

Spatial modeling of rangeland potential vegetation environments

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Abstract

Potential vegetation environments (e.g., habitat types, range sites, ecological sites) are important to land managers because they provide a conceptual basis for the description of resource potentials and ecological integrity. Efficient use of potential vegetation classifications in regional or subregional scale assessments of ecosystem health has been limited to date, however, because traditional ecological unit mapping procedures often treat such classifications as ancillary information in the map unit description. Accordingly, it is difficult, if not impossible, to describe the precise location, patch size, and spatial arrangement of potential vegetation environments from most traditional ecological unit maps. Recent advances in remote sensing, geographic information systems (GIS), terrain modeling, and climate interpolation facilitate the direct mapping of potential vegetation through a predictive process based on gradient analysis and ecological niche theory. In this paper, we describe how a predictive vegetation mapping process was used to develop a 30 m raster-based map of 4 grassland, 5 shrubland, and 6 woodland habitat types across the Little Missouri National Grasslands, North Dakota. Discriminant analysis was used in developing this potential vegetation map based on 6 primary geographic information system themes. Geoclimatic subsections and remotely sensed vegetation lifeform maps were used in predictive model stratification. Terrain indices, LANDSAT satellite imagery, and interpolated climate information were used as independent (predictor) variables in model construction. A total of 616 field plots with known habitat type membership were used as dependent variables and assessed by a jackknife discriminant analysis procedure. Accuracy values of our map ranged from 54 to 77% in grasslands, 62 to 100% in shrublands, and 70 to 100% in woodlands dependent on geoclimatic subsection setting. Techniques are also described for generalizing the 30 m pixel resolution habitat type map to appropriate ecological unit maps (e.g., landtype associations) for use in ecosystem health assessments and land use planning.

Resumen

Los ambientes de vegetación potencial (por ejemplo, tipos de hábitat, sitios de pastizal, sitios ecológicos) son importantes para el manejador de terrenos porque ellos proveen una base conceptual para la descripción de los recursos potenciales y la integridad ecológica. A la fecha, el uso eficiente de clasificaciones de vegetación potencial en evaluaciones de la salud del ecosistema a escala regional y subregional ha sido limitado, esto debido a que los procedimientos tradicionales de mapeo de unidades ecológicas a menudo tratan tales clasificaciones como información secundaria en la descripción de la unidad de mapeo. De acuerdo a esto, es difícil, si no imposible, describir la localidad precisa, el tamaño de parche y el arreglo espacial de los ambientes de vegetación potencial a partir de los mapas mas tradicionales de unidad ecológica. Avances recientes en el área de sensores remotos, sistemas de información geográfica, modelaje de terreno e interpolación de clima facilitan el mapeo directo de la vegetación potencial a través de un proceso predictivo basado en el análisis de gradientes y la teoría ecológica de nichos. En este artículo describimos como un proceso predictivo de mapeo de vegetación fue usado para desarrollar un mapa raster de 30 m de tipos hábitat de 4 zacatales, 5 matorrales y 6 bosques a través de los pastizales nacionales de "Little Missouri" de North Dakota. Se uso análisis discriminante en el desarrollo de este mapa de vegetación potencial basado en 6 temas primarios de sistemas de información geográfica. En el modelo de estratificación predictiva se utilizaron subsecciones geoclimáticas y mapas de formas de vida derivados de vegetación procesada con sensores remotos. Indices de terreno, imagen satelital LANDSAT e información climática interpolada se utilizaron en el modelo como variables independientes (predictivas). Se usaron un total de 616 parcelas de campo con tipo de hábitat conocido como variables dependientes y evaluadas por procedimiento de un análisis discriminante de navaja. Los valores de certeza de nuestro mapa variaron de 54 a 77% en los zacatales, de 62 a 100% en los matorrales y de 70 a 100% en los bosques, dependiendo de la subsección geoclimáticas en la que se encontraban situados. También se describen las técnicas para generalizar los mapas de tipo de hábitat de resolución de 30 m por pixel a mapas apropiados de unidades ecológicas (por ejemplo, asociaciones de tipo de terreno) para el uso en las evaluaciones de salud del pastizal y la planeación del uso de la tierra.

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Potential vegetation classifications such as ecological sites (RISC 1983), ecological types (USDA, FS 1991) and range sites (Shiflet 1973) are commonly used by land management agencies as a framework for organizing natural resource information, and also as a tool for communicating "natural" baseline conditions for ecosystem health assessments, predictions of vegetation response to management, and resource value potentials. Most potential vegetation classifications utilize indicator plant species to describe environments with similar responses to management. Habitat type (Daubenmire 1968, Pfister et al. 1977, Mueggler and Stewart 1980, Hironaka et al. 1983, Jensen et al. 1988) is an example of a potential vegetation classification system that is widely used by various U.S. land management agencies because relatively few diagnostic species are required to determine a site's ecological potential. In developing habitat type classifications, minimally disturbed, late seral or "climax" plant communities are sampled to determine which combinations of plant species indicate unique environments for management (Pfister et al. 1977). These classifications are, in turn, contrasted with various abiotic components of sampled sites (e.g., soil properties, climate, and geology) to facilitate a better understanding of the complex environments that a habitat type actually represents (Jensen et al. 1990).

Hierarchical ecological unit maps are often used as a basis for the spatial description of potential vegetation (Bailey et al. 1994, Cleland et al. 1997). For example, in the USDA, Forest Service ECOMAP hierarchy (Cleland et al. 1997), the composition of potential vegetation environments is commonly included as ancillary information in the ecological map unit description. Each ecological mapping unit often contains more than 1 dominant potential vegetation type, depending on classification level and mapping scale; hence, this approach commonly does not provide adequate spatial representation of potential vegetation (e.g., patch size, shape, and connectivity) for many land use planning objectives. Consequently, new approaches for directly mapping potential vegetation are now required in most assessments of ecosystem health.

