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A REMOTE SENSING AND GIS-BASED MODEL OF HABITAT AS A PREDICTOR OF BIODIVERSITY

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✦ ABSTRACT

Conservation biologists need better methods for predicting species diversity. This research investigated some new methods to analyze biodiversity patterns through the use of Geographic Information Systems and remote sensing technologies. We tested the correlation between remotely sensed habitat types and species distributions. The goal was not to do away with ground-based fieldwork, but rather to optimize and focus fieldwork by using GIS and remotely sensed data as tools for making the work more accurate and specific. Our research was conducted at a fine (30 x 30 m) landscape scale using on-the ground locations of birds, butterflies, and plants in the northwest portion of the Greater Yellowstone Ecosystem. Three remotely sensed forest types (distinguished by species density and coverage) and six remotely sensed meadow types (ranging from xeric to hydric) were surveyed and coverage data were collected for grasses, shrubs, forbs and trees. Presence/absence data were collected for birds and butterflies. The objectives of this research were: 1) to determine the extent of the correlation between spectral reflectance patterns and plant or animal species distribution patterns, and 2) to test the spatial correspondence of species diversity "hotspots" among taxonomic groups. Field surveys in 1993 and 1994 validated the vegetation density, cover, and moisture gradients expected from satellite data interpretation. Both tree species composition and diameter at breast height were significant in discriminating among forest types. Twenty-two species of grasses and forbs were significant in distinguishing among meadow types. However, a smaller percentage of the animal species was significantly correlated with one habitat type. In order to find a strong correlation between species distribution patterns and remotely sensed data, a species must be moderately common and show some habitat specificity. Hotspots of species diversity coincided for shrubs, grasses, forbs, birds, and butterflies and were found in mesic meadows.

✦ INTRODUCTION

The loss of biodiversity has become a global concern during the last decade (Wilson 1988, Reid and Miller 1989). What conservation biologists need now are better methods to predict species diversity so that areas of high species richness can be protected and rare or declining species identified. The need to predict these areas of high species richness and species of concern is even more pressing as we enter an era of potential global climate change.

Prerequisites to good management of biological diversity are adequate floral and faunal inventories for the lands in question and a firm foundation in community ecology. Biologists are just beginning to grapple with issues of how to assess

biodiversity and create databases that will be valuable to a wide spectrum of users (Scott et al. 1990, Scott et al. 1993, Davis et al. 1990, Noss 1983, Margules and Austin 1991). However, species lists are only a first step in addressing larger questions regarding relationships between species and their environments, in particular, species responses to environmental change. Understanding the environmental parameters that define species distributions is an even more important component of biodiversity assessment.

One of the many possible objectives for terrestrial biodiversity assessments, and a potentially fruitful one, is development of testable hypotheses concerning the relationships between geographic variation in species distribution patterns, and variation in environmental gradients. Vertebrate biologists have been using knowledge of an animal's habitat to predict its presence or absence for decades (e.g., Baker 1956, Armstrong 1972). Many studies have produced testable hypotheses relating variations in terrestrial species associations to inferred or measured variations of physical environmental factors (e.g., Simpson 1964, Owen 1990, Pyle 1982, James 1971, Terborgh 1970, Debinski 1991,1994a, Kindscher 1994, Kindscher 1995). However, scientists are just beginning to use remote sensing data as a predictor of animal species distribution patterns (Scott et al. 1993, De Wulf et al. 1988, Saxon 1983, Tueller 1989, Stoms and Estes 1993).

The emergence of landscape ecology as a discipline has been instrumental in helping scientists understand spatial patterns of species distribution (Turner 1989, Urban et al. 1987, Noss 1983). As these relationships are better understood, it may be possible to predict species diversity based upon landscape level habitat analysis using Geographic Information Systems (GIS) and remotely sensed data (Urban et al. 1987, Turner 1989, McLaughlin et al. 1992, Rich et al. 1992 a,b) at fine-scale resolutions. Conversely, such analyses can help optimize sampling strategies or allow us to test hypotheses regarding the spatial correspondence of species diversity patterns among taxonomic groups (e.g., Prendergast et al. 1993). Although patterns of community structure are produced by a variety of interactions, analysis of the patterns themselves can also prove helpful in broadening our interpretations. For example, Kolasa (1989) used pattern analysis to develop a hierarchical model describing observed patterns of species abundance.

