

# Empirical Relationships between Structural and Spectral Factors of Yellowstone Lodgepole Pine Forests

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## Abstract

Multiple regression analysis was used to examine the relationships between spectral and biotic factors within the lodgepole pine (*Pinus contorta* var. *latifolia*) forests of Yellowstone National Park. Field-sampled data on forest overstory and understory conditions were regressed against Landsat Thematic Mapper (TM) radiance values and transformed TM data for 70 stands. Factors relating to the physical structure of the forest canopy (height, basal area, biomass, and leaf area index (LAI)) are best predicted using a combination of visible and middle-infrared Thematic Mapper bands. Other overstory factors (density, size diversity, mean diameter, and number of overstory species) were not well explained by the TM data or by combinations of TM data with transformed spectral data. Understory factors (number of seedlings; number of understory species; total cover by forbs, grasses, and shrubs; and total living and nonliving cover) were poorly explained by regression models incorporating spectral and transformed spectral data.

## Introduction

Remotely sensed multispectral data collected from satellites provide a systematic, synoptic ability to assess conditions over large areas on a regular basis. In recent years, there has been increasing interest in utilizing remotely sensed data for extracting biophysically important variables, relating observed spectral reflectance to leaf area index (LAI), biomass, net primary productivity, and vegetation moisture content (Jensen, 1983; Waring *et al.*, 1986; Hobbs and Mooney, 1990). Furthermore, mapping and prediction of biophysical forest factors (i.e., age, leaf area, biomass, basal area) at a landscape to regional scale has important management implications for assessing insect infestation susceptibility, predicting forest fire behavior, and estimating plant and animal species habitat and diversity. The mountain pine bark beetle (*Dendroctonus ponderosae*), for example, tends to infest stands of mature lodgepole pine, attacking the trees at approximately 150 to 180 years age, and forest fuel loadings and ignition potential increase directly with stand maturity (Bradley *et al.*, 1992; Despain, 1990).

Several studies have used correlation or regression analysis to examine relationships between spectral response and coniferous forest structural factors, including basal area and biomass (Franklin, 1986; Peterson *et al.*, 1986; Sader *et al.*, 1990; Leblon *et al.*, 1993), crown closure (Butera, 1986; Pe-

terson *et al.*, 1986), diameter at breast height (Cohen and Spies, 1992; Oza *et al.*, 1989), height and density (Danson and Curran, 1993; Cohen and Spies, 1992; Walsh, 1987), and leaf area index (Spanner *et al.*, 1990; Peterson *et al.*, 1986; Spanner *et al.*, 1984). Statistical analyses performed in the abovementioned studies have either related a single structural factor to a single spectral variable, or related multiple structural or spectral variables to a single spectral or structural variable. The objectives of this paper were to identify the structural factors and factor interactions contributing to recorded spectral reflectance, and to develop regression models for predicting lodgepole pine forest structural factors from Landsat Thematic Mapper (TM) data.

Two conditions that can confound such analyses are the use of raw digital numbers (DN) values rather than physical variables such as radiance or reflectance, and the absence of control over effects of topography and abiotic conditions upon spectral response. Radiance values recorded by a satellite sensor are converted to DNs through the use of gain and offset values. Because of sensor degradation over time, gain and offset values are subject to adjustment over the life of a system, and are different for sensors even of the same type (e.g., Landsat 4 TM and Landsat 5 TM) (Musick, 1986; Suits *et al.*, 1988; Gallo and Eidenshink, 1988). A specific radiance or reflectance level will not be expressed as a constant DN value over time, or between sensors (Hill and Sturm, 1991). Relationships between DN values and biophysical factors are therefore time- and sensor-specific (Graetz, 1990). To avoid this problem, remotely sensed data for this study were converted to radiance values prior to statistical analysis.