Recent advances in remote sensing, terrain modeling, climate interpolation, and geographic information systems software facilitate such direct mapping of potential vegetation by a process commonly referred to as "predictive vegetation mapping" (Franklin 1995). In this approach, potential vegetation environments are

modeled based on mapped environmental variables that are considered to influence vegetation pattern, whether directly or indirectly (Austin and Smith 1989). Predictive vegetation mapping is founded in ecological niche theory and vegetation gradient analysis; it is based on the premises that vegetation distribution can be predicted from the spatial distribution of environmental variables that correlate with or control plant distributions (Franklin 1995).

The primary objective of this paper is to develop a habitat type map using a predictive vegetation mapping process for the Little Missouri National Grasslands of North Dakota. A secondary objective is to illustrate how raster-based maps of potential vegetation (and associated information) can be effectively generalized from 30 m cells to appropriate ecological unit maps, and subsequently used in ecosystem health assessments and land use planning.

Materials and Methods

Study area

This study was conducted within the Little Missouri National Grasslands (hereafter referred to as the Grasslands) of western North Dakota (Lat. 47° 15'N, Long. 103° 30'W), an area of approximately 809,380 ha that is managed primarily by the USDA, Forest Service, for cattle grazing, oil and gas leasing, wildlife habitat, and recreation uses (Fig. 1). These grasslands encompass an area of diverse terrain and vegetation pattern and include 3 subsections (Nesser et al. 1997) of the Northern Great Plains Section (Bailey 1995). The Missouri Plateau Subsection (331 Fd) is characterized by rolling plains, fans, and terraces formed in mixed sedimentary alluvium. Steep to very steep hills, deeply entrenched drainageways, and narrow to wide valley bottom settings formed in residual and alluvial sedimentary materials characterize the Little

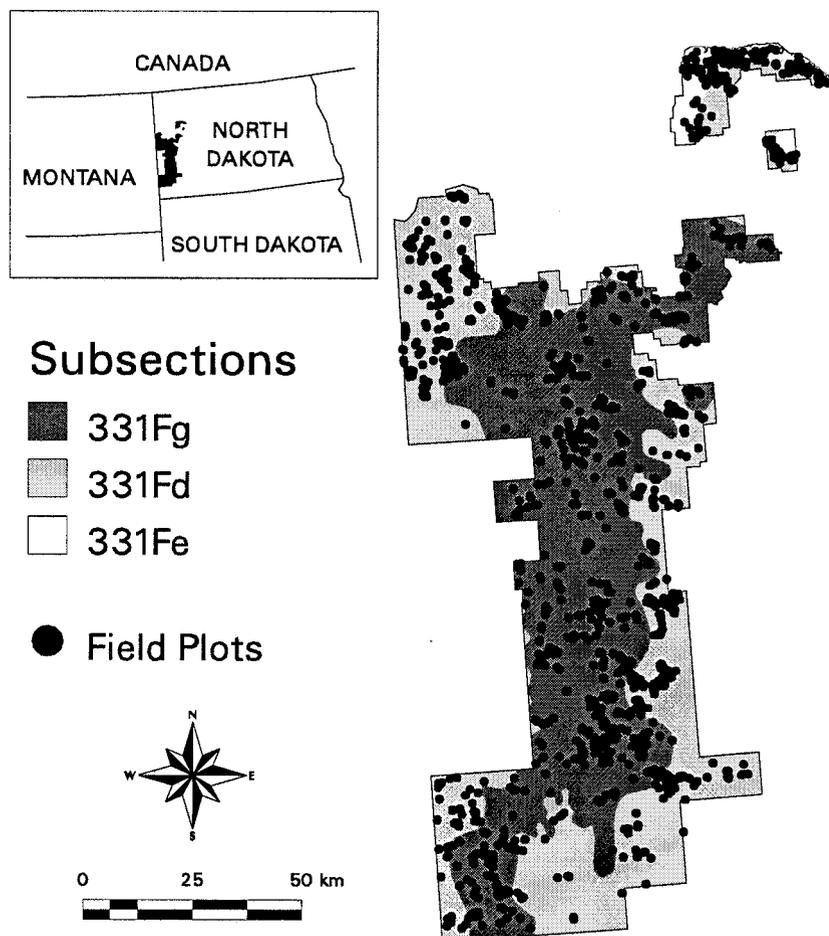


Fig. 1. The study area stratified by geoclimatic subsections and field plots used in describing known habitat type locations within the Little Missouri National Grasslands.

Missouri Badlands (331Fg). The Missouri Breaks Subsection (331 Fe) is characterized by rolling hills, river breaks, terraces and floodplains that formed in alluvium, sedimentary rock, and glacial till materials. Dominant soil great groups (Soil Survey Staff 1975) of the study area include: Haploborolls, Argiborolls, Argiustolls, Natrustolls and Ustorthents (Whitman 1978, Nesser et al. 1997).

The climate of the Grasslands is continental and semi-arid (characterized by hot summers and cold winters). Elevations range from about 350 m along river bottoms to 1,070 m within the Badlands. Precipitation fluctuates annually and seasonally with over 70% occurring between April and September (Whitman 1978). A moisture-temperature gradient exists across the study area from the SW to the NE corners. Along this gradient, average annual precipitation increases from 360 to 410 mm; average annual temperature decreases by 1° C, and the frost free period decreases from 135 to 115 days. A more detailed description of geoclimatic settings within the study area has been developed by the Custer National Forest at the landtype association level (Cleland et al. 1997).

