Determining Successional Stage of Temperate Coniferous Forests with Landsat Satellite Data

Abstract

Thematic Mapper (TM) digital imagery was used to map forest successional stages and to evaluate spectral differences between old-growth and mature forests in the central Cascade Range of Oregon. Relative sun incidence values were incorporated into the successional stage classification to compensate for topographic induced variation. Relative sun incidence improved the classification accuracy of young successional stages, but did not improve the classification accuracy of older, closed canopy forest classes or overall accuracy. TM bands 1, 2, and 4; the normalized difference vegetation index (NDVI); and TM 4/3, 4/5, and 4/7 band ratio values for old-growth forests were found to be significantly lower than the values of mature forests (P ≤ 0.034). The Tasseled Cap features of brightness, greenness, and wetness also had significantly lower old-growth values as compared to mature forest values (P ≤ 0.010). Wetness and the TM 4/5 and 4/7 band ratios all had low correlations to relative sun incidence (r² ≤ 0.16). The TM 4/5 band ratio was named the "structural index" (SI) because of its ability to distinguish between mature and old-growth forests and its simplicity.

Introduction

The identification of successional stages in the conifer forests of the Pacific Northwest region of the U.S.A. is important to both forest managers and wildlife biologists. Current information on the location and distribution of all forest ages and structures is needed to manage public lands for multiple use objectives. Recently, identifying remaining stands of old-growth forest has been highlighted (Ripple *et al.*, 1991a). However, information on younger stand development is necessary and critical in determining future timber supply and wildlife habitat (Brown, 1985; Harris, 1984).

Satellite imagery has been used in the past to classify Northwest forests. Landsat Multispectral Scanner (MSS) data have been used in western Washington to identify old-growth forests (Eby, 1987), and to identify forest species groups (Cibula, 1987). Landsat Thematic Mapper (TM) data have been used in northern California to quantify stand structural characteristics of basal area and foliage biomass (Franklin, 1986). Recent studies in western Oregon and Washington have employed TM data to map old-growth forests (Green and Congalton, 1990); to relate the structural attributes of young, mature, and old-growth stands to the TM Tasseled Cap indices (Cohen and Spies, 1992); and to measure stand volume and basal area (Ripple *et al.* 1991b).

Distinguishing old-growth from mature forests has been difficult because both successional stages tend to have large trees, and high basal and leaf areas. Most forest stand parameters such as biomass, leaf area index, volume, and, in general, vegetation amount have asymptotic relationships to single band spectral data beginning at moderate to high levels of these stand parameters (Ripple *et al.*, 1991b; Spanner *et al.*, 1990a; Horler and Ahern, 1986). Differences in old-growth and mature forests are determined by a combination of overstory and understory structural and compositional factors from ground based surveys. However, remote sensing data primarily measure only canopy overstory characteristics.

Two of the most distinguishing features observed at the canopy level are differences in the number and size of gaps in the forest canopy and the heterogeneity of tree sizes (Spies *et al.*, 1990; Spies and Franklin, 1991). In general, old-growth canopy gaps tend to be horizontally larger (85m² versus 19m²), but less numerous than those characteristic in mature stands (Spies *et al.*, 1990). Old-growth forests also have a greater range of tree sizes (Spies *et al.*, 1990). Both of these features create dark shadows in the old-growth forest canopies which contrast sharply with sunlit tree crowns.

Identifying forest successional stages in dissected mountainous terrain is complicated due to the dark shadowing on steep north-facing slopes and the high variability in illumination conditions. Eby (1987) used Landsat MSS near-infrared band 4 imagery to identify old-growth forest stands with 80 percent accuracy. Sun incidence angle was used to stratify the study area into normally illuminated and shaded areas for post-classification sorting. Walsh (1987) found that terrain orientation in southern Oregon mountains was often more important in determining TM band values than either crown size or crown density. We hypothesized that reflectance of forest stands in the Cascade Range of Oregon would also be significantly influenced by terrain orientation due to the steep elevational gradients and sharply dissected valleys. Previous studies also indicate that both sun angle (Guyot *et al.*, 1989; Conese *et al.*, 1988; Leprieur *et al.*, 1988; Pinter *et al.*, 1985), and plant architecture or canopy structure can influence measured reflectance (Williams, 1991; Guyot *et al.*, 1989; Pinter *et al.*, 1985). Slope, sun angle, plant architecture, and canopy structure can determine whether vegetation response to incident sun light is best modeled by a Lambertian or non-Lambertian model (Jones *et al.*, 1988; Leprieur *et al.*, 1988; Hugli and Frei, 1983; Teillet *et al.*, 1982; Smith *et al.*, 1980).