Topography has a significant influence upon the spectral response of a forest stand, as demonstrated by Walsh (1987) and Cohen and Spies (1992). By relating Landsat MSS spectral responses to stand and site characteristics by use of multiple regression models, Walsh (1987) determined that cover type, slope angle, and slope aspect explained much of the spectral variability. In high relief areas, topographic factors were major contributors to spectral variation, while in areas of gentle terrain, topographic effects were minimal and canopy characteristics were primary determinants of spectral response. Topographic effects on spectral response have been addressed in various studies by adjusting spectral response as a function of slope and aspect (Spanner *et al.*, 1990), by explicitly incorporating topographic information into the analysis (Fiorella and Ripple, 1993), or by restricting analysis

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to sites of relatively low relief (Butera, 1986). The research described in this paper adopted the third approach. Analysis of lodgepole pine forest spectral-structural relationships for this study was restricted to stands on a single geological substrate and within a narrow range of topographic conditions. While this stratification limits the potential extrapolation of the predictive equations to areas of different terrain, it increases the confidence in the existing predictive equations, because variation among stands is therefore a function of biotic, rather than topographic, differences.

## Study Area

Yellowstone National Park is located in northwestern Wyoming in the northern Rocky Mountains (Figure 1). The park contains several temperate coniferous forest types, including Douglas-fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta* var. *latifolia*), whitebark pine (*Pinus albicaulis*), subalpine fir (*Abies lasiocarpa*), and Engelmann spruce (*Picea engelmannii*) (Despain, 1973). Lodgepole pine occupies approximately 83 percent of the total forested area (Despain, 1983). Habitat types common to the area have been defined by Romme (1982) and Steele *et al.* (1983), and early postfire succession in the region has been extensively researched by Lyon and Stickney (1976) and Taylor (1969).

We focused our research on the Central Plateau region of Yellowstone, a gently rolling upland with an elevation range of 2100 to 2600 m. Low-relief high-altitude montane plateaus are typical of the Yellowstone region, with the Central, Pitchstone, Madison, Solfatara, Mirror, and Two Ocean Plateaus comprising the majority of the park area. Surficial geology of the Central Plateau consists of Pinedale glacial till and rubble overlying Quaternary rhyolite (Richmond and Waldrop, 1975; Waldrop and Pierce, 1975), producing sandy, nutrient-poor soils that act as a primary control upon the forest communities. Romme (1982) described two major upland forest habitat types within the Little Firehole River watershed immediately west of the Central Plateau. On more xeric upland sites, the lodgepole pine/elk sedge (*Pinus contorta*/*Carex geyeri*) habitat type dominates while, in more mesic uplands, the subalpine fir/grouse whortleberry (*Abies lasiocarpa*/*Vaccinium scoparium*) habitat type is dominant. Subalpine fir and Engelmann spruce are also present on north-facing slopes, seeps, and riparian corridors. Understory vegetation is dominated by grouse whortleberry, elk sedge, Ross's sedge (*Carex rossii*), and pinegrass (*Calamagrostis rubescens*) (Despain, 1990).

## Methods

Forest stands were located in the field using a combination of National Aerial Photography Program (NAPP) 1:40,000-scale color-infrared photography and topographic maps. Terrain effects on spectral response were minimized by selecting stands on slopes of less than 3 percent, between 2100 and 2500 m elevation, and on the Pinedale Till/Rubble surficial geology type. Aspect was considered less critical at the low slope angle and, therefore, was not used for stratification. Sample sites were distributed across the Central Plateau region. Environmental measurements for each stand were taken within a 20- by 25-m plot, except in young, dense stands where a 10- by 10-m plot was used. Particular care was taken in the field to ensure that plots were located in the center of a homogeneous stand to avoid edge effects. Diameter at breast height (DBH) was tallied in 5-cm size classes by species for trees greater than 2.5 m in height, using a Biltmore stick (Myers and Shelton, 1980). Counts were also performed for standing dead trees in the same size classes. Trees less than 2.5 m high were tallied as seedlings by species. Height of the dominant overstory was calculated for each sample plot using a clinometer, averaging values for