Vegetation of the study area is typical of the mixed grass prairie in the Northern Great Plains. Kuchler (1964) characterized the potential vegetation of this area as a wheatgrass-needlegrass (*Agropyron-Stipa*) association. Dominant species include western wheatgrass (*Agropyron smithii* (Rydb.)), green needlegrass (*Stipa viridula* (Trin.)), needle and thread grass (*Stipa comata* (Trin. & Rupr.)), blue grama (*Bouteloua gracilis* (H.B.K.) Lag.) and threadleaf sedge (*Carex filifolia* (Nutt.). Little bluestem (*Andropogon scoparius* (Michx.)) and prairie sandreed (*Calamovilfa longifolia* (Hook.)) also occur and commonly occupy micro-sites on short slopes and sandy areas, respectively. Various broadleaf and coniferous tree species and shrubs are found on steep north-facing slopes, narrow drainages and draws, and in wide valleys along streams and rivers.

Characterization of field plots

A total of 616 field plots were used to map and describe habitat types in this study (Fig. 1). These plots were sampled by Custer National Forest personnel between 1987 and 1996 for a variety of objectives including: resource inventories, habitat type and seral plant community classification efforts, and ground truth sampling associated with existing vegetation and land cover satellite imagery map-

ping. Despite the fact that these plots were obtained for different objectives, they all followed standardized field sampling procedures as outlined in the Ecological Inventory and Analysis Guide of USDA, Forest Service, Northern Region (USDA-FS 1988). This facilitated consistent use of field plot data in subsequent analyses. Sampling protocols associated with these field plots are briefly described below.

Field plots were 0.04 ha size and were subjectively located without preconceived bias (Mueller-Dombois and Ellenberg 1974) on representative habitat type settings across the study area (i.e., plots were randomly placed within clearly delineated habitat types). Data collected at each plot included: soil morphology, elevation, geology, landform, landform position, production by lifeform, canopy cover by lifeform, ground cover, canopy cover and plant height by species, and geographic location coordinates (latitude, longitude). Location data were derived from both 1:24,000 topographic maps and global positioning systems (GPS). Accuracy for non-GPS plot positions is within 100 m, and accuracy for GPS data ranges from 1 to 30 m, depending on whether or not data were differentially corrected. The habitat type membership of each plot was determined based on floristic and abiotic characteristics following hierarchical dichotomous classification key structures developed for the study area by Jensen et al. (1992).

Predictor variables

A variety of raster-based climatic, topographic, and satellite imagery variables (Table 1) were associated with each field plot using ARC/INFO Geographic Information System (GIS) software for subsequent use as predictor variables in potential vegetation map construction. Nine climatic variables (Table 1) were calculated for a 200 m grid using a soil-climate interpolation model developed by the USDA, Natural Resource Conservation Service (NRCS) (Waltman et al. 1997). Primary input parameters for this model include: daily temperature and precipitation from local weather stations; soils data from USDA, NRCS, 1:250,000 STATSGO database; and topographic data from a 30 m digital elevation model. The original 200 m climatic grid was re-sampled to a 30 m resolution to relate climate variables with the other predictor variables used in this study.

Six topographic variables (Table 1) were calculated across the study area using a 30 m digital elevation model. Slope aspect was categorized into 3 classes: no aspect (slopes < 5%), high solar aspect (135 to 315 degrees), and low solar aspect (316 to 134 degrees). A terrain shape index (TSI) was calculated following procedures described by McNab (1989), with positive values indicating concave topography (moisture accumulation) and negative values indicating convex topography (moisture depletion).

Table 1. List of raster-based biophysical predictor variables used in potential vegetation modeling.

Variable Symbol	Variable Name
Climatic Variables	
CST_AMDX	Annual Moisture Surplus/Deficient (mm)
CST_BIO5	Biological Window (days when soil above 5 °C)
CST_BIO8	Biological Window (days when soil above 8 °C)
CST_FFPX	Frost Free Period (days)
CST_GDD	Growing Degree Days above 10 °C
CST_MAAT	Mean Annual Air Temperature (°C)
CST_MSDX	Mean Summer Moisture Deficit (mm)
CST_PET	Potential Evapo-transpiration (mm)
CST_SRPX	Soil Rating for Plant Growth
Topographic Variables	
TSI	Terrain Shape Index
Elev	Elevation (m)
Flat	No Solar Aspect Class (Slopes < 5%)
High	High Solar Aspect Class (aspect 135°– 315° and slopes > 5%)
Low	Low Solar Aspect Class (aspect 316° – 134° and slopes > 5%)
Slp	Slope (%)
Satellite Imagery Variables	
MNDVI	Modified Normalized Vegetation Difference Index
TM1	Landsat Thematic Mapper Band 1 (blue, 0.45 – 0.52 µm)
TM2	Landsat Thematic Mapper Band 2 (green, 0.52 – 0.60 µm)
TM3	Landsat Thematic Mapper Band 3 (red, 0.63 – 0.69 µm)
TM4	Landsat Thematic Mapper Band 4 (NIR, 0.76 – 0.90 µm)
TM5	Landsat Thematic Mapper Band 5 (MIR1, 1.55 – 1.74 µm)
TM6	Landsat Thematic Mapper Band 6 (thermal, 10.4 – 12.5 µm)
TM7	Landsat Thematic Mapper Band 7 (MIR2, 2.08 – 2.35 µm)

Table 2. Habitat types denoted with a (x) are those identified in the final discriminant analysis of potential vegetation environments stratified by lifeform (grasslands, shrublands, and woodlands) and subsection.