Primary objectives of this study were (1) to develop a successional stage map for use in wildlife habitat analysis, (2) to compare the spectral characteristics of old-growth and mature forests, and (3) to evaluate the topographic influence

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on spectral signatures and the usefulness of sun incidence data in mapping forest successional stage.

Methods

Study Site

The H.J. Andrews Experimental Forest study site is located in the Central Cascade Range of Oregon. Elevations range from 414 to 1630 metres above mean sea level (MSL). The study area falls within the western hemlock (*Tsuga heterophylla*) zone (Franklin and Dyrness, 1973), and the dominant tree species in this zone is Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco.), a subclimax species. Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) is a common understory or codominant species in older stands. Above 1100 metres, the study area falls into the Pacific silver fir (*Abies amabilis*) zone (Franklin and Dyrness, 1973). These higher elevation forests are dominated by noble fir (*Abies procera* Rehd.) or Pacific silver fir (*Abies amabilis* (Dougl.) Forbes).

Timber harvesting in the Experimental Forest began in 1950. These replanted, managed stands represent approximately 25 percent of the forest landscape. The slope-aspects in the study area are predominately north, northwest, south, and southeast, and slope-aspect determined moisture gradients are evident. South facing slopes tend to be drier and more susceptible to wildfires than are north facing slopes (Teensma, 1987).

Computer-Assisted Classification and Mapping

An area including the H.J. Andrews Experimental Forest was extracted from a 30 July 1988 TM quarter-scene (scene ID Y5161218271). The TM data were rectified to a Universal Transverse Mercator (UTM) grid using a nearest neighbor resampling method.

Preliminary classification results indicated that topographic shadowing was an important factor in mapping successional stages. Eby's (1987) study indicated that the use of sun incidence angle could reduce confusion between mature and old-growth forests due to topography (Eby, 1987). Thus, a relative sun incidence band was used with the six TM reflective bands in the classification to evaluate its utility in compensating for the unequal illumination on southern versus northern slopes.

Relative sun incidence was calculated from a 1:250,000-scale digital elevation model (DEM) data using the ERDAS RELIEF program (Figure 1). This program calculates direct illumination which is equal to the cosine of the angle between the surface normal and the incident beam for each pixel. The output values of −1 to 1 were rescaled from 0 to 255. The sun incidence band was resampled to a 30- by 30-metre cell size using a nearest neighbor resampling method to register it to the TM data. These data represented the relative amount of incident sunlight to a surface based on sun azimuth and sun elevation at the time of the satellite overpass, but did not consider atmospheric influences or diffuse illumination of adjacent slopes. The sun incidence model assumed a uniform Lambertian behavior of all vegetation types. The model was not used to correct band values, but was used to guide spectral class formation by further dividing classes by relative illumination levels. Two spectral classes could potentially have the same true spectral vector, but could be distinguished based on illumination levels.

All six TM reflective bands (1,2,3,4,5, and 7) were used in two different classifications. The first classification used only the six TM bands and the second classification used the six TM bands plus the relative sun incidence band. An unsupervised, iterative self-organizing data analysis technique (ISODATA) was used to develop 99 spectral classes. The spectral

signatures generated with ISODATA provided the input to a maximum-likelihood classifier. Ancillary data, which included the locations of old-growth and mature forest reference plots, and 1988, 1:12,000- and 1972, 1:20,000-scale true color aerial photographs were used in assigning class groupings. The output classes were grouped into one of the five successional stage categories. Final maps were smoothed to remove isolated pixels using a moving 3 by 3 window and a majority rule.

Successional Stage Mapping

Five successional stage categories were defined based on wildlife habitat requirements (Brown, 1985): (1) grass-forb and shrub, (2) open sapling pole, (3) closed sapling pole and small sawtimber, (4) mature or large sawtimber, and (5) old-growth (Table 1). These successional stages provide significantly different habitats for wildlife species and are determined primarily by stand structural characteristics rather than species composition (Brown, 1985).