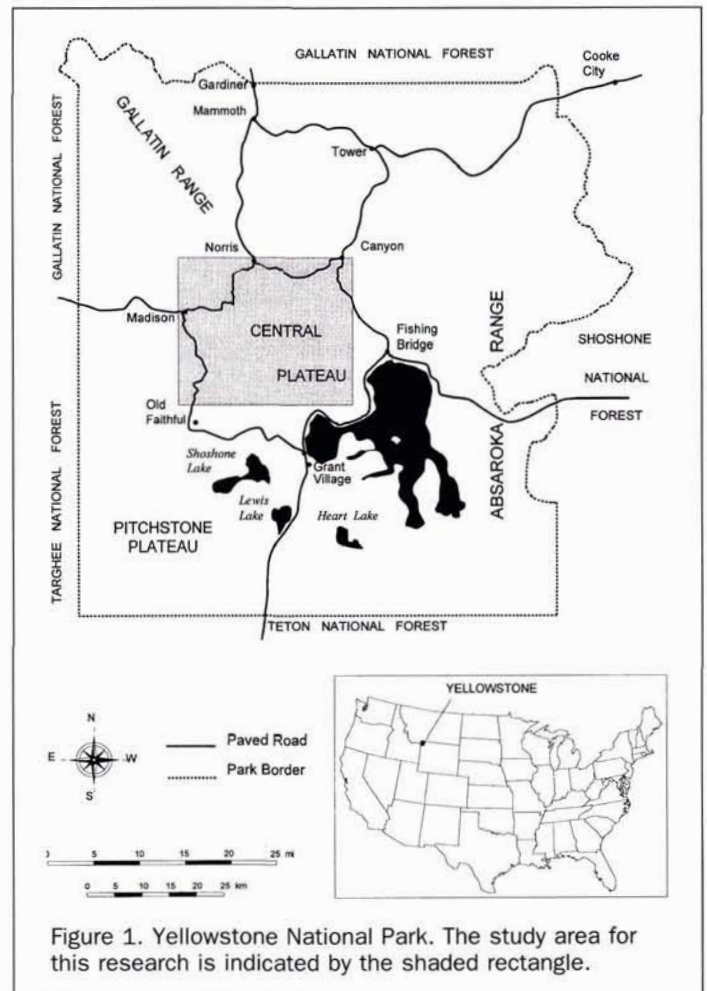


Figure 1. Yellowstone National Park. The study area for this research is indicated by the shaded rectangle.

five dominant trees. Twenty 0.5- by 0.5-m understory quadrats were placed at equal intervals along four transects within each plot, and understory vegetation was recorded by species as percent cover within each quadrat using the Daubenmire technique (Daubenmire, 1959). Ground cover not occupied by herbaceous or low woody plants was classified by percent cover into moss/lichen, litter, persistent litter (dead-fall and sticks larger than 1 cm diameter), rock, and soil. Seventy stands were sampled, representing a diversity of lodgepole pine forest-cover types.

Overstory density and seedling density were computed from size-class data collected for each stand. All data were normalized to a one-hectare standard unit. Size diversity was calculated by counting the number of size classes in which trees were tallied in a plot, and dividing the total by 16 (16 being the maximum possible number of size classes). Basal area for living and dead stems was computed using the mean diameter value for each size class (e.g., 2.5 cm for the 0- to 5-cm size class) (Knight, 1978). Biomass for living overstory species was computed using the allometric equations from Gholz *et al.* (1979), summing species totals to derive total stand live biomass. Leaf area index was computed for each stand using the basal area equations of Kaufman *et al.* (1982). Total percent living cover, and percent cover by life form (e.g., shrubs, grasses, and forbs) was computed for each plot.