Habitat Type	Missouri Plateau	Missouri Breaks	Little Missouri Badlands
Grassland Habitat Types			
<i>Agropyron smithii</i> - <i>Stipa comata</i>	X	X	X
<i>Agropyron smithii</i> - <i>Stipa viridula</i>	X	X	X
<i>Agropyron smithii</i> - <i>Stipa viridula</i> - <i>Bouteloua gracilis</i>	X		X
<i>Andropogon scoparius</i> - <i>Carex filifolia</i>			
<i>Calamovilfa longifolia</i> - <i>Carex</i>			
<i>Stipa comata</i> - <i>Carex filifolia</i>	X	X	X
Shrubland Habitat Types			
<i>Artemisia cana</i> - <i>Agropyron smithii</i>	X	X	X
<i>Artemisia tridentata wyomingensis</i> - <i>Agropyron smithii</i>	X		X
<i>Juniperus horizontalis</i> - <i>Andropogon scoparius</i>	X	X	X
<i>Rhus aromatica</i> - <i>Agropyron spicatum</i>			X
<i>Rhus aromatica</i> - <i>Muhlenbergia cuspidata</i>	X	X	X
<i>Sarcobatus vermiculatus</i> - <i>Agropyron smithii</i>			
Woodland Habitat Types			
<i>Fraxinus pennsylvanica</i> - <i>Prunus virginiana</i>			X
<i>Fraxinus pennsylvanica</i> - <i>Symphoricarpos occidentalis</i>	X		X
<i>Fraxinus pennsylvanica</i> / <i>Ulmus americana</i> - <i>Prunus virginiana</i>	X	X	
<i>Juniperus scopulorum</i> - <i>Oryzopsis micrantha</i>			X
<i>Populus deltoides</i> - <i>Juniperus scopulorum</i>			X
<i>Quercus macrocarpa</i> - <i>Prunus virginiana</i>	X	X	

Two geographically distinct LANDSAT Thematic Mapper (TM) images were acquired for the Grasslands and processed for use in this study (Winne et al. Unpublished). Dates associated with these 2 images were June 1993 and July 1994, which were the most recent cloud-free image dates available for continuous coverage of the Grasslands. The 7 sensors of LANDSAT have proven useful to vegetation pattern mapping in previous research (Sabins 1987). In this study, these 7 spectral bands and a MNDVI value were assigned to a 30 m grid (Table 1). The MNDVI value was derived from spectral bands 3, 4, and 5 and has proven effective in distinguishing areas of high versus low biomass production in other studies (Sabins 1987).

Potential vegetation mapping

A potential vegetation map of habitat types for the Grasslands was developed through the following sequential steps: 1) identification of the habitat types to be mapped, 2) delineation of appropriate biophysical strata for modeling, and 3) multivariate statistical analysis and development of potential vegetation model rule sets by appropriate strata.

The 18 habitat types of the Grasslands described in previous classification efforts (Jensen et al. 1992) were initially considered for mapping in this study. Those types appropriate for mapping were identified by

considering both the grain size (spatial resolution) of the predictor variables and the patch size of habitat types as they commonly occur across the study area. Given that the spatial resolution of the predictor variables ranged from 30 m to 200 m, we felt that predicting habitat types with average patch sizes of less than 1 hectare would be inappropriate. Accordingly, 3 habitat types that tended to occur in patches of less than 1 ha (DiBenedetto 1998) were not mapped, but treated as inclusions within the remaining habitat types in final map construction. These habitat types included: *Andropogon scoparius*-*Carex filifolia*, *Calamovilfa longifolia*-*Carex*, and *Sarcobatus vermiculatus*(Hook.)-*Agropyron smithii* (Table 2).

In predictive vegetation mapping, predictions based on the chosen environmental variables are greatly influenced by the stratification process used in map preparation (Hutchinson 1982). Accordingly, a study area is commonly stratified by appropriate environmental variables prior to multivariate classification and mapping to reduce the potential number of vegetation classes and separate classes that are "spectrally similar" but geographically disjunct (Franklin 1995).

The initial stratification used to predict the distribution of habitat types in this study was based on the 3 subsections (Fig. 1) previously mapped within the Grasslands at a 1:500,000 scale (Nesser et al. 1997). These

were selected because they effectively delineated major differences in climate, geology, and landform across the study area, yet they were large enough to contain sufficient numbers of plots for modeling. Although landtype association polygons (mapped at a 1:100,000 scale) represented more refined delineations of geoclimatic settings within the Grasslands, they were not used as strata in habitat type modeling because of insufficient plot sample sizes within individual mapping units.

Lifform level maps of existing vegetation (i.e., grasslands, shrublands, and woodlands) developed previously for the Grasslands (Redmond et al. 1997) were used for secondary stratification within subsections during development of habitat type map rule sets. Because vegetation lifform maps were highly accurate (i.e., over 90% accuracy) and most current disturbance processes within the Grasslands (e.g., herbivory, fire) do not change the lifform conditions of a site, the use of lifform maps as secondary strata in habitat type modeling was considered appropriate. Assumptions we made in selecting lifform maps as a secondary strata included the fact that large stand consuming fires within the Grasslands have been effectively removed since homesteading began about 100 years ago (i.e., fire is currently not a major disturbance process). Additionally, herbivory by cattle rarely changes the lifform status of a vegetation stand (i.e., most woodlands and shrublands maintain their overstory structures despite changes to understory species composition). The resultant 9 strata (3 subsections times 3 lifforms) and the habitat types modeled within each of these 9 strata are presented in Table 2. An overview of the various GIS themes used in discriminant analysis modeling of potential vegetation at the habitat type level of ecological classification is presented in Fig. 2.