An accuracy assessment was performed on both classifications using a stratified random sample of pixels. Pixels were stratified by the successional stages from the classification which used relative sun incidence (Congalton, 1988). Twenty pixels were selected for classes which occupied a small area in the classified image, and 40 pixels were selected for classes which occupied a large area in the classified image. Pixels selected for accuracy assessment had to be surrounded by pixels of the same class to allow for error in locating the point on aerial photographs.

Sample selection in managed stands was limited to one sample per stand, and to the coverage of the 1988, 1:12,000-scale photographs. The sampling points were transferred from the digital successional stage map to the raw Landsat image file, and the image file was then used to locate the points on the aerial photographs. The successional stage at each accuracy point was determined by a forest ecologist who was very familiar with the area, but not familiar with either of the Landsat classifications. The same set of points was used to evaluate the classification without the sun incidence band. Error matrices with percent correct, percent commission error, and Kappa statistics (Congalton *et al.*,

Figure 1. Shaded relief map for the H.J. Andrews. Dark areas indicate areas of low incident light, and light areas indicate areas of high incident light.

TABLE 1. DESCRIPTION AND CRITERIA FOR SUCCESSIONAL STAGE CLASSES (ADAPTED FROM BROWN, 1985)[1], DBH = DIAMETER AT BREAST HEIGHT.

Stand Condition	Description/Criteria
Grass-forb, Shrub	Grasses and/or shrubs dominate Trees < 10 ft (3.0 m) tall Conifer closure < 30% Soil, Rock 0–10 years old (± 5 years)
Open Sapling-Pole	Trees > 10 ft (3.0 m) tall Canopy closure 30-60% Trees ≥ 1 in. (2.5 cm) DBH 10–15 years old (± 5 years)
Closed Sapling-Pole Small Sawtimber	Canopy closure 60-100% (usually close to 100%) Little understory vegetation 20–90 (± 20 years) years old
Mature, Large Sawtimber	Tree mean DBH ≥ 21 in. (53.3 cm) Trees ≥ 100 ft tall 1 or 2 story stands Crown cover < 100% 90–200 (± 20 years) years old
Old-growth	Tree mean DBH ≥ 26 in. (66.0 cm) 2 or 3 story stands Crown cover < 100% Large amounts of snags and down woody debris 200 + years old (± 30 years)

[1] Ages adapted for study area.

1983) were calculated to evaluate the differences between the classifications.

Spectral Characteristics of Old-Growth and Mature Forest

Mean spectral values of a 3 by 3 window from each of 22 old-growth and 19 mature forest stands were compared to determine whether old-growth and mature forest stands were spectrally distinct. TM spectral data were extracted from locations of known U.S. Forest Service old-growth and mature forest reference plots that fell within, or were adjacent to, the H.J. Andrews Forest. Accuracy sampling points which were identified as mature forest stands, and were not already represented by the reference plots, were also used in this analysis. The Wilcoxon Rank Sum test (Devore and Peck, 1986), a non-parametric measure of the difference in the mean values, was used to determine which single TM band, TM band transformation, or Tasseled Cap feature (Crist and Cicone, 1984) provided the best separation between 22 old-growth and 19 mature forest stands.

Sun Incidence

Regression analysis was used to examine the relationship of TM band 4 band values for old-growth, mature, and young conifer forest stands, to relative sun incidence. The analysis was used to determine if these successional stages fit the Lambertian model, and to determine whether the forest canopy response differed between forest successional stages. A Lambertian model assumes that light is scattered uniformly in all directions and is determined by slope orientation with respect to the sun. Differences in land cover do not influence model values.

The old-growth and mature stand data from the rank sum test were regressed against sun incidence. Data for young stand observations were taken from managed Douglas-fir stands in the H.J. Andrews forest that had regenerated to a closed canopy condition (ages ranged from 29 to 35 years old). TM band 4 was selected for analysis because of its ability to distinguish mature and old-growth spectral values ($P = 0.0009$) and because it had the highest correlation coefficient ($r^2 = 0.78$) to relative sun incidence values of older stands. Regression lines were fitted using the reduced major axis technique to minimize error in both the x and y directions (Curran and Hay, 1986).

Results

Successional Stage Mapping

Accuracy assessment results are found in Tables 2 and 3. Both the classification performed with the relative sun incidence band, and the classification performed without the relative sun incidence band, had the identical overall percent accuracy (78.3). The highest level of confusion was found between mature and old-growth forests. In both classifications, the mature category had both the lowest percent correct (69) and the highest percent commission error (55) of any category. The classification with sun incidence had higher mapping accuracy for both the grass-forb, and shrub, and open sapling-pole classes (85 and 81 percent, respectively) than the classification performed without sun incidence (80 and 69 percent, respectively).

