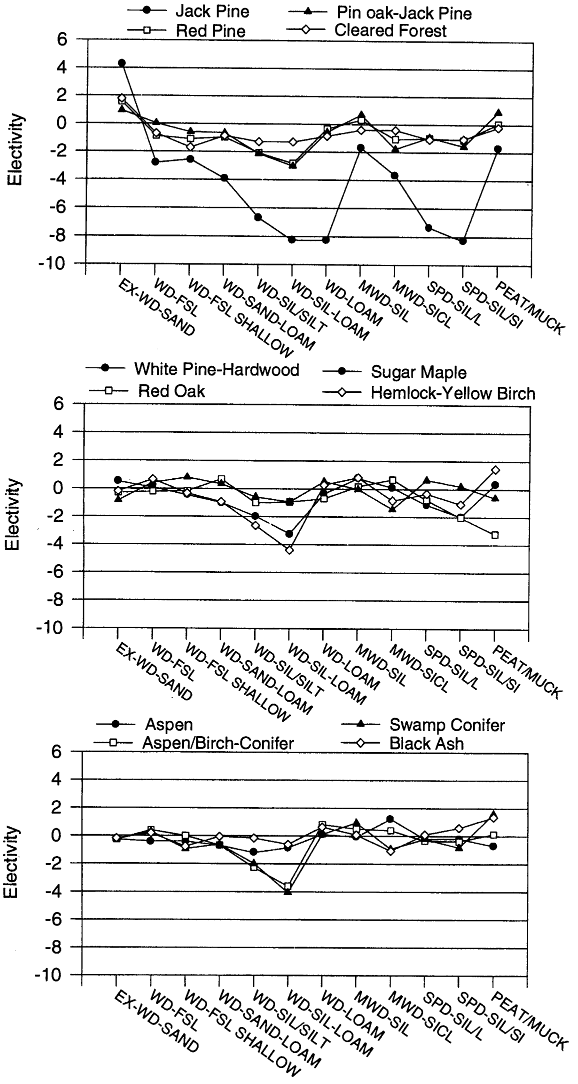

FIG. 5. Electivity of 12 land cover classes by ecological region. Cover classes derived from Wolter et al. (1995).

duction and pasturelands tended to occur in ecosystems characterized by well-drained silts with silt- or loam-textured subsoils (Fig. 5). These regions had relatively low percentages of forested lands.

DISCUSSION

The ability to develop classification criteria and key quantitative variables in advance, and to incorporate data published according to specified data standards, can remove much of the subjectivity involved in the development of ecological classifications. While the concept of forest ecosystems existing in nested spatial hierarchies defined by factors operating at multiple spatial scales has been well described (Bailey 1983, Barnes et al. 1982, Damman 1979, Rowe 1984, O'Neill et al. 1986), the mechanisms and data for implementing these ideas have been less clear. Often ecosystem boundaries have been defined by consensus, and in some cases are political boundaries (Kotar et al. 1988). This approach is not necessarily repeatable, and the derived units may not relate mechanistically to the ecological processes (e.g., succession, nutrient cycling) that define and characterize ecosystems. The development of well-defined criteria, standardized data, and robust analytical methods can improve both the repeatability and interpretability of ecological classifications.

While standardized data layers and analytical methods are relatively objective, there are a number of decisions that require some understanding of the landscape under study. In our case, the use of texture and drainage as primary driving variables in the physiographic classification required an understanding of predominant ecological factors influencing Lake States forests. While these decisions were supported by a large body of research in the region, this type of information is not uniformly available or applicable to all landscapes. There were also data processing questions, such as determining the number of classification levels, selecting important variables, or generalizing map lines, that required subjective decisions. Moreover, it is unrealistic to expect that the process of ecoregional classification can be accomplished entirely by spatial and numeric analyses; human understanding is also an important component (Host et al. 1993). Nonetheless, the identification of relevant standardized databases and analytical protocols is important for developing more objectively based and ecologically relevant classifications, and for ensuring that classifications developed over adjacent regions or by different agencies are comparable.