Statistical Analysis

The statistical analysis used in habitat type map construction included 2 steps. First, the stepwise multivariate analysis of variance test of the Statistical Package for the Social Sciences (SPSS) was used to determine which sets of predictor variables best discriminated between the habitat type membership of all field plots within the Grasslands. Second, variables that significantly ($P < 0.01$) reduced Wilks' Lambda in the above stepwise MANOVA analysis were then used to compute Fisher

GIS Themes

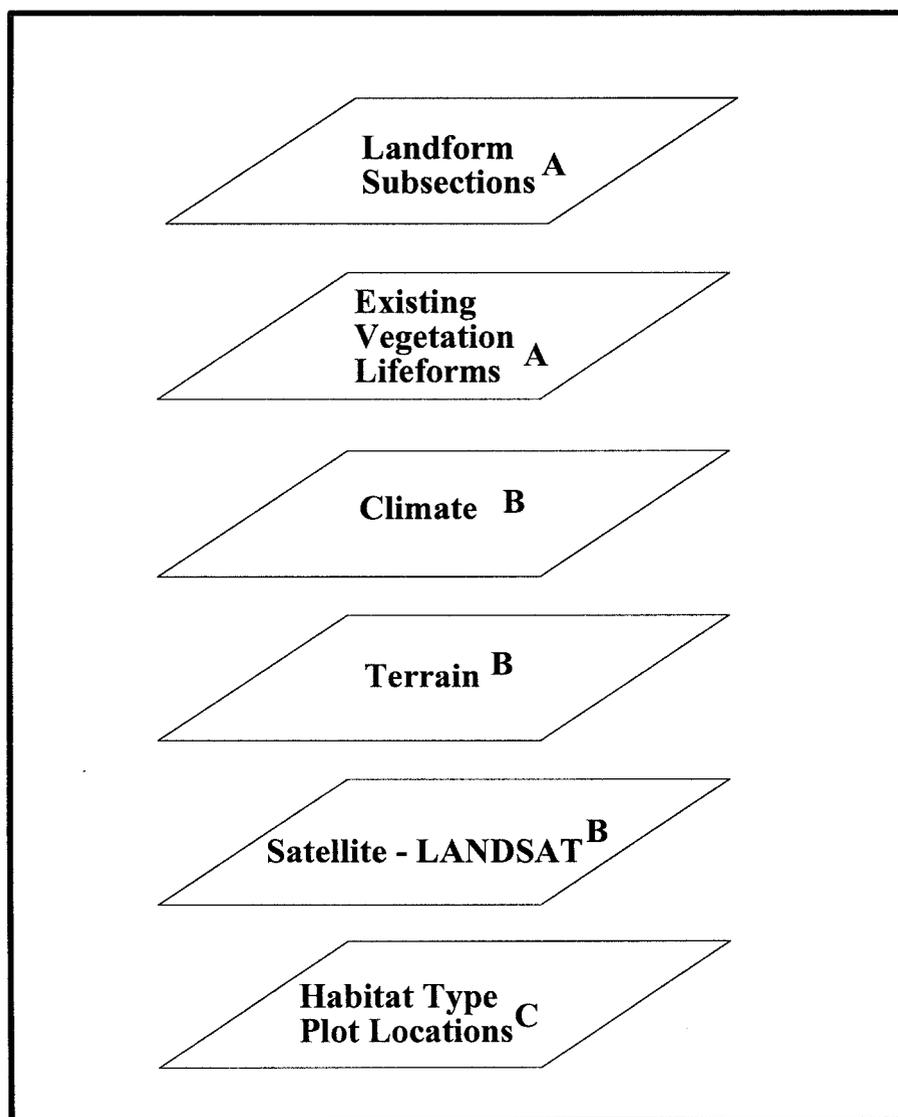


Fig. 2. The 6 basic Geographic Information System data themes used in discriminant analysis modeling of habitat types across the Little Missouri National Grasslands. (A = information used in model stratification, B = information used as independent "predictor" variables in model construction, and C = information used as dependent variables in model construction).

canonical discriminant functions for habitat type prediction by mapping strata. Assessment of the habitat type classification accuracy associated with each of the 9 discriminant analysis strata runs for the Grasslands was determined by a jackknife procedure (Norusis 1985). All plot data were used in developing our habitat type model. We did not split the dataset in our accuracy assessment, because the sample sizes associated with certain habitat types

were not adequate once we stratified the data by subsection and lifeform.

The final habitat type map of the Grasslands was registered to a 30 m raster base using Fisher canonical discriminant functions stratified by 9 biophysical environment settings. This map was subsequently generalized to a variety of cartographic presentations based on similarities of predicted habitat type compositions within landtype association and landtype

polygons. Clustering of similar polygons was based on Ward's (1963) clustering algorithm in these analyses.

Results and Discussion

Accuracy assessment of the potential vegetation map

An example of our 30 m raster-based habitat type map of the Grasslands developed by discriminant analysis procedures is presented in Fig. 3. Classification accuracy of the complete projection is presented by subsection and lifeform in Table 3, and values are relatively high compared to previous predictions of vegetation pattern by similar discriminant analysis procedures (Franklin et al. 1989, Jensen et al. 1990, Franklin and Wilson 1991, Lowell 1991). Results of this analysis indicate that predictions of habitat types based on biophysical variables (Table 1) were consistently more accurate within woodland (70 to 100%) as opposed to shrubland (62 to 100%) and grassland (54 to 77%) settings across all 3 subsections of the Grasslands. Conversely, accuracy for habitat type predictions across all lifeforms was highest in the Missouri Breaks, followed by the Missouri Plateau and the Little Missouri Badlands subsections (Table 3). These results support the use of environmental stratification for predictive vegetation mapping. Further support was offered by an initial discriminant analysis of habitat types across the Grasslands that was stratified by the 3 lifeforms described above but by only 1 geoclimatic setting (i.e., the Northern Great Plains section). Results of that analysis (DiBenedetto 1998) indicated a habitat type classification accuracy rate of only 20, 32, and 54%, respectively, for grassland, shrubland, and woodland lifeforms across the study area. Stratification of Fisher discriminant mapping functions by subsections (geoclimatic settings) greatly improved the accuracy of predicted habitat type distributions in this study.