A mid-summer date was selected to capture peak vegetation greenness during the short growing season and avoid the cloud and snow cover commonly occurring in the spring and fall in the Yellowstone region. Landsat TM data (31 July

TABLE 1. BIOPHYSICAL FACTORS USED IN ANALYSES

Name	Description and Units
<b>Overstory Factors</b>	
Age	Age of the dominant overstory (years)
Height	Height of the dominant overstory (m)
Mean diameter	Mean tree diameter (cm)
Live density	Overstory live density (trees/ha)
Overstory species	Number of overstory species (count)
Size diversity	Size diversity (scale 0–1) (index value)
Live basal area	Basal area of live trees (m <sup>2</sup> /ha)
Dead basal area	Dead basal area (m <sup>2</sup> /ha)
Total biomass	Total overstory aboveground biomass (kg/ha)
Total LAI	Total overstory leaf area index (LAI)
<b>Understory Factors</b>	
Understory species	Number of understory species (richness)
Total non-living	Total nonliving understory cover (%)
Total living	Total living understory cover (%)
Forbs	Total cover by forbs (%)
Shrubs	Total cover by shrubs (%)
Grasses	Total cover by grasses (%)
Seedlings	Number of seedlings (trees/ha)

1991) were converted from DN values to units of radiance (mW/cm<sup>2</sup>/sr/μm) (Markham and Barker, 1986). The Chavez (1988) improved dark-object subtraction method was applied to the radiance data to compensate for haze effects. Data were registered to a Universal Transverse Mercator (UTM) coordinate system. Spectral values for each stand were extracted from the TM data, averaging the values for a 3-by-3-pixel block surrounding the location of each sample plot. A scene-specific Tasseled Cap transformation (Crist and Ciccone, 1984) and several vegetation indices were computed from the TM data:

- Normalized difference vegetation index (NDVI):  

$$\frac{TM4 - TM3}{TM4 + TM3} \quad (1)$$
- Vegetation Condition Index (VCI):  

$$TM7/TM4 \quad (2)$$
- Greenness Condition Index (GI):  

$$TM4/TM3 \quad (3)$$
- Mid-IR/red reflectance index (MIRI):  

$$\frac{TM7 - TM3}{TM7 + TM3} \quad (4)$$
- Scene-specific Tasseled Cap transformation:  
 TC 1 (Brightness) =  $0.4395(TM1) + 0.5416(TM2) + 0.5406(TM3) + 0.4647(TM4) + 0.0704(TM5) + 0.0169(TM7)$  (5)
- TC 2 (Greenness) =  $-0.2254(TM1) - 0.2054(TM2) - 0.3599(TM3) + 0.8795(TM4) - 0.0437(TM5) - 0.0461(TM7)$  (6)
- TC 3 (Wetness) =  $0.4154(TM1) + 0.1777(TM2) - 0.3618(TM3) - 0.0537(TM4) - 0.7526(TM5) - 0.3095(TM7)$  (7)

Stepwise multiple regression analysis was selected as the analysis method to answer several questions relating to the relationships between forest stand structure and spectral response: What stand structural factors contribute to stand spectral response? To what degree of confidence can stand structural factors be predicted from spectral data? Do band transformations or indices improve the predictability of stand structural factors? To reduce collinearity among the biotic data, highly redundant variables (as determined from correlation analysis) were eliminated and summary variables (e.g., total biomass, total forb cover, etc.) were used wherever possible (Table 1). Regression analysis results were tested for

significance at  $\alpha = 0.05$ . Beta values, or standardized partial regression coefficients, were used to assess the relative importance of each independent variable in the regression equations (Clark and Hosking, 1986).

## Results

### Spectral Data as Dependent Variables

Multiple regression models for the spectral models predicting TM spectral response as a function of biotic factors are shown in Table 2. All spectral variables were well explained by the environmental variables, with a maximum R<sup>2</sup> of 0.87 for TM band 7, and the lowest was 0.60 for TM band 4. Variables indicative of stand development and canopy condition were selected by the stepwise regression analysis as the best predictors of spectral reflectance. With the exception of the regression equations for TM4, height explains the majority of variance in the spectral bands. Height is negatively related to spectral reflectance of TM bands 1, 2, 3, 5, and 7, indicating that as height increases, spectral reflectance decreases. Overstory live density also entered as a significant variable in the regression equations for TM bands 3, 4, 5, and 7. Understory plant species richness (number of species/stand) and seedling density entered positively in the TM equations, but beta values for the two variables were low for TM bands 1, 2, 3, and 5.