Gap Analysis was developed by the U.S. Fish and Wildlife Service as a technique to compare locations of plant and animal habitats to those of existing preserves, thereby identifying gaps in habitat and/or species protection. Gap Analysis uses LANDSAT Thematic Mapper (TM) imagery to determine boundaries of vegetation types and then incorporates other data to label the vegetation types to series level (Scott et al. 1993). Given the knowledge of the geographical limits of a species' distribution, its ecological limiting factors, and its habitat preferences, species distributions are predicted within a map polygon using county of occurrence data and habitat-association matrices (Scott et al. 1993). Overlays of several species can be used to create a composite map of species richness throughout an area. Many factors besides vegetation type affect species presence and can cloud the observed relationship between species and vegetation (Flather et al. 1995). Even if a habitat appears suitable, the species of interest may not be present due to historical factors, interspecific interactions, or factors extrinsic to the specific site. Another problem with Gap Analysis is the scale at which it is conducted. Scott et al. (1993) used a minimum mapping unit of 100 ha and mapped at a scale of 1:100,000. We would argue that for many species of conservation concern (and especially smaller-bodied organisms like songbirds and butterflies), this scale is too coarse because microhabitats play an important role in determining suitable habitat. Gap analysis assumes that the microhabitats selected by these finer-scaled species are incorporated into the larger polygons, yet the Gap approach has not been tested at multiple scales (Flather et al. 1995). Furthermore, little prediction error or sensitivity analysis testing has been done for the Gap models. Thus, it would be advantageous to test these relationships with fine-scale mapping units (on the order of a few hectares) first.

After conducting a park-wide inventory of Glacier National Park for birds and butterflies (Debinski 1991), we began to investigate alternative methods to predict species diversity based upon landscape level habitat analysis (e.g., Maurer 1994, McLaughlin et al. 1992, Stoms and Estes 1993, Rich et al. 1992 a,b). The goal was to use intensive, local field sampling to extrapolate species distribution

patterns within a region. The hypothesis was that plant and animal distributions (biodiversity) could be correlated to patterns of spectral reflectance as recorded by satellite remote-sensing instruments at a scale of 30 x 30 m pixels. In essence, our approach was similar to Gap analysis, but the scale was finer, and we took the opposite approach to creating a species-habitat model; we were testing the ability to find relationships between remotely sensed data and species assemblage data rather than assuming such a relationship and then predicting species distributions. We initiated this research project using remote sensing and GIS analysis of landscape to predict species distributions of grasses, forbs, shrubs, trees, birds and butterflies.

✦ OBJECTIVES

From field observations, it appeared that there were significant relationships between remotely sensed data and vegetation. For example, sagebrush *Artemesia tridentata* tended to be found on dry M5 and M6 sites, while sedges *Carex* spp. tended to be found on wet M1 and M2 plots. However, these relationships had yet to be quantified through statistical analysis. The major objective of our research was to determine the extent of the relationship between spectral reflectance patterns, as measured through remote sensing instruments, and the distribution of plant or animal species. The goal was not to do away with ground-based fieldwork, but rather to optimize and focus fieldwork by using GIS and remotely sensed data as tools for making the work more accurate and specific.

✦ STUDY AREA

The study area for this research project was a 500 sq. mile area in the northwest corner of the Greater Yellowstone Ecosystem (Fig. 1). The Landsat scene extended from Porcupine Creek to Bacon Rind Creek (north/south) and from the crest of the Madison Range to the crest of the Gallatin Range (east/west). This area was chosen for three reasons. First, it is one of the largest intact ecosystems in the continental U.S. and includes a wide range of elevation and moisture gradients. Second, lists of birds and butterfly species were available for the ecosystem (Bowser 1988, Brussard 1989). Finally, we had several years experience conducting research in the region.

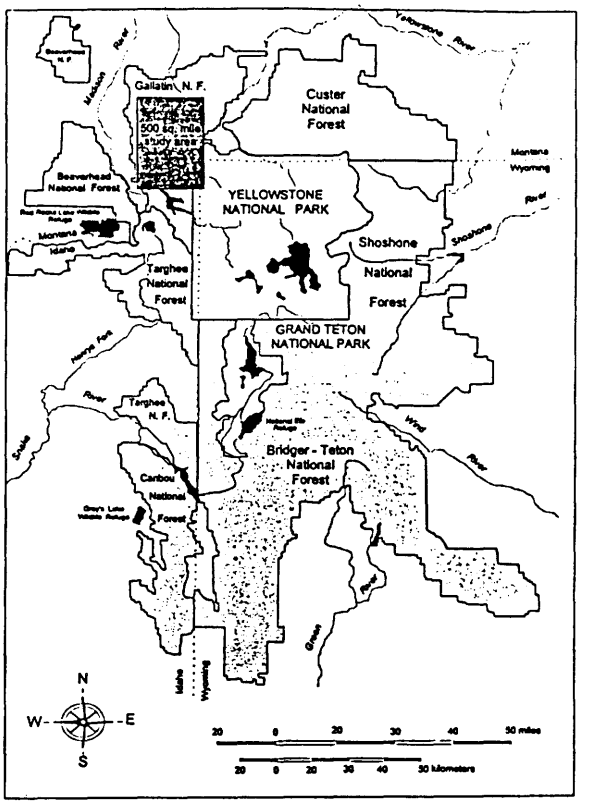

Figure 1. The Greater Yellowstone Ecosystem with study area darkened. Study area encompasses 500 sq. miles including northwest corner of Yellowstone National Park and southeast portion of the Gallatin National Forest.