Spectral Characteristics of Old-Growth and Mature Forest

All mean TM band values for old-growth forest were lower than those of mature forest (Table 4). The nonparametric test (Wilcoxon Rank Sum, Table 4) for the difference in mean old-growth and mature forest stand band values showed that wetness ($P = 0.00003$) and the TM 4/5 ratio ($P = 0.00005$) were the best band transformations, and TM band 4 ($P = 0.0009$) was the best single TM band for distinguishing between these two successional stages. Thematic Mapper bands

TABLE 2. ERROR MATRIX FOR THE CLASSIFICATION WITH SIX TM BANDS (1,2,3,4,5,7)

	REFERENCE DATA					
TM DATA	Grass-forb. Shrub	Open Sapling-Pole	Closed Sapling-Pole-Small Sawtimber	Mature, Large Sawtimber	Old-Growth	Percent Commission Error
Grass-forb. Shrub	16	2	0	0	0	11
Open Sapling-Pole	3	11	1	0	0	27
Closed Sapling-Pole Small Sawtimber	1	2	21	1	2	22
Mature, Large Sawtimber	0	1	3	9	7	55
Old-Growth	0	0	0	3	37	8
Percent Correct	80	69	84	69	80	78.3

Overall Percent Correct = 78.3
Kappa = 0.717

1 and 2; the normalized difference vegetation index (NDVI); and the TM 4/3, TM 4/7, brightness, and greenness band transformations were also highly significant ($P \leq 0.0341$). Correlations between relative sun incidence and wetness, TM 4/5 band ratio, and TM 4/7 band ratio were lower ($r = 0.16, 0.14$, and 0.10, respectively) than those to any other band or band transformation (r ranged $r = 0.49$ to 0.80 for all other bands; and $r = 0.71, 0.78, 0.67$, and 0.69 for TM 3, TM 4, NDVI, and TM 4/3 ratio, respectively).

Sun Incidence
The mean TM 4 band values for old-growth, mature, and young forest stands are shown with their respective incident light levels (Figures 2, 3, and 4, respectively). Mature forest stands had a higher correlation ($r^2 = 0.74$) with relative incident light than old growth forest stands ($r^2 = 0.39$) or young stands ($r^2 = 0.32$). Young forests had a steeper regression slope ($0.768X$) than either the mature stands ($0.284X$) or the old-growth stands ($0.255X$).

Discussion

Successional Stages
The relative sun incidence band improved classification accuracy in younger successional stages (grass-forb and shrub, and open sapling pole), but did not improve classification accuracy for older successional stages. In both the grass-forb and shrub, and open sapling pole stands conditions, the understory vegetation (i.e., grass, herbs, and shrubs) rather than the conifer canopy has the greatest affect on band values (Franklin, 1986; Spanner et al., 1990a). The broad leaf species that dominate these earlier seral stages may be better represented by a Lambertian surface, and therefore better modeled by the relative sun incidence band than are the older stands. The lack of improvement in classification accuracy of older successional stages in the classification with sun incidence may be explained in part by the non-Lambertian characteristics of these stands.

Jones et al. (1988) found vegetation type (deciduous forest, coniferous forest, agriculture) determined whether a Lambertian or non-Lambertian sun incidence model was more successful in correcting illumination problems in SPOT HRV multispectral imagery. Deciduous vegetation had higher percent accuracy with the Lambertian model, while conifer vegetation had higher percent accuracy with a non-Lambertian model. The non-Lambertian model was a Minnaert reflectance model where the surface exhibits less than Lambertian characteristics.

Canopy architecture can also affect band values in that planophile canopies tend to have higher band values than a erectile canopies, and may more likely fit the Lambertian reflectance model (Pinter et al., 1985). Deciduous vegetation tends to be more "planophile" or horizontally flat than coniferous vegetation. Because deciduous plants dominate younger successional stages, the Lambertian sun incidence model may be better suited to these successional stages.