Regression results (R<sup>2</sup>) for the transformed spectral data were lower than for untransformed TM data (Table 3). Height and overstory density entered into all equations for transformed spectral data, and were the most significant variables explaining variance in spectral response. Height and density

TABLE 2. MULTIPLE REGRESSION MODELS PREDICTING LANDSAT TM SPECTRAL RESPONSE FROM BIOPHYSICAL FACTORS

Spectral Response	R <sup>2</sup>	Biophysical Factor	Coefficients	Beta Weights
TM1	0.83	Height	-3.317	-0.783
		Understory species	2.730	0.358
		Seedlings	0.001	0.240
		Grasses	-0.693	-0.106
TM2	0.79	(Constant)	138.153	
		Height	-3.295	-0.756
		Understory species	2.486	0.317
		Seedlings	0.001	0.233
TM3	0.83	(Constant)	141.951	
		Height	-4.145	-0.714
		Live density	-0.005	-0.248
		Overstory species	-7.103	-0.144
TM4	0.60	Grasses	-1.448	-0.162
		Understory species	2.628	0.251
		Seedlings	0.001	0.145
		(Constant)	180.766	
TM5	0.81	Understory species	4.729	0.507
		Dead basal area	-1.954	-0.435
		Size diversity	-28.075	-0.187
		Seedlings	0.001	0.266
TM6	0.87	Live density	0.004	0.250
		(Constant)	277.487	
		Height	-1.626	-0.674
		Live density	-0.003	-0.342
TM7	0.87	Grasses	-0.848	-0.229
		Understory species	0.875	0.201
		Seedlings	0.001	0.136
		Overstory species	-3.046	-0.148
TM7	0.87	(Constant)	97.537	
		Height	-0.783	-0.745
		Live density	-0.001	-0.448
		Grasses	-0.263	-0.163
TM7	0.87	Overstory species	-1.298	-0.145
		(Constant)	33.325	

TABLE 3. MULTIPLE REGRESSION MODELS PREDICTING TRANSFORMED LANDSAT TM VALUES FROM BIOPHYSICAL FACTORS

Transformed Values	R <sup>2</sup>	Biophysical Factor	Coefficients	Beta Weights
TC1	0.80	Height	-6.350	-0.758
		Understory species	6.500	0.431
		Seedlings	0.001	0.259
		Dead basal area	-1.015	-0.140
		Grasses (Constant)	-1.569	-0.122
TC2	0.69	Dead basal area	467.461	
		Height	-1.518	-0.323
		Height	2.343	0.432
		Live density	0.007	0.365
		Total non-living (Constant)	-0.922	-0.267
TC3	0.73	Height	304.073	
		Height	1.361	0.716
		Live density	0.003	0.450
		Grasses	0.673	0.231
		Understory species (Constant)	-0.542	-0.158
VCI	0.85	Height	29.262	
		Height	-0.002	-0.616
		Dead basal area	0.001	0.309
		Live density	-0.001	-0.332
		Total living (Constant)	-0.001	-0.126
NDVI	0.84	Height	0.098	
		Height	9.148	0.466
		Live density	0.034	0.466
		Shrubs	2.810	0.124
		Overstory species	34.335	0.206
		Grasses	4.172	0.138
GI	0.71	Mean diameter (Constant)	3.685	0.209
		Total LAI	118.010	
		Total LAI	0.091	0.357
		Height	0.028	0.248
		Height	0.036	0.285
		Live density	0.001	0.246
MIRI	0.64	Overstory species (Constant)	0.212	0.195
		Dead basal area	0.001	0.349
		Live density	-0.001	-0.469
		Height	-0.002	-0.358
		Grasses	-0.002	-0.247
		Forbs (Constant)	-0.004	-0.296

were equally weighted in the equation predicting NDVI values. Height and number of understory species entered as important predictor variables for Tasseled Cap 1 (TC1), similar to the regression equations for visible TM bands (TM1, TM2, and TM3). The predictive equation for the Greenness Index (GI), a simple ratio of TM4/TM3, contained in nearly equal positive beta weights the following overstory variables: total LAI, height, overstory live density, number of understory species, and total understory living cover.