CRITERIA FOR CHOICE OF TAXA

Plant species can be viewed both as a component of the species diversity as well as a component of habitat diversity as a plant community. The presence of a particular plant species at a specific site can be highly indicative of the particular microhabitat of that site. Because the plant species with dominant cover play a major role in determining what reflectance patterns are measured by satellite, we believed that it was imperative to test the relationship between the remotely sensed habitat types and the plant community. If plant species distribution patterns could not be predicted using remotely sensed data, relationships between remotely sensed data and animal taxa would be highly unlikely. Thus, a plant survey is the critical link

between remotely sensed data, habitat, and other species distribution patterns.

Butterflies were a preferred taxa for testing the hypothesis that remotely sensed data can be used to predict species distributions. Some butterfly species are moderately host-specific, while others are highly host-specific herbivorous insects and their diversity may be correlated with underlying plant diversity. Butterflies are also well-known taxonomically and reliably identified in the field (Kremen 1992). Over one hundred different species reside in the Greater Yellowstone Ecosystem (Bowser 1988, Brussard 1989).

Birds were chosen to test the hypothesis because they are ecologically diverse and use a wide variety of food and other resources. Therefore, they reflect the condition of many aspects of the ecosystem. They also represent several trophic groups or guilds, and by having a short generation time, they exhibit quick responses to environmental change (Steele et al. 1984). Finally, they are good indicators because they are conspicuous, ubiquitous, intensively studied, and often appear to be more sensitive to environmental changes than other vertebrates (Morrison 1986). Over one hundred different species reside in the Greater Yellowstone Ecosystem.

✦ METHODS

GIS AND REMOTE SENSING ANALYSIS

The remotely sensed data included three visible, one near infrared, and two middle infrared bands. Landsat 5 Thematic Mapper (TM) data from a 31 July, 1991 scene were registered to a Universal Transverse Mercator (UTM) coordinate system using ground control points selected from maps covering the study area, and resampled to 30 x 30 m. Digital elevation model (DEM) data were obtained from the U.S. Geological Survey (USGS) projected to UTM coordinates, and the maps of slope, aspect, and elevation created using ERDAS GIS software. TM pixel brightness values was converted to radiance values (watts/m^2/steradian/ nanometer) to account for effects of changing instruments and calibration drift. Six bands were available to describe each 30 x 30 m pixel. TM data transformations were used to extract vegetation information (i.e., Tasseled Cap, Principal Components Analysis, and Normalized Difference Vegetation Index (NDVI)). To avoid sampling on cliffs or extremely steep slopes, areas of greater than 30 degrees slope were masked out on the Landsat data.

These remotely sensed data were then clustered into 50 spectrally distinct classes, and classified using a minimum distance classifier. Cluster classes were evaluated using U.S. Forest Service (USFS) stand survey maps, aerial photography, and personal knowledge of the study area. The 50 classes were then combined to form eleven spectrally distinct vegetation cover types. To facilitate location of study sites during fieldwork, the map was converted to vector format and plotted on translucent Mylar, allowing overlay onto a 1:24,000 scale USGS topographic maps of the study region (Fig. 2).

Five forest habitat types and six meadow habitat types were identified in the preliminary analysis. Forest types included Douglas Fir *Pseudotsuga menzesii* (DF), Whitebark Pine *Pinus albicaulis* (WB), and mixed conifer Lodgepole Pine *Pinus contorta*, Engleman's Spruce, *Picea englemanii*, and Douglas Fir of three different densities (F1-F3). Meadows ranged from M1 (sedge meadow) to M6 (dry grassland with sagebrush). We inventoried five spatially distinct examples of each of the F1-F3 and M1-M6 habitat types (nine habitat types, total sites = 45).