Spectral Characteristics of Old-Growth and Mature Forests
The interpretation of the mature and old-growth forest rank sum results requires attention on two points: (1) old-growth and mature forests can be very similar, and (2) mainly overstory features are directly measured by remote sensing data. Old-growth forests have larger canopy gaps and a greater heterogeneity of tree sizes than do mature forests. Both the large gaps and tree size heterogeneity create dark shadows in old-growth canopies which are in sharp contrast to the sunlit tree crowns. Spectral bands which accentuate the high contrast between pixels dominated by shadows and gaps from pixels dominated by tree crowns are likely to best distinguish old-growth and mature forests.

While not all single TM bands significantly differentiate between old-growth and mature forests, the mean TM values for all old-growth stands was always lower than that for all mature stands. Old-growth Douglas-fir forests have higher leaf area per unit ground area than mature forests of 90 to 130 years old (Franklin et al., 1981). Douglas-fir forests can continue to accumulate live biomass until 400 to 500 years of age and maintain those levels without declining appreciably through 700 to 900 years of age (Franklin and Spies, 1988). Because of spectral asymptotes, it is unlikely that higher leaf areas and live biomass accounted for lower band values for old-growth forests in absorption bands (bands 1, 3, 5, and 7) as compared with mature forest values. Band values become asymptotic above LAIs of approximately 6 (Spanner et al., 1990b), and old-growth LAIs are normally higher than 6 in this location (Franklin et al., 1981). Lower old-growth values were most likely due to shadowing from the uneven tree sizes and the high number of large canopy gaps in old-growth forests.

Also, the fire history of the study area indicates that the majority of the wild fires of the 1800s occurred on the drier south facing slopes (Teensma, 1987). These fires were responsible for the establishment of the mature and natural closed canopy stands in the study area. Because most of the mature forests are located on south facing slopes, these forests are highly illuminated at the time of the Landsat overpass and would subsequently have higher band values due to topographic influences. Rank sum test results for difference

TABLE 3. ERROR MATRIX FOR THE CLASSIFICATION WITH SIX TM BANDS (1,2,3,4,5,7) AND THE RELATIVE SUN INCIDENCE BAND.

TM DATA	REFERENCE DATA					
	Grass-forb, Shrub	Open Sapling-Pole	Closed Sapling-Pole-Small Sawtimber	Mature, Large Sawtimber	Old-Growth	Percent Commiss Error
Grass-forb, Shrub	17	2	1	0	0	15
Open Sapling-Pole	3	13	4	0	0	35
Closed Sapling-Pole Small Sawtimber	0	1	19	0	0	5
Mature, Large Sawtimber	0	0	1	9	10	55
Old-growth	0	0	0	4	36	10
Percent Correct	85	81	76	69	78	78.3