Our classification is similar to and nests within the larger scale classifications by Bailey (1983), or more recently, Albert (1995), who has developed an ecoregional classification for Michigan, Minnesota, and Wisconsin. In the more restricted area of northwestern Wisconsin, our classification subdivides several of Albert's units, which are similar in soil texture but differ in drainage characteristics. The spatial resolution of our classification is analogous to the Landtype Association level (map units are 100s to 1000s of hectares) within the national hierarchy of classification units adopted by the U.S. Forest Service (Cleland et al. 1994), whereas Albert's (1995) map delineates the landscape at the section and subsection level (10s to 1000s of square kilometres). An advantage to the quantitative hierarchical approach adopted by these systems is that classification criteria can be applied to regional areas across ownership boundaries, whereas detailed classifications developed by specific management agencies tend to focus on data collected within single ownerships.

The climatic classification provides an increased spatial resolution over previous efforts. Rauscher (1984) developed one of the first climatic classifications of the Lake States. Principal components (PCs) were derived from National Oceanic and Atmospheric Administration data, and a PC score was assigned to each inter-

TABLE 5. Percent area of a Landsat-derived cover type that occurs within a physiographic region. Physiographic regions and cover types are arranged along a moisture gradient from dry to moist. For an explanation of physiographic regions see Table 2.

	Physiographic region				
Dominant cover type	EX-WD-SAND	WD-FSL-SHALLOW	WD-SL/L	WD-SiL/Si	WD-SiL/L
Jack pine	94.16 (+)*	0.17 (−)	0.29 (−)	0.00 (−)	0.00 (−)
Red pine	50.98 (+)	0.74 (−)	5.26 (−)	0.32 (−)	0.11 (−)
Pin oak–jack pine	36.00 (+)	1.22 (−)	7.11 (−)	0.30 (−)	0.09 (−)
Cleared forest	56.30 (+)	0.40 (−)	5.85 (−)	0.71 (−)	0.00 (−)
White pine	26.57 (+)	1.40 (−)	5.11 (−)	0.35 (−)	0.07 (−)
Hard red oak	13.83 (−)	1.83 (−)	22.37 (+)	0.93 (−)	0.69 (−)
Sugar maple	8.48 (−)	4.72 (+)	17.30 (+)	1.43 (−)	0.69 (−)
Hemlock–yellow birch	15.27 (−)	1.57 (−)	5.42 (−)	0.18 (−)	0.02 (−)
Aspen	14.10 (−)	1.44 (−)	6.79 (−)	0.77 (−)	0.74 (−)
Aspen/birch–conifer	14.18 (−)	2.14 (−)	6.96 (−)	0.26 (−)	0.05 (−)
Black ash	15.32 (−)	1.02 (−)	12.09 (−)	2.12 (−)	0.94 (−)
Swamp conifer	14.24 (−)	0.85 (−)	7.23 (−)	0.35 (−)	0.03 (−)

* Signs in parentheses indicate positive (+) or negative (−) association based on the electivity index. The formula to calculate electivity for each cover type on physiographic regions was: $E_{ij} = \ln[(r_{ij})(1 - p_j)/(p_j)(1 - r_{ij})]$, where r_{ij} was the proportion of cover type i on physiographic region j, and p_j was the proportion of the landscape occupied by physiographic region j.

section of a 25 by 25 km grid distributed over the study area. PC scores were assigned based on proximity to a weather station, rather than by interpolation. A resulting cluster analysis of seven principal component axes resulted in identification of 20 homogeneous climatic regions across Minnesota, Wisconsin, and Michigan (Rauscher 1984). Two major and two smaller of these climatic regions occurred in our study area. Of these, the boundary between Rauscher's two major units (4 and 18) paralleled the northern boundary of unit IV, but was ≈30 km south of this boundary. Given that Rauscher used a 25-km grid size, the classifications appear fairly concordant.