SPECIES AND HABITAT CHARACTERIZATION IN SAMPLE SITES

Trees were sampled for species composition and cover by establishing a 100 m transect and surveying every tree within 3 m on either side of the transect line (Brower et al. 1990). Five spatially distinct areas were surveyed for each of three forest types (F1, F2, F3) during 1993. Grasses, forbs, and shrubs were also surveyed in five spatially distinct areas for each of the six meadow types during 1994. Twenty-five 1 m^2 plots were established at 4 m intervals along a 100 m transect, and each plot was surveyed for total coverage on a per species basis for all grasses, forbs, and shrubs. The species cover was determined by two observers visually estimating and agreeing on the sum of the greatest spread of foliage for each species in each plot (Daubenmire 1959). In

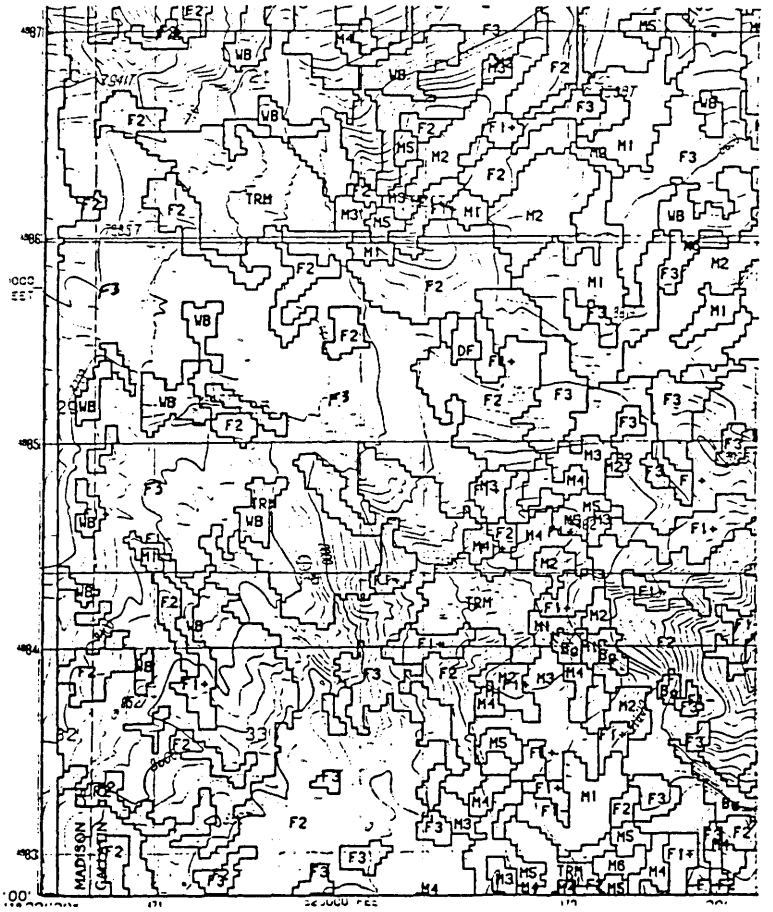

Figure 2. An example of a map of spectrally distinct vegetation cover types overlayed on a 1:24,000 scale USGS topographic map. Habitat types are based upon remote sensing cluster analyss followed by ground-truthing with USFS stand survey maps and aerial photos. Codes are as follows: Mixed conifer forest *Pinus contorta, picea englemanii,* and *Pseudotsuga menzezii* of high density (F3), lower density (F2), and fairly sparse forest (F1), *Pseudotsuga menzezii* forest (DF), *Pinus albicaulis* forest (WB), hydric/lush meadow (M1), decreasing moisture gradient of meadows (M2-M4), moist sagebrush/cinquefoil meadow (M5), and xeric, mostly dry sagebrush shrubland (M6) tallus (TRM), and background/steep slopes (Bg).

some groups, where species identification was problematic, species were clumped within the genus to calculate a total cover for the genus rather than the species. These genera were: *Agoseris, Agropyron, Agrostis, Arabis, Arenaria, Aster, Astragalus, Bromus, Carex, Corydalis, Crepis,Cryptantha, Draba, Erigeron, Festuca, Juncus, Oxytropus, Poa, Potentilla, Ranunculus, Senecio, Solidago,* and *Senecio.*

Presence/absence data were collected for butterflies and birds during 1993, employing previously developed methods (Debinski 1991, Debinski and Brussard 1992). Birds were surveyed from 0530-1000 hrs. in thirty-five sites comprising three forest types (F1-F3) and six meadow types (M1 - M6). Auditory and visual surveys were conducted using four observers (two groups of two) moving systematically through the 100 x 100 m plots for 45 minutes. Bird surveys were repeated three times at each site during the course of a summer. Butterflies were surveyed from 1000-1630 hrs. in 23 meadows of type M1-M6. Butterflies were censused by netting and releasing for 20 minutes in three randomly selected 50 x 50 m subplots within each larger 100 x 100 m plot. Sites of this scale were chosen to minimize habitat heterogeneity. Sampling for butterflies was repeated at least two, and preferrably three times during the course of the 1993 field season.