Significance of biophysical environment predictor variables in discriminating habitat type patterns

The climatic, topographic, and spectral variables listed in Table 1 were analyzed by a stepwise MANOVA to determine which variables best discriminated between the habitat type membership of field plots and, therefore, should be used in developing Fisher canonical discriminant functions for habitat type mapping. Results of this analysis are presented in Table 4,

Habitat Types

- AGSM/STCO
- AGSM/STVI
- Other HT's

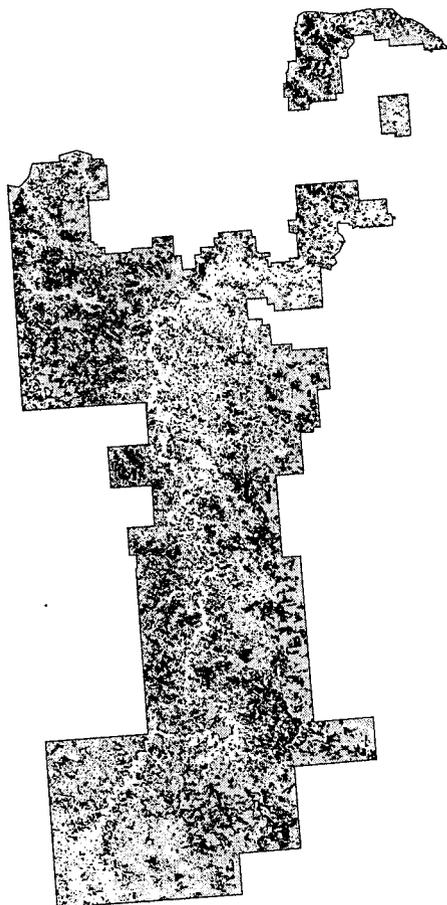
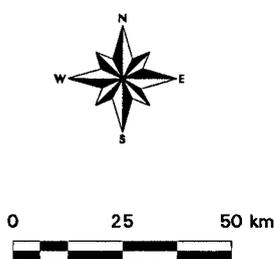


Fig. 3. A 30 m raster-based projection of 2 dominant grassland habitat types across the Little Missouri National Grasslands. (AGSM = *Agropyron smithii*, STCO = *Stipa comata*, and STVI = *Stipa viridula*).

which displays by subsection/lifeform strata, those predictor variables that significantly ($P < 0.01$) reduced Wilks' Lambda and were, in turn, used in Fisher canonical discriminant function calculations.

An examination of the top 3 predictor variables within each column of Table 4 (i.e., those in bold print) suggests that subsections are useful strata in habitat type prediction because they partition the landscape into units that have different predictor variable relations at the lifeform level. For example, within the grassland habitat types, the top 3 predictor variables are different between each of the subsections studied. Variables CST_PET, Flat, and TM5 were the best predictors of grassland habitat types within the Missouri Plateau subsection; however, variables ELEV, CST_FFPX, and MNDVI were the best predictors in the Missouri Breaks subsection, and variables TSI, CST_MAAT, and TM6 were the best predictors in the Little Missouri Badlands subsection (Table 4). Shrubland habitat types exhibit this same relation, with different rankings for the top 3 predictor variables among subsection

groupings. Only within the woodland habitat types did the top 3 predictor variables display some commonality between subsections (i.e., CST_PET and SLP).

Lifeform-based stratifications of the Grasslands were also useful in habitat type prediction because they effectively partitioned subsections into units that have different predictor variable relations. For example, within the Missouri Plateau subsection only the variables CST_PET and SLP were within the top 3 predictor variables across 2 or more lifeforms.

Similarly, only the variable CST_MAAT was shared as a top predictor between lifeforms within the Little Missouri Badlands subsection, and none of the top 3 predictor variables were shared between lifeforms within the Missouri Breaks subsection (Table 4). These results indicate that the environmental stratification process used in this predictive vegetation mapping study of the Grasslands (i.e., partitioning by subsection and existing vegetation lifeform settings) was effective in habitat type prediction as indicated by the classification accuracy values presented in Table 3.

Consistently higher accuracy within woodlands, followed by shrublands and grasslands, across the 3 subsection strata (Table 3) suggests that the predictor variables used in model construction (Table 1) are reasonable indicators of available soil moisture. This interpretation is supported by previous habitat typing efforts within the Grasslands, in which all researchers concluded that woodlands occupied the most mesic sites, followed by shrublands and grasslands in decreasing order of available soil moisture (Hansen et al. 1984, Hirsh and Baker 1984, Girard et al. 1989, Jensen et al. 1992). Accordingly, it appears that available soil moisture is the primary factor influencing habitat type distribution across the Grasslands. A secondary factor considered important in determining habitat type distribution patterns across the Grasslands is available soil nutrients. This factor is associated with soil types; unfortunately, these were unavailable in digital format and could not be included in this study. Consequently, the broad-level subsection environments of the Grasslands (which were primarily mapped based on differences in landform and surface geology) were the best correlates for soil patterns and associated soil nutrient and waterholding capacities. Observed soil patterns across the Grasslands are most complex within the Little Missouri Badlands followed by the Missouri Plateau and Missouri Breaks

Table 3. Overall classification accuracy of Fisher canonical discriminant functions in predicting the habitat type membership of field plots by subsection and lifeform strata groupings. Accuracy is expressed as the percent of sites correctly predicted within each lifeform and subsection group. "N" is the number of field plots used in modeling potential vegetation environments within each group.