Interpolated climatic data is particularly valuable when the distribution of weather stations is sparse. Denton (1985) used interpolated PC scores for a climatic classification of Michigan, and Briggs and Lemin (1992) employed a similar method to identify climatic regions in Maine. While our study area was much smaller than these previous two studies, interpolated temperature and precipitation data revealed climatic variation induced by the presence of Lake Superior, as well as more subtle gradients related to topography and latitude.

The physiographic classification described here was based on available data sources. In general, the development of physiographic classifications will require multiple data sources. In the Lake States, detailed Pleistocene classifications are often available only on a county-by-county basis. The STATSGO database, on the other hand, has been completed for the conterminous United States (Lytle et al. 1996). While this database may be inappropriate for detecting fine-scale soil differences, it does quantify variation in soil texture and drainage across regional landscapes and is thus helpful for this level of classification. Digital elevation models (DEMs), which are raster databases of elevation data, can both clarify physiographic boundaries and quantify variation in slopes and elevations within regions. This database was unavailable for our region at the time of this study, but is currently completed or under development over much of the United States and represents an important resource for future classification work.

Regional classifications can be verified, in part, with independent data related to ecosystem composition. Our analysis of Landsat forest cover data indicated that the combined physiographic and climatic classification of northwestern Wisconsin successfully quantified regional-scale variation in existing forest composition. This type of validation is not possible in systems where vegetation is used as an a priori factor in developing the classification. While disturbance and stand history can confound species–environment relationships at local scales, our analysis shows that regional patterns in composition can be delineated using relatively straightforward data sources and analyses. In addition, the positive association of species with regional ecosystems provides evidence that the classification incorporates those environmental factors that affect species composition. These same factors likely influence ecosystem functional processes as well, such as productivity, nutrient dynamics, and potential successional pathways. We are currently developing a spatial predictive model of forest succession and disturbance, which includes this regional ecological land classification as a functional input data layer (Mladenoff et al. 1996).

CONCLUSIONS

Regional ecosystem classification is important for understanding the potential distribution of species and the productivity of the landscape. It also provides a tool for interagency strategic planning across regional areas and ownership boundaries. Lastly, these classi-

TABLE 5. Continued.

Physiographic region						
WD-L	MWD-FSL	MWD-SiL	MWD-SiCL	SPD-SiL/L	SPD-SiL/Si	PEAT/MUCK
0.00 (−)	0.17 (−)	3.94 (−)	0.41 (−)	0.01 (−)	0.00 (−)	0.36 (−)
0.21 (−)	0.74 (−)	23.20 (+)	5.27 (−)	5.22 (−)	2.37 (−)	2.08 (+)
0.17 (−)	1.22 (−)	30.76 (+)	2.67 (−)	5.55 (−)	1.50 (−)	4.71 (+)
0.13 (−)	0.40 (−)	12.95 (−)	9.61 (−)	4.81 (−)	2.52 (−)	1.59 (−)
0.21 (−)	1.40 (−)	32.39 (+)	15.13 (+)	4.53 (−)	1.01 (−)	2.72 (+)
0.15 (−)	1.83 (−)	20.90 (+)	24.03 (+)	6.24 (−)	0.95 (−)	0.08 (−)
0.51 (+)	4.72 (+)	17.97 (−)	3.68 (−)	21.92 (+)	8.21 (+)	1.05 (−)
0.39 (+)	1.57 (−)	33.47 (+)	6.58 (−)	9.49 (−)	2.43 (−)	7.86 (+)
0.33 (+)	1.44 (−)	16.96 (−)	35.29 (+)	10.45 (−)	5.58 (−)	0.93 (−)
0.67 (+)	2.14 (−)	26.83 (+)	19.06 (+)	9.35 (−)	4.67 (−)	2.18 (+)
0.55 (+)	1.02 (−)	19.14 (+)	5.23 (−)	13.71 (+)	11.44 (+)	7.09 (+)
0.32 (+)	0.85 (−)	36.16 (+)	5.88 (−)	10.59 (−)	3.04 (−)	8.69 (+)

fications provide a context for finer scale, more operational classifications at the local level. Recently developed public and private spatial databases, GIS technologies, and multivariate statistical analysis provide a more standardized and quantitative approach toward the development of regional ecological classifications.