DEVELOPING AND TESTING THE MODELS

Stepwise discrminant analysis, ANOVA and logistic regression were used to test for relationships between species frequencies patterns and remotely sensed habitat types. These analyses were used to 1) determine which species had significant relationships with the remotely sensed habitat types, 2) determine whether the size classes (DBH) of trees differed among remotely sensed forest types, and 3) determine whether hotspots of species diversity corresponded among taxonomic groups. Each taxonomic group was tested separately for relationships with remotely sensed data, and subgroups (e.g. shrubs, forbs, grasses) were also analyzed. Total coverage for all vegetation plots within a transect was standardized to 100%. Stepwise discriminant analysis was conducted using a subset of the data, excluding species which occured in less than 2 percent coverage in every transect (total species = 80).

Multivariate analysis of the bird and butterfly data was conducted by using a modified presence/absence matrix which weighted the number of species occurrences relative to the number of times a site was surveyed. This data set provided more information than a simple presence/absence matrix. The number of occurrences of each species per site was summed over all the samples, rather than merely indicating whether or not the species has ever been seen at that site. In order to adjust for inconsistencies in sampling effort, each species/site combination was scored as $p_{ij} = m_{ij}/n_j$, where m_{ij} is the number of occurrences for species i, and n_j is the total number of samples taken at site j.

✦ RESULTS

The analysis of the 1993 and 1994 field data showed several important relationships between remotely sensed habitat types and species distribution patterns of vegetation, birds, and butterflies. Field surveys in 1993 validated the vegetation density, composition, and moisture gradients expected from satellite data interpretation. Field data supported the expected gradient of increasing forest density from F1 to F3 forests. In addition, we observed that F3 forests tended to be located on steep, north-facing slopes. Discriminant analysis was used to determine whether F1, F2, and F3 forests differed significantly with respect to tree species composition and DBH (diameter at breast height). The same species were found over all forest types, but the relative abundance of each species and DBH were significant in discriminating between forest types. F1 forests tended to have fewer trees (0.034 trees/m^2) with larger DBH (mean = 10.61cm), while F2 and F3 forests had more trees (0.07 and 0.067 trees/m^2) and larger DBH values [(F2 mean DBH = 8.59cm, F3 mean DBH = 7.35cm ($F = 7.971$ for DBH; df = 2,502, a = 0.05, table value F = 3.07)]. F1 forests were composed of a combination f *Pinus contorta*, *Picea englemanii*, and *Pseudotsuga menzezii* while F2 forests were primarily *Picea englemanii* and *Pseudotsuga menzezii* with less *Pinus contorta*. F3 forests were primarily composed of *Picea englemanii* with less *Pinus contorta* and *Pseudotsuga menzezii* ($F = 21.73$, df = 2,502, a = 0.05, table value F = 3.07).

Analysis of the grass, forb, and shrub cover data revealed several strong relationships between species distribution patterns and remotely sensed meadow types. Ground-truth data confirmed the moisture gradient for meadows predicted from the satellite data. M1 and M2 meadows were sedge marshes with some standing water. M3 meadows were characterized by willow thickets and were located near streams. M4 meadows were of medium moisture with cinquefoil and mixed herbaceous vegetation, while M5 meadows had a mixture of sagebrush and herbaceous vegetation. M6 meadows were characteristically south-facing, rocky, and covered with sagebrush. One hundred and forty-three species (or species groups) of plants were observed in 1994 on 30 meadow sites. Twenty-two of these species were statistically significant in distinguishing among remotely sensed habitat types. Several of these species showed clear trends in total coverage which either increased or decreased around a specific habitat type (Table 1).

A total of 74 bird species and 38 butterfly species were observed during the surveys (Tables 2 and 3). Several species of birds exhibited a habitat preference (Tables 2 and 4). For example, a stepwise discriminant analysis of species distribution

Table 1. Grass, shrub, and forb coverage in each of six remotely sensed meadow types. Species noted below are those that were significant in discriminating meadow types based upon discriminant analysis results ($p<0.05$).