**Environmental Data as Dependent Variables**

Two analyses were performed using the environmental data as dependent variables. The first analysis used only the six TM bands as predictors, and the second analysis used all TM and transformed spectral variables. Table 4 shows the multiple regression models and associated statistics for the environmental models using the TM data set. R<sup>2</sup> results were high for equations predicting overstory factors and low to insignificant for understory variables. Height, live basal area, total LAI, and age were predicted (R<sup>2</sup> = 0.80, 0.63, 0.62, and 0.62, respectively) by a combination of visible and middle-infrared bands. The middle-infrared bands contributed most significantly to explaining variance in all four equations. TM5 explained 62 percent of the variance in total leaf area index, and was inversely related to total LAI. TM7 was the only

spectral variable entering into the equation predicting total stand biomass (R<sup>2</sup> = 0.47).

Mean tree diameter, size diversity, live density, and number of overstory species were less well predicted by the TM data (R<sup>2</sup> = 0.56, 0.37, 0.36, and 0.31, respectively). TM bands recording visible light (TM1, TM2, and TM3) entered as the most significant variables explaining variance in the regression models for the four biotic factors. In contrast, the regression model for predicting dead basal area incorporated only infrared bands (TM4 and TM7) to explain 43 percent of the variance in the data set. Understory variables (number of seedlings, number of understory species, total cover by forbs, nonliving cover, and total cover by shrubs) were poorly explained by the spectral data, with only single spectral bands entering the equations (Table 4). Total understory living cover and total cover by grasses were not predictable using TM data.

Multiple regression models were not substantially improved by incorporating transformed TM data (Table 5). Models for biomass and LAI were improved by the use of the NDVI instead of a mid-infrared TM band. The model fit for dead basal area was increased from 0.43 to 0.56, but R<sup>2</sup> values for age, live basal area, overstory live density, and forbs were lower than R<sup>2</sup> values for the TM-only models. Regres-

TABLE 4. MULTIPLE REGRESSION MODELS PREDICTING BIOPHYSICAL FACTORS FROM LANDSAT TM BANDS

Biophysical Factor	R <sup>2</sup>	Spectral Variables	Coefficients	Beta Weights
Height	0.80	TM7	-1.526	-1.604
		TM1	-0.124	-0.528
		TM5	0.518	1.250
		TM4	-0.035	-0.186
		(Constant)	27.552	
Live basal area	0.63	TM7	-1.230	-0.471
		TM1	-0.228	-0.353
		(Constant)	75.591	
Age	0.62	TM1	-2.300	-0.674
		TM5	11.421	1.908
		TM7	-25.474	-1.853
		TM4	-1.422	-0.510
		(Constant)	440.805	
Total LAI	0.62	TM5	-0.164	-0.788
		(Constant)	16.590	
Total biomass	0.58	TM7	-429.668	-0.768
		(Constant)	13224.217	
Mean diameter	0.56	TM1	-0.478	-1.812
		TM2	0.282	1.102
		(Constant)	32.385	
Dead basal area	0.43	TM4	-0.097	-0.438
		TM7	0.475	0.432
		(Constant)	31.174	
Size diversity	0.37	TM1	-0.004	-0.611
		(Constant)	1.040	
Live density	0.36	TM7	-167.456	-0.671
		TM1	92.933	1.501
		TM3	-52.835	-1.170
		(Constant)	206.679	
Overstory species	0.31	TM1	-0.015	-0.562
		(Constant)	3.465	
Understory species	0.31	TM4	0.060	0.563
		(Constant)	-11.233	
Seedlings	0.29	TM5	276.499	0.542
		(Constant)	-11897.410	
Forbs	0.28	TM1	0.039	0.412
		TM4	0.019	0.254
		(Constant)	-7.259	
Shrubs	0.13	TM3	-0.055	-0.369
		(Constant)	10.716	
Total non-living	0.11	TM4	-0.104	-0.345
		(Constant)	111.233	