ACKNOWLEDGMENTS

Linework for the Lee Clayton's Pleistocene Geology map was obtained from the University of Wisconsin—Extension Geological and Natural History Survey. This research was funded in part by cooperative research agreement USDA/23-91 of the North Central Forest Experiment Station, USDA Forest Service. This is contribution number 152 of the Center for Water and the Environment, Natural Resource Research Institute, and publication number 26 of the Natural Resources Geographic Information System Laboratory.

LITERATURE CITED

Albert, D. A. 1995. Regional landscape ecosystems of Michigan, Minnesota, and Wisconsin: A working map and classification. North Central Forest Experiment Station General Technical Report **NC-178**.

Albert, D. A., S. A. Denton, and B. V. Barnes. 1986. Regional landscape ecosystems of Michigan. School of Natural Resources, University of Michigan, Ann Arbor, Michigan, USA.

Anderson, J. R., E. E. Hardy, J. T. Roach, and R. E. Witmer. 1976. A land use and land cover classification system for use with remote sensor data. United States Geological Survey Professional Paper **964**.

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

———. 1989. Explanatory supplement to ecoregions map of the continents. Environmental Conservation **16**:307–309.

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

Briggs, R. D., and R. C. Lemin, Jr. 1992. Delineation of climatic regions in Maine. Canadian Journal of Forest Research **22**:801–811.

Clayton, L. 1984. Pleistocene geology of the Superior Region, Wisconsin. University of Wisconsin Geological and Natural History Survey, Information Circular Number 46, Madison, Wisconsin, USA.

Cleland, D. T., T. R. Crow, P. E. Avers, and J. R. Probst. 1992. Principles of land stratification for delineating ecosystems. Pages 40–50 *in* Taking an ecological approach to management. U.S. Forest Service Watershed and Air Management Publication **WO-WSA-3**.

Cleland, D. T., J. B. Hart, G. E. Host, K. S. Pregitzer, and C. W. Ramm. 1994. Field guide: ecological classification and inventory system of the Huron-Manistee National Forests. U.S. Forest Service, Huron-Manistee National Forest, Cadillac, Michigan, USA.

Curtis, J. T. 1959. The vegetation of Wisconsin. University of Wisconsin Press, Madison, Wisconsin, USA.

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

Denton, S. R. 1985. Ecological climatic regions and tree distributions in Michigan. Dissertation. University of Michigan, Ann Arbor, Michigan, USA.

Denton, S. R., and B. V. Barnes. 1988. An ecological climatic classification of Michigan: a quantitative approach. Forest Science **34**:119–138.

ERDAS. 1991. ERDAS field guide. Version 7.5. ERDAS, Atlanta, Georgia, USA.

ESRI. 1992. Arc/Info User's Manual. Environmental Systems Research Institute, Redlands, California, USA.

Hammond, E. H. 1970. Classes of land-surface form. Pages 62–63 *in* The national atlas of the United States of America. U.S. Geological Survey, Washington, D.C., USA.

Host, G. E., and K. S. Pregitzer. 1992. Geomorphic influences on ground-flora and overstory composition in upland forests of northwestern Lower Michigan. Canadian Journal of Forest Research **22**:1547–1555.

Host, G. E., K. S. Pregitzer, C. W. Ramm, J. B. Hart, and D. T. Cleland. 1987. Landform-mediated differences in successional pathways among upland forest ecosystems in northwestern Lower Michigan. Forest Science **33**:445–457.