Species	M1	M2	M3	M4	M5	M6
Festuca sp.	3.9	10.5	29.8	62.4	105.6	125.2
Aster integrifolius	56.0	24.7	8.7	2.0	0.1	0.2
Thalictrum dasycarpum	2.1	0.4	2.4	0.0	0.0	0.0
Geum triflorum	0.5	4.6	10.2	28.2	21.7	0.0
Polemonium pulcherrimum	4.3	1.2	0.6	0.0	0.0	0.0
Agrostis scabra	1.5	0.7	0.1	0.2	7.2	0.0
Aster campestris	0.0	8.5	7.0	1.2	3.1	12.8
Arctostaphylos uva-ursi	1.0	.23	4.1	0.0	0.0	0.0
Trifolium longipes	6.0	24.8	0.4	1.4	1.9	0.0
Salix Wolfii	29.0	34.8	0.0	0.0	0.0	0.0
Bromus sp.	14.4	10.5	11.5	18.6	15.8	3.3
Eriogonum umbellatum	0.0	0.1	0.3	2.7	6.8	1.6
Muhlenbergia richardsonis	0.0	10.1	0.2	0.0	0.0	0.0
Equisetum hyemale	7.9	2.1	0.2	0.0	0.0	0.0
Salix bebbiana	6.8	0.0	29.7	0.0	0.0	0.0
Lomatium triternatum	1.2	4.1	2.6	0.0	0.0	0.0
Phleum pratense	13.8	22.1	8.4	18.2	15.8	0.6
Senecio sp.	17.8	4.2	0.1	0.3	6.1	0.1
Symphoricarpos albus	0.0	0.0	6.1	0.0	0.0	0.0
Fragaria virginiana	30.5	26.1	34.0	25.4	16.5	0.0
Danthonia intermedia	0.0	0.2	0.5	0.5	12.2	0.0
Arenaria hookeri	0.0	0.0	1.4	0.3	3.0	3.8

patterns by habitat showed seven bird species had significantly different frequencies in forest versus meadow habitats: Mountain chickadee *Parus atricapillus*, Brown creeper *Certhis familiaris*, American crow *Corvus brachyrhynchos*, Orange-crowned warbler *Vermivora celata*, Hermit thrush *Hylocichla guttata*, American robin *Turdus migratorius*, and Song sparrow *Melospiza melodia*. All of these species except tht Song sparrow showed a preferrence for forest. When habitats were clumped into broad categories, (M1-M2, M3-M4, M5-M6, and F1-F3) preferences were as follows, Mountain chickadee (F1-F3), Song sparrow (M1-M2), Rufous sided towhee *Pipilo erythrophthalmus* (M1-M2), Dark-eyed junco *Junco hyemalis* (F1-F3), Violet-green swallow *Tachycineta thalassina* (M5-M6), and Hairy woodpecker *Dendrocopos villosus* (M3-M4). Significant differences among forest preference were as follows: American robin (F3), Red-breasted nuthatch *Sitta canadensis* (F3), Ruby-crowned kinglet *Regulus calendula* (F1) and Song sparrow (M1-M2)

Several butterfly species were found only in hydric or xeric habitat groups (Table 3), but only two species showed significant relationships with one specific habitat type in stepwise discriminant analysis ($\alpha=0.5$). *Colias pelidne* was significantly correlated with M6 meadows and was found only in M6 meadows, while *Plebejus icariodes* was found in all meadows, but showed a preference for drier meadows. Six butterfly species showed a habitat preference for dry meadows (e.g. F2, M5-M6), or mesic to xeric meadows (M3-M6). Five species were found solely in M3 meadows, and one species *Boloria frigga* was found only in hydric meadows (M1-M3). Four species were found in all meadow types.

Species richness was highest for plants (forbs, grasses, and shrubs), birds and butterflies in M3 meadows (Table 5). M3 meadows supported a strikingly higher diversity of birds (41 species) relative to all other meadow and forest habitat types. M3, M5, and M6 meadows all supported high species diversity of butterflies (24, 23, and 23 species respectively). Forbs, grasses, and shrubs showed a less striking difference in diversity among meadow types, but M3 meadows had the highest species richness.

Table 2. Bird species distribution relative to six meadow habitats (M1-M6) and three forest habitats (F1-F3). Meadow types incorporate a moisture gradient (M1, extremely hydric to M6, extremely xeric) and forest types incorporate a density gradient (F1, low density to F3, high density.