Overall Percent Correct = 78.3
Kappa = 0.718

TABLE 4. RESULTS OF A NONPARAMETRIC TEST (WILCOXON RANK-SUM) FOR THE DIFFERENCE BETWEEN OLD-GROWTH (N = 22) AND MATURE (N = 19) FOREST MEAN VALUES OF SEVEN TM SPECTRAL BANDS, SEVEN BAND TRANSFORMATIONS, AND RELATIVE SUN INCIDENCE. STANDARD ERROR (SE) VALUES ARE IN PARENTHESES.
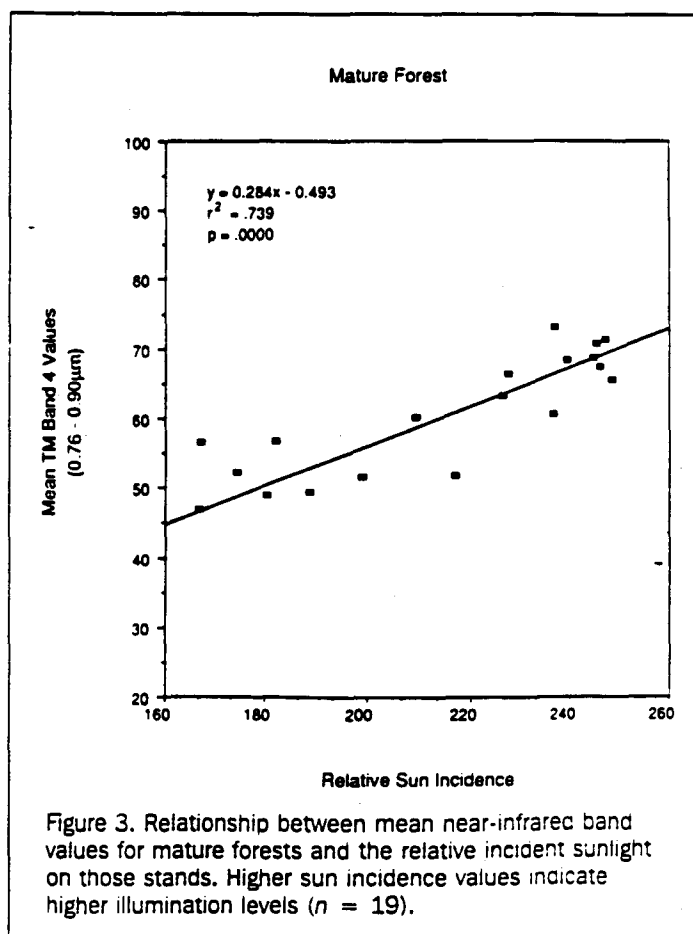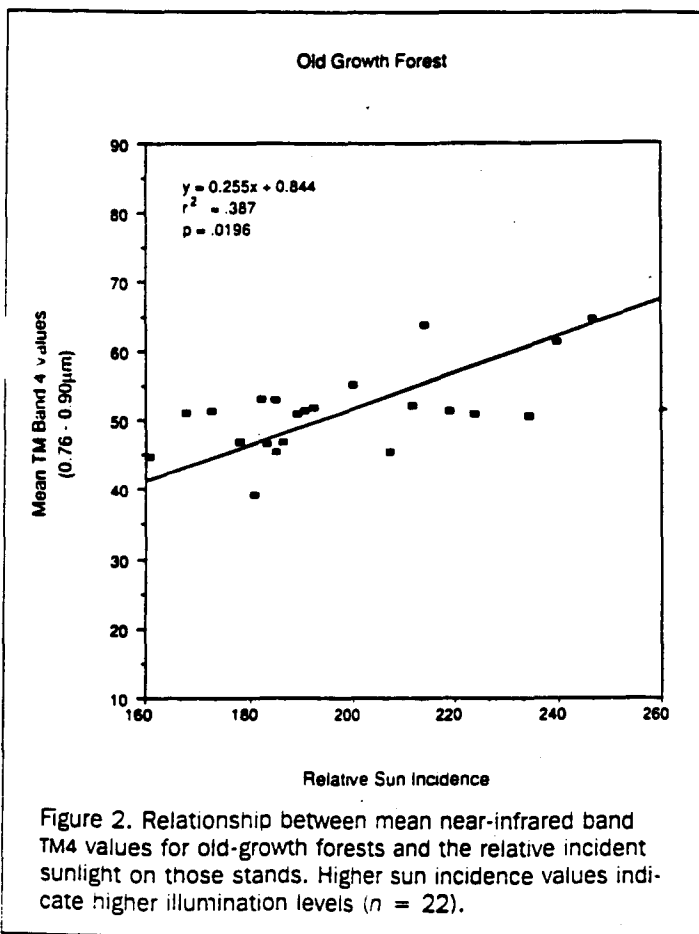
TM Band/Index	Mature $\bar{X}$ (SE)	Old-Growth $\bar{X}$ (SE)	Two Tailed Probabilities
TM 1 (0.45 − 0.52μm)	60.03 (0.348)	59.02 (0.331)	0.0341
TM 2 (0.52 − 0.60μm)	21.00 (0.252)	20.20 (0.127)	0.0103
TM 3 (0.63 − 0.69μm)	16.84 (0.217)	16.47 (0.149)	0.2597
TM 4 (0.76 − 0.90μm)	60.51 (1.961)	51.29 (1.297)	0.0009
TM 5 (1.55 − 1.75μm)	28.04 (1.071)	26.52 (0.656)	0.3333
TM 6 (10.4 − 12.5μm)	134.28 (0.637)	134.20 (0.409)	0.9686
TM 7 (2.08 − 2.35μm)	7.74 (0.349)	7.61 (0.208)	0.7633
NDVI [(TM 4 − 3)/(TM 4 + 3)]	0.56 (0.008)	0.51 (0.007)	0.0001
Ratio TM 4/3	3.58 (0.083)	3.11 (0.065)	0.0004
Ratio TM 4/5 (SI)	2.17 (0.040)	1.94 (0.024)	0.00005
Ratio TM 4/7	7.93 (0.211)	6.78 (0.143)	0.0004
Relative Sun Incidence	214.84 (6.904)	197.67 (5.080)	0.0917
Brightness	81.46 (1.874)	74.80 (1.181)	0.0100
Greenness	13.48 (1.228)	7.41 (0.869)	0.0010
Wetness	15.87 (0.426)	13.44 (0.230)	0.00003

in relative sun incidence on old-growth and mature forests supports this theory (P = 0.0917). Walsh (1987) found similar results in that aspect was often more important in determining TM band values than crown size or crown density.