Host, G. E., K. S. Pregitzer, C. W. Ramm, D. P. Lusch, and D. T. Cleland. 1988. Variation in overstory biomass among glacial landforms and ecological land units in northwestern Lower Michigan. Canadian Journal of Forest Research **18**: 659–668.

Host, G. E., C. W. Ramm, E. A. Padley, K. S. Pregitzer, J. B. Hart, and D. T. Cleland. 1993. Field sampling and data analysis methods for development of ecological land classifications: an application on the Manistee National Forest. U.S. Forest Service General Technical Report **NC-162**.

Jacobs, J. 1974. Quantitative measurement of food selection: a modification of the forage ratio and Ivlev's electivity index. Oecologia **14**:413–417.

Jenkins, S. H. 1979. Seasonal and year-to-year differences in food selection by beavers. Oecologia **44**:112–116.

Johnson, L. B., G. E. Host, J. K. Jordan, and L. L. Rogers.

1991. Use of GIS for landscape design in natural resources management: habitat assessment and management for female black bear. Pages 507–517 *in* Proceedings of GIS/LIS '91, 28 October–1 November, Atlanta, Georgia, USA.

Jordan, J. 1983. Application of an integrated land classification. Pages 65–82 (435) *in* G. R. Mroz, editor. Proceedings of Artificial Regeneration of Conifers in the Upper Great Lakes Region. Michigan Technical University, Houghton, Michigan, USA.

Koppen, W. 1931. Grundiss der Klimakunde. Walter de Gruyter, Berlin, Germany.

Kotar, J., J. A. Kovach, and C. T. Locey. 1988. Field guide to forest habitat types of northern Wisconsin. Department of Forestry, University of Wisconsin, Madison, Wisconsin, USA.

Kuchler, A. W. 1964. Potential natural vegetation of the conterminous United States. American Geographical Society Special Publication 36, New York, New York, USA.

Lytle, D. J., N. B. Bliss, and S. W. Waltman. 1996. Interpreting the state soil geographic database (STATSGO). Pages 49–52 *in* M. F. Goodchild, L. T. Steyaert, B. O. Parks, C. A. Johnston, D. Maidment, M. Crane, and S. Glendinning, editors. GIS and environmental modeling: progress and research issues. GIS World Books, Fort Collins, Colorado, USA.

Mladenoff, D. J., and G. E Host. 1994. Ecological perspective: current and potential applications of remote sensing and GIS to ecosystem analysis. Pages 218–242 *in* V. A. Sample, editor. Remote sensing and GIS in resource management planning, analysis, and decision making. Island Press, Washington, D.C., USA.

Mladenoff, D. J., G. E. Host, J. Boeder, and T. R. Crow. 1996. LANDIS: a spatial model of forest landscape disturbance, succession, and management. Pages 175–180 *in* M. F. Goodchild, L. T. Steyaert, B. O. Parks, C. A. Johnston, D. Maidment, M. Crane, and S. Glendinning, editors. GIS and environmental modeling: progress and research issues. GIS World Books, Fort Collins, Colorado, USA.

Mladenoff, D. J., and J. Pastor. 1993. Sustainable forest ecosystems in the northern hardwood and conifer forest region: concepts and management. Pages 145–180 *in* G. H. Aplet, N. Johnson, J. T. Olson, and V. A. Sample, editors. Defining sustainable forestry. Island Press, Washington, D.C., USA.

Mladenoff, D. J., T. A. Sickely, R. G. Haight, and A. P. Wydeven. 1995. A regional landscape analysis and prediction of favorable gray wolf habitat in the northern Great Lakes region. Conservation Biology **9**:279–294.

Mladenoff, D. J., and F. Stearns. 1994. Eastern hemlock regeneration and deer browsing in the northern Great Lakes region: a re-examination and model simulation. Conservation Biology **7**:889–900.

Omernick, J. M. 1987. Ecoregions of the conterminous United States. Annals of the Association of American Geographers **77**:118–125.