	M1	M2	M3	M4	M5	M6	F1	F2	F3
Vermivora celata			X					X	
Dendroica petechia			X					X	
Dendroica coronata			X	X	X		X	X	X
Dendroica townsendi			X					X	X
Oporornis tolmiei			X					X	
Geothlypis trichas		X	X				X		
Wilsonia pusilla			X						
Euphagus cyanocephalus	X	X		X	X	X			
Molothrus ater			X					X	
Piranga ludoviciana			X				X	X	X
Passerina amoena			X						
Pheucticus melanocephalus									X
Carpodacus cassinii			X			X	X	X	
Pinicola enucleator							X		
Carduelis pinus			X				X	X	X
Loxia curvirostra			X						X
Chlorura chlorura		X	X		X	X			
Passerculus sandwichensis		X		X					
Melospiza melodia	X	X	X	X	X	X	X	X	
Pooecetes gramineus		X	X	X	X	X			
Junco hyemlalis			X	X	X	X	X	X	X
Tachycineta bicolor			X					X	
Spizella passerina		X	X	X		X	X	X	X
Zonotrichia leucophrys		X	X	X	X	X	X	X	X
Corvus brachyrhynchos				X			X	X	X
Perisoreus canadensis				X			X	X	
Cyanocitta stelleri						X		X	
Pica pica						X			
Nucifraga columbiana			X	X			X	X	X
Parus atricapillus			X				X	X	X
Parus gambeli			X	X			X	X	X
Sitta canadensis			X				X	X	X
Certhia americana							X	X	
Troglodytes aedon			X						
Turdus migratorius		X	X	X	X	X	X	X	X
Catharus guttatus							X	X	X
Catharus ustalatus							X	X	X
Catharus fucenscens							X		
Sialia currucoides		X	X		X	X			
Myadestes townsendi			X	X	X	X			
Regulus satrapa			X				X	X	X
Regulus calendula			X			X	X	X	X
Stirnus vulgaris			X				X	X	X
Vireo gilvus		X	X	X			X	X	X
Stellula calliope			X			X	X	X	X
Coloptes auratus		X	X			X	X	X	X
Sphyrapicus ruber							X		
Sphyrapicus varius							X		
Sphyrapicus thyroideus							X		
Picoides villosus			X						
Picoides pubescens			X						X
Tyrannus verticalis									X
Sayornis saya							X		
Empidonax traillii			X						
Empidonax hammondii			X						
Empidonax oberholseri			X						
Empidonax minimus		X	X						
Contopus sordidulus								X	
Contopus borealis		X	X					X	
Tachycineta thalassina						X		X	
Iridoprocne bicolor		X	X	X	X	X			
Riparia riparia		X							
Stelgidopteryx ruficollis		X		X		X			
Petrochelidon pyrrhonota			X	X		X			

Table 3. Butterfly habitat specificity based upon results of 1993 field season. X denotes species presence in meadows M1 - M6, where M1 represents the hydric extreme of the moisture gradient and M6 represents the xeric extreme of the moisture gradient in the Greater Yellowstone Ecosystem.

	M1	M2	M3	M4	M5	M6
Parnassius pheobus					X	X
Parnassius proto	X	X	X	X	X	
Pieris napi	X	X	X	X	X	X
Colias interior					X	X
Colias philodice						X
Colias eurytheme				X		
Colias pelidne						X
Anthocharis sara			X	X	X	X
Euchloe ausonide	X	X	X	X	X	X
Lyceana cupreus				X	X	
Gaeides xanthoides			X		X	X
Lyceana heteronea		X			X	X
Lycaena helloides		X	X			X
Lycaena mariposa			X			
Plebejus saepiolus		X	X	X	X	X
Plebejus icariodes		X	X	X	X	X
Plebejus acmon			X	X	X	X
Plebejus glandon			X			
Euphilotes enoptes			X			
Vanessa cardui	X	X	X	X	X	X
Nymphalis milberti		X		X		
Polygonia faunus		X				
Chlosyne palla			X			
Phyciodes tharos		X				
Physiodes campestris		X	X	X	X	X
Boloria frigga	X	X	X			
Boloria selene			X			
Boloria epithore		X	X	X	X	X
Speyeria atlantis		X	X		X	X
Speyeria mormonia			X	X	X	X
Cenonympha hadenii		X	X	X	X	X
Cenonympha inornata		X	X	X	X	X
Cercyonis oetus			X		X	X
Oeneis uhlerii					X	X
Oeneis chryxus					X	
Erebia epipsodea	X	X	X	X	X	X

✦ DISCUSSION

The goal of this research was to explore new uses of remotely sensed data as predictors of plant and animal species locations and to determine the correlation in species richness patterns among taxa. We expected spectral reflectance patterns to be relatively good predictors of vegetation. This expectation was met by our data analysis. Tree species and mean DBH were both significantly related to remotely sensed forest habitat types. Twenty-two species of grasses and forbs were significant in discriminating among meadow types. *Festuca* sp., *Aster campestris*, and *Arenaria hookeri* were associated with the driest meadows, *Agrostis scabra*, *Erigonum umbellatum*, and *Danthonia intermedia* with M5's, *Geum triflorum*, and *Bromus* sp. with M4's, *Thalictrum dasycarpum*, *Arctostaphylos uva-ursi*, *Symphoricarpos albus*, *Salix bebbiana* and *Fragaria virginiana* with M3's, *Triflolium longipes*, *Salix wolfii*, *Muhlenbergia richardsonis*, *Lomatium tritenatum*, and *Phleum pratense* with wetter M2's, and *Aster integrifolius*, *Polemonium pulcherrimum*, *Equisetum hyemale*, and *Senecio* sp. with the wettest M1 meadows. All of these relationships make sense given known habitat preferrence of these species.