Subsection	Grassland Habitat Types	Shrubland Habitat Types	Woodland Habitat Types
	(%)	(%)	(%)
Missouri Plateau	66; N = 86	88; N = 57	90; N = 31
Missouri Breaks	77; N = 62	100; N = 15	100; N = 41
Little Missouri Badlands	54; N = 97	62; N = 69	70; N = 158

Table 4. Stepwise multivariate analysis of variance listing of biophysical predictor variables that best discriminated between habitat types within the Little Missouri National Grasslands (All of the Wilk's Lambda values presented are highly significant ($P < 0.01$), with larger numbers indicating those variables that best discriminated habitat type membership of field plots.) Results are presented by the nine subsection/lifeform strata groupings used in developing Fisher Canonical Discriminant Functions for habitat type mapping. Variable symbols are described in Table 1.

	Missouri Plateau			Missouri Breaks			Little Missouri Badlands		
	Grass-lands	Shrub-lands	Wood-lands	Grass-lands	Shrub-lands	Wood-lands	Grass-lands	Shrub-lands	Wood-lands
Climate Variables									
CST_AMD		0.08			0.43			0.17	0.31
CST_BIO5		0.11	0.05		0.24			0.28	
CST_BIO8		0.13		0.24	0.03	0.12		25	
CST_FFPX	0.26	0.09		0.36					
CST_GDD	0.28					0.29		0.32	
CST_MAA			0.12			0.11	0.76		0.52
CST_MSDX									
CST_PET	0.42		0.34			0.38			
CST_SRPG	0.24	0.33					0.64		0.29
Topographic Variables									
TSI	0.22		0.21				0.86	0.20	
Elev		0.26		0.50		0.14			0.35
Flat	0.36						0.56		
High			0.10		0.06			0.15	
Low		0.16							
Slp		0.56	0.50						0.66
Satellite Imagery Variables									
MNDVI	0.30		0.07	0.30		0.19			0.44
TM1		0.41							
TM2						0.22			
TM3				0.26			0.60		
TM4		0.20							
TM5	0.33							0.24	0.38
TM6						0.16	0.69		
TM7								0.13	

subsections. As a result, it is not surprising that habitat type predictions were poorest within the Little Missouri Badlands subsection (Table 3).

Management applications

The 30 m habitat type grid produced in this study provides a valuable base map for land use planning because it can be used to describe potentials for resource use, plant community succession pathways, and reference conditions associated with minimally altered ecosystem states (Jensen et al. 1991). Management, however, does not occur at the level of individual 30 m cells. Thus, to facilitate effective use of such base maps in land use planning, they can be associated to appropriately scaled mapping units such as ecological units or multiscale drainage basins depending on specific planning needs (Jensen et al. 1996, 1997). In the following discussion we present some examples of how the habitat type map developed in this study can be effectively generalized to different ecologically based mapping units for a variety of land management uses.

An example of a generalization of our habitat type map for general planning purposes is provided in Figure 4. This map was created by attributing the percent

composition of predicted habitat types to each of the Natural Resource Conservation Service soil polygons within the Grasslands, and then clustering these polygons into similar groups based on habitat type composition. The 4 cluster groupings presented in Figure 4 provide a generalization of habitat type patterns across the Grasslands useful to broad-level planning efforts (e.g., forest plan revisions or regional scale ecological assessments). For example, Cluster 1 delineates broad valley bottom settings dominated by woodland and mesic shrub communities. Rolling prairie environments with a predominance of grassland habitat types are displayed in cluster groups 2 and 3. The highly dissected badland environments of the Grasslands are represented by Cluster 4.

Spatial projections of resource value potentials and condition are also facilitated by potential vegetation maps, and are illustrated for year long cattle-forage production potential in Figure 5a. This example was developed based on data collected for reference site (minimally disturbed) plots, which were summarized to describe various late seral plant community characteristics by habitat type (see Jensen et al. 1992). Weighted averages of these values based on habitat type composition within each soil polygon were then calculated by

lifeform and across all lifeforms to develop the map presented in Figure 5a. The low, moderate, and high class ratings displayed in Figure 5a are based on average soil polygon values with high values indicating the upper 33% of polygons (>384 kg/ha), low values indicating the lower 33% of polygons (< 244 kg/ha) and moderate values indicating the middle 33% of polygons (244 to 384 kg/ha).

A similar summarization process to that described above was used in estimating the current condition of yearlong cattle-forage production across the Grasslands (Fig. 5b). In this example, ratings were based on the percent similarity between current (from existing vegetation maps) and reference conditions (from potential vegetation maps) and ranged between 24% and 136%. The low, moderate, and high class ratings displayed in Figure 5b are also based on average soil polygon values; and the percent similarity to reference condition values associated with these three classes are 24% to 61%, 62% to 98%, and 99 to 136%, respectively. Ratings of greater than 100% for forage condition occurred because some areas within the Grasslands have been converted from native prairies to crested wheatgrass communities (*Agropyron cristatum* (L.)(Gaertn.)), which commonly have higher forage production