O'Neill, R. V., D. L. DeAngelis, J. B. Waide, and T. F. Allen. 1986. A hierarchical concept of ecosystems. Princeton University Press, Princeton, New Jersey, USA.

Pastor, J., and M. Broschart. 1990. The spatial pattern of a northern conifer–hardwood landscape. Landscape Ecology **4**:55–68.

Pastor, J., and D. J. Mladenoff. 1992. The southern boreal–northern hardwood forest border. Pages 216–240 *in* H. H. Shugart, R. Leemans, and G. B. Bonan, editors. A systems analysis of the global boreal forest. Cambridge University Press, Cambridge, England.

Peet, R. T., and O. Loucks. 1977. A gradient analysis of southern Wisconsin forests. Ecology **58**:485–499.

Potzer, J. E. 1948. A pollen study in the tension zone of Lower Michigan. Butler University Botanical Studies **8**: 161–177.

Rauscher, H. M. 1984. Homogeneous macroclimatic regions of the Lake States. U.S. Forest Service Research Paper **NC-240**.

Rowe, J. S. 1984. Forestland classification: limitation of the use of vegetation. Pages 132–147 *in* J. G. Bockheim, editor. Proceedings of the symposium for forest land classification: experience, problems, and perspectives (March 18–20, 1984). Department of Soil Science, University of Wisconsin, Madison, Wisconsin, USA.

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

Russo, J. M., A. M. Liebhold, and J. G. Kelly. 1993. Mesoscale weather data as input to a gypsy moth phenology model. Journal of Economic Entomology **86**:838–844.

Soil Survey Staff. 1992. State soil geographic data base (STATSGO) data user's guide. USDA Soil Conservation Service Miscellaneous Publication **1492**.

Spies, T., and B. V. Barnes. 1985. A multifactor ecological classification of the northern hardwood and conifer ecosystems of Sylvania Recreation Area, Upper Peninsula, Michigan. Canadian Journal of Forest Research **15**:949–960.

Tou, J. T., and R. C. Gonzalez. 1974. Pattern recognition principles. Addison-Wesley, Reading, Massachusetts, USA.

USDA. 1957. Soils of the North Central Region of the United States. U.S. Department of Agriculture, Soil Conservation Service, North Central Regional Publication 76, Bulletin **544**.

U.S. Geological Survey. 1985. Digital line graphs from 1: 100,000 scale maps. U.S. Geological Survey data user's guide 2. Reston, Virginia, USA.

———. 1990. Land use and land cover digital data from 1: 250,000 and 1:100,00 scale maps. U.S. Geological Survey data user's guide 4. Reston, Virginia, USA.

White, M. A., D. J. Mladenoff, G. E. Host, P. Wolter, and T. R. Crow. 1993. Analyzing regional forest landscape structure across ownership categories and ecological land units. Eighth Annual Landscape Ecology Symposium, Oak Ridge, Tennessee, USA.

Wilkinson, L. 1990. SYSTAT: the system for statistics. SYSTAT, Evanston, Illinois, USA.

Williams, D. W., and A. M. Leibhold. 1995. Forest defoliators and climate change: potential changes in spatial distribution of outbreaks of western spruce budworm (Lepidoptera: Tortricidae) and gypsy moth (Lepidoptera: Lymantriidae). Environmental Entomology **24**:1–9.

Wolter, P. T., D. J. Mladenoff, G. E. Host, and T. R. Crow. 1995. Improved forest classification in the northern Lake States using multi-temporal Landsat imagery. Photogrammetric Engineering and Remote Sensing **61**:1129–1143.

Zak, D. R., K. S. Pregitzer, and G. E. Host. 1986. Landscape variation in nitrogen mineralization and nitrification. Canadian Journal of Forest Research **16**:1258–1263.

ZedX. 1995. Database description: Minnesota, Michigan, and Wisconsin. Hi-Rez Data Climatological Series, ZedX, Boalsburg, Pennsylvania, USA.