The next step was to determine whether spectral reflectance patterns could be correlated to distributions of selected animal taxa. Several species of birds and butterflies were associated with one or more remotely sensed habitat types. Statistical analysis revealed several significant species/habitat relationships. Seven bird species were significant in distinguishing between meadow and forest habitats. Six bird species were significant in distinguishing among finer gradations of habitat subsets (e.g., forests, hydric, mesic, and xeric meadows). Four bird species were significant in distinguishing among forest habitats. All of these species/habitat relationships make sense given known habitat preferences, except the Hairy woodpecker in M3-M4.

Table 4. Total occurrence of bird species significantly related to one habitat type based upon results of stepwise discriminant analysis. Species are listed in order of inclusion in stepwise discriminant analysis.

Meadow versus Forest Categorization (alpha =0.05)

Species	Meadow	Forest
Mountain chickadee	.030	.482
Brown creeper	.000	.130
American crow	.015	.148
Orange-crowned warbler	.015	.019
Hermit thrush	.000	.130
American robin	.394	.648
Song sparrow	.561	.037

Clumped Habitat Categorization (alpha =0.05)

Species	M1-M2	M3-M4	M5-M6	F1-F3
Mountain chickadee	.000	.067	.000	.482
Song sparrow	.800	.600	.333	.037
Rufous-sided towhee	.067	.000	.000	.000
Dark-eyed junco	.133	.483	.238	.926
Violet green swallow	.000	.000	.095	.000
Hairy woodpecker	.000	.033	.000	.000

Differences Among Forest Categorizations (alpha = 0.1)

Species	F1	F2	F3
American robin	.548	.528	.933
Red-breasted nuthatch	.500 .	500	.800
Ruby-crowned kinglet	.714	.667	.600
Song sparrow	.048	.055	.000

Table 5. Species Richness in Remotely Sensed Meadows of the Greater Yellowstone Ecosystem

	M1	M2	M3	M4	M5	M6	F1	F2	F3	
Grass, forbs, shrubs	83	79	95	82	72	61				
Butterflies		6	18	24	17	23	23			
Birds		2	17	41	17	10	18	30	32	23

However, this can be explained by the fact that many of the moist meadows had aspen *Populus tremuloides* stands on their edges. The woodpeckers were using the aspen for nesting, and the meadows for foraging. Two of the 38 butterfly species showed statistically significant differences in frequency among meadow types. However, several other species showed trends in this direction. Species richness patterns did show similar trends across taxonomic groups. M3 meadows supported the highest species richness for birds, butterflies, and vegetation (shrubs, grasses, and forbs). It was not possible to compare species richness among forest sites due to limitations in taxa sampled.

Plants were more highly correlated with remotely sensed habitat types than were animals. This can be explained by several factors: (1) the remote sensing image is actually reflecting the presence of these plants on the ground, (2) plant data was measured in terms of coverage and animal data was measured as presence or absence, (3) plants are stationary and fixed on the landscape, whereas animals are moving through the landscape matrix and may or may not be present when the data are being collected.

The lack of significant relationships between butterflies and remote sensing habitat types may also be due to a limited data set. 1993 was an extremely wet and cold summer; some butterfly sampling sites were only surveyed twice due to poor weather which limited sampling of butterflies. Finally, one would not expect all species to be significantly correlated with one remotely sensed habitat type. Species that were found in only a few sites do not provide enough data for rigorous statistical relationships. Similarly, species found in a range of habitat types (e.g. M1-M3) will not demonstrate a statistical correlation with one specific habitat type using discriminant analysis. Thus, in order to build predictive models of species habitat relationships using remote sensing and GIS methods, a species must be common enough and habitat specific enough to exhibit a significant relationship with one or more remotely sensed habitat types.

Large-scale application of this technique could be particularly valuable for finding new locations of rare species with known habitat associations (e.g., a species restricted to dense forest or wet meadows). Our methodology may make it possible to survey a small fraction of the ecosystem (e.g., 5%) to find the specific habitat of rare species, such as the butterfly *Euphydryas gillettii*. *E. gillettii* is a specialist on black twinberry *Lonicera involucrata*, is found in mesic meadows, and its populations are declining (Debinski 1994b). Our model could also be valuable in monitoring the effects of global climate change on certain species distributions (e.g., Hobbs 1990), however, the limitations of these technologies must be recognized. Extremely rare species and species that are not habitat specific must be monitored using more field intensive methods.

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