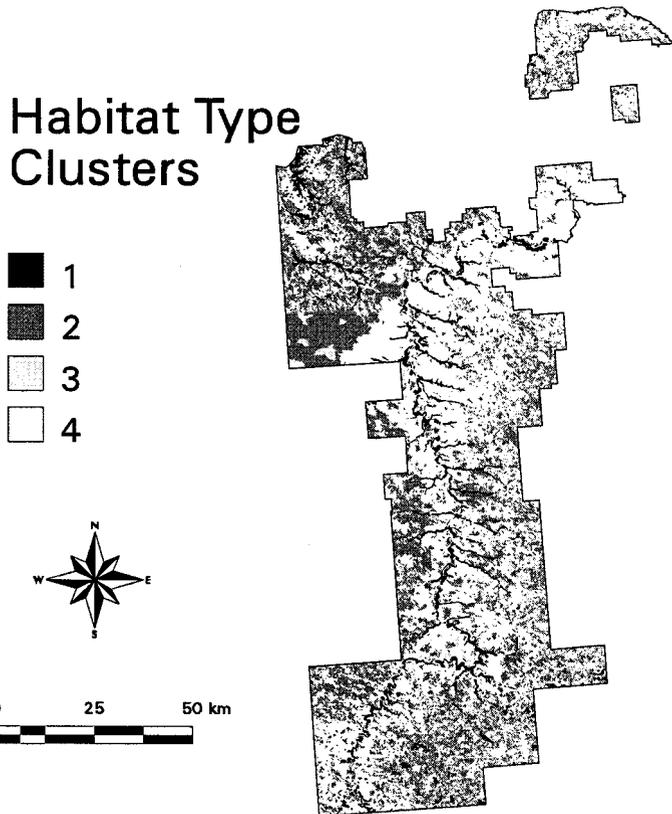


Fig. 4. Generalized habitat type cluster groupings of the Little Missouri National Grasslands appropriate to regional and subregional scale ecological assessments and land use planning.

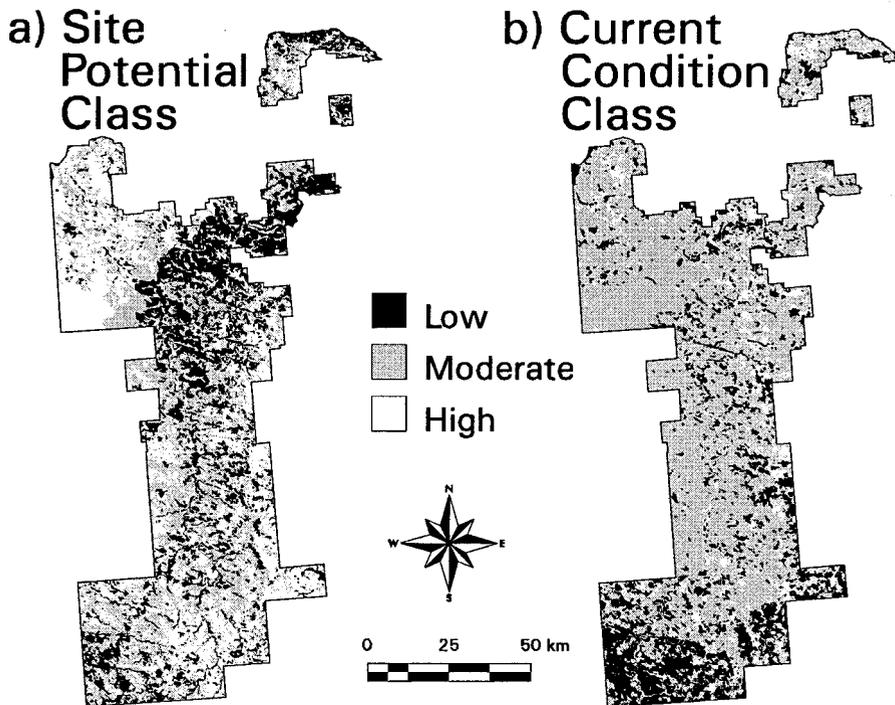


Fig. 5. Year long cattle forage production class ratings for the Little Missouri National Grasslands. (a = site potential ratings based on reference conditions, b = current condition ratings based on the degree of similarity between existing and reference conditions)

values than native reference communities. For a more complete discussion concerning the use of ecological classifications in broad-level assessments of rangeland health and condition, the reader is referred to Jensen et al. 2000.

Conclusions

The discriminant analysis procedure used to model potential vegetation environments in this study was very effective in predicting habitat types; however, the large number of observations (i.e., field plots) required in this type of analysis might limit its use in other areas. Depending on the number, spatial distribution, and quality of field plot data, as well as the types and spatial resolution of mapped predictor variables available for a study area, a variety of other techniques also can be used in predictive vegetation mapping (see Franklin 1995 for a thorough review). Examples of these other modeling approaches include: Boolean logic, simple regression, multiple regression, logic regression, classification trees, neural networks, simple rule-based methods, and fuzzy logic. Each of these methods have characteristic strengths and weaknesses and may or may not be appropriate to a particular mapping effort given data availability, software limitations, and the personal experience of the research analyst. Regardless of the approach used in predictive vegetation mapping, we offer the following key points that should be considered in future efforts:

- Ensure that the vegetation patterns to be predicted are appropriate given their characteristic range of landscape patch sizes and the grain size of the predictor variables used in modeling (e.g., grain should be 5 to 10 times smaller than average patch size).
- Stratification of a study area into more homogeneous environments greatly improves the performance of a predictive vegetation model.
- When possible, the biophysical variables considered for inclusion in a predictive vegetation model should be tested at multiple spatial scales to determine the appropriate grain size for such information. For example, climate interpolation models (Thornton et al. 1997, Waltman et al. 1997) can be run at 30 m, 90 m, and 1 km resolution to access the spatial scale at which different climatic attributes influence the pattern of interest.
- Gradient-oriented field sampling (Austin and Heylingers 1991, Austin et al. 1994,

Bourgeron et al. 1994) should be used in plot selection to facilitate direct testing of assumed relations between biophysical variables and vegetation patterns.

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