TABLE 5. MULTIPLE REGRESSION MODELS PREDICTING BIOPHYSICAL FACTORS FROM COMBINED TM AND TRANSFORMED TM DATA

Biophysical Factor	R <sup>2</sup>	Spectral Variables	Coefficients	Beta Weights
Height	0.80	TM7	-1.625	-1.708
		TC3	-0.471	-0.894
		TM4	-0.052	-0.272
		(Constant)	80.303	
Live basal area	0.62	NDVI	0.112	0.809
		TM4	-0.088	-0.167
		(Constant)	6.493	
Age	0.58	TM1	-3.901	-1.144
		GI	-104.918	-0.930
		VCI	-1404.770	-0.428
		(Constant)	953.299	
Total LAI	0.66	NDVI	0.028	1.100
		TC2	-0.034	-0.368
		(Constant)	1.893	
Total biomass	0.59	NDVI	-23.093	0.771
		(Constant)	-3731.919	
Mean diameter	0.56	TM1	-0.478	-1.812
		TM2	0.282	1.102
		(Constant)	32.385	
Dead basal area	0.56	VCI	297.765	1.135
		TC3	0.364	0.598
		(Constant)	-25.929	
		TM1	-0.005	-0.706
Size diversity	0.46	VCI	-3.948	-0.503
		GI	-0.141	-0.524
		(Constant)	1.743	
		MIRI	-13841.02	-0.302
Overstory species	0.31	TC3	150.499	1.090
		TM5	89.913	0.827
		(Constant)	-22909.91	
		TM1	-0.015	-0.562
Understory species	0.31	(Constant)	3.465	
		TM4	0.060	0.563
		(Constant)	-11.233	
Seedlings	0.29	TM5	276.499	0.542
		(Constant)	-11897.41	
Forbs	0.26	TC1	0.024	0.513
		(Constant)	-7.335	
Shrubs	0.20	GI	3.039	0.448
		(Constant)	-4.320	
		TM4	-0.104	-0.345
Total non-living	0.11	(Constant)	111.233	
		GI	6.555	0.754
Total living	0.16	TM1	0.153	0.585
		(Constant)	-24.454	

sion models for mean diameter, number of overstory species, number of understory species, number of seedlings, and non-living cover remained unchanged. Total understory living cover was marginally predictable ( $R^2 = 0.16$ ) by combining the Greenness Index (GI) with TM1 (Table 5), but the low  $r^2$  values suggests that the equation is of little value for practical estimation of understory living cover from satellite imagery.

## Discussion

Statistical relationships between the stand structural and spectral data are consistent with field observations of lodgepole pine forests in Yellowstone. High seedling densities, high understory species diversity, and relatively high cover by forbs are found in open, dry sites with little or no forest overstory. Understory species diversity, total plant cover, and number of seedlings decrease as the overstory develops and shades the forest floor, and the overstory canopy dominates spectral response (Stenback and Congalton, 1990). The relative contribution of the understory to site spectral response exceeds that of the overstory, and such sites exhibit high

spectral brightness and low greenness. Understory species richness and seedling density function more as indicators of site environmental conditions than as direct controls over reflectance. High values for these two factors occur for open, less dense regenerating stands, and both factors show an inverse beta weight relationship with height in regression equations.

Results suggest that multiple interacting stand structural factors control the spectral reflectance of a forest stand, a conclusion reached by other studies examining spectral response of coniferous forest (Danson and Curran, 1993; Franklin and Luther, 1995; Spanner *et al.*, 1990; Cohen and Spies, 1992). Based on interpretation of beta weights, height and live density consistently enter as the most important contributors to the spectral response of the stand, with similar weighting. This suggests that the two form a "composite" biotic variable, in that no single biotic factor affects spectral reflectance, but that several factors in combination control spectral reflectance. A similar conclusion was reached by Danson and Curran (1993), who suggested that tree height and diameter combined to form an index of crown volume, which in turn combined with density for an index of canopy volume. The multidimensionality of spectral data has been recognized for nearly two decades (Kauth and Thomas, 1976; Richardson and Weigand, 1977; Crist and Ciccone, 1984). Recent studies are indicating that biotic effects on spectral reflectance are complex and may form two or more dimensions as well (Jakubauskas, 1996; Cohen and Spies, 1992; Danson and Curran, 1993).

Multivariate analysis indicates that several forest structural factors may be predicted from remotely sensed data with a high level of statistical significance. LAI and total biomass can be predicted using single bands of TM data, but multiple bands are required for equations predicting height and live basal area. Leaf area index (LAI) correlated poorly with TM4, but correlated highly with the normalized difference vegetation index (NDVI), which agrees with the findings of Spanner *et al.* (1990). LAI also correlated highly with the visible and mid-infrared bands. Strong correlations were noted between total biomass and the middle-infrared bands. Transformations of the original TM data were generally of low value in improving  $r^2$  values in regression equations predicting environmental factors from spectral data, a conclusion of related studies (Peterson *et al.*, 1986; Fiorella and Ripple, 1993).  $R^2$  values for equations for dead basal area and size diversity were the most improved with the addition of transformed data (0.43 to 0.56 and 0.37 to 0.46, respectively). Both equations incorporated the Vegetation Condition Index (VCI), a simple ratio of the middle-infrared to the near-infrared TM bands.

Estimation of forest structural parameters from satellite spectral response must take into account the ecology and environmental context of the structural-spectral relationships. The regression equations for stand age, for example, have statistically significant  $r^2$  values of 0.62 for original TM data (Table 2) and 0.58 for TM and transformed data (Table 3). Spectral response is not a function of age; rather, it is a function of structural factors such as biomass, LAI, density, basal area, and height that themselves are to a large part a function of age. Differing site conditions can produce dramatically different values of these structural parameters for identically aged stands.

## Conclusions

Results indicate that several lodgepole pine forest factors are predictable from remotely sensed data. Biotic factors relating to the gross physical structure of the forest canopy (height, basal area, biomass, and LAI) are best predicted using the middle-infrared bands (TM5 and TM7) or a combination of

visible (TM1, TM2, and TM3) and middle-infrared bands. Factors relating specifically to understory condition are poorly predicted by spectral data, even with the inclusion of data transformations or indices. Data transformations (e.g., NDVI, Tasseled Cap), while they provide some measure of data reduction, do not substantially increase the strength of the statistical relationship between spectral and biotic variables.

The occurrence of one or both of the TM middle-infrared bands in nearly all equations for predicting forest structural factors underscores the importance of this spectral region for forest remote sensing, a conclusion reinforced by the findings of Franklin and Moulton (1990). It is critical that future satellite sensor systems include at least one mid-IR band if the data from that system are to have any applicability for estimating forest structure parameters. Two new systems recently launched or planned for launch (the Indian IRS 1C LISS-III and the SPOT-4 systems, in particular) incorporate middle-infrared sensors not included in the sensor packages of their respective predecessors.

Further research should explore the use of multitemporal data for empirical estimation of coniferous forest factors. Studies employing multitemporal data might take advantage of different solar elevation angles that alter and accentuate the relationships between illuminated canopy, shadowed canopy, illuminated background, and shadowed background (Jakubauskas 1996; Price, 1993; Cohen and Spies, 1992; Danson and Curran, 1993; Li and Strahler, 1985). Predictability of biotic factors that show a strong seasonal variation, in particular, living understory cover, may increase if regression equations incorporate imagery from peak greenness and senescent periods in this ecosystem.

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