Rank sum results indicate that TM bands 1, 2, and 4 showed significant differences between old-growth and mature forests, whereas TM bands 3, 5, 6, and 7 did not. Previous studies indicate that TM bands 3, 5, and 7 are sensitive to vegetation amount, but are not useful for distinguishing between moderate to high values of LAI or biomass (Spanner

et al., 1990a; Horler and Ahern, 1986). Old-growth and mature stands both have high vegetation amounts and all pixels, whether in gaps or in mature or old-growth canopies, will be relatively dark.

TM bands 1, 2, and 4 may highlight differences between gaps and forest. This contrast results from mixed pixels dominated by either gaps and shadows (dark) or trees (light). TM band 1 has been found to be able to distinguish between healthy and defoliated conifer canopies where living and dead parts of the canopy are contrasted (Nelson et al., 1984).

Figure 2. Relationship between mean near-infrared band TM4 values for old-growth forests and the relative incident sunlight on those stands. Higher sun incidence values indicate higher illumination levels (n = 22).

Figure 3. Relationship between mean near-infrared band values for mature forests and the relative incident sunlight on those stands. Higher sun incidence values indicate higher illumination levels (n = 19).

In a similar way, dark canopy gaps and sunlit crowns may be contrasted. TM band 4 values generally increase with vegetation amount due to the scattering of light by internal leaf structure (Knipling, 1970). High TM 4 band values on sunlit crowns should contrast sharply with dark shadows in old-growth forests. In mature forests, overall TM 4 band should be bright because sunlit crowns dominate. NDVI and the TM 4/3 band ratio were also able to distinguish between mature and old-growth forests. The utility of these band transformations for spectral discrimination was probably due to the inclusion of TM band 4 and the reduction in topographic induced variation.

Cohen and Spies (1992) found that wetness was the best Tasseled Cap feature for distinguishing old-growth from mature forest stands, while brightness and greenness did not appear to distinguish between these two forest types. In this study, brightness and greenness did separate old-growth from mature forests, but wetness was more highly significant than either of these. Wetness was also better than all other single TM bands and most band ratios. TM 4/5 had a similar significance level ($P = 0.00005$) to wetness, and was also highly correlated to wetness ($r^2 = 0.97$). Although the Tasseled Cap wetness index is a contrast between TM bands 1 through 4 versus TM bands 5 and 7, it appears that, for older forests, the significant feature in wetness may be the contrast between TM 4 versus TM 5. Therefore, we suggest using TM 4/5 rather than wetness because it is simpler to calculate and interpret. The TM 4/5 was named the "structural index" (SI) because we have also found the TM 4/5 ratio to be an excellent predictor of stand age in young managed Douglas-fir forests.

Correlations between SI and stand age ($r = 0.96$, $n = 61$) were higher than all individual bands and six multiband transformations, including the Tasseled Cap indices (Fiorel. and Ripple, unpublished data). Figure 5 shows the response of TM 4, TM 5, and SI on a natural forest in the Three Sister Wilderness, an area adjacent to the H.J. Andrews forest. The figure illustrates how much of the topographic shadowing effect is removed with the SI.

Wetness, SI, and TM 4/7 band ratios all had low correlations with relative sun incidence. Cohen and Spies (1992) found that the topographic effect was minimized in wetness and it appears that this is also the case for SI and TM 4/7 based on correlations of these band ratios to relative sun incidence. In both this study and the study by Cohen and Spies (1992), old-growth forests had lower mean wetness values than did mature forests. Cohen and Spies (1992) found that lichen, bark, and wood all have lower wetness values than sunlit Douglas-fir, western hemlock, and western red cedar canopies. They hypothesized that the lower wetness values for old-growth forest was due to the increase of lichen, snags, and broken topped trees in old-growth forests compared with mature forests.

Sun Incidence

Results from the successional stage classifications indicate that the inclusion of sun incidence as an extra spectral band did not significantly improve overall classification results, and, in fact, decreased the mapping accuracy of older forest. One explanation for the decreased accuracy observed for young, mature, and old-growth conifer stands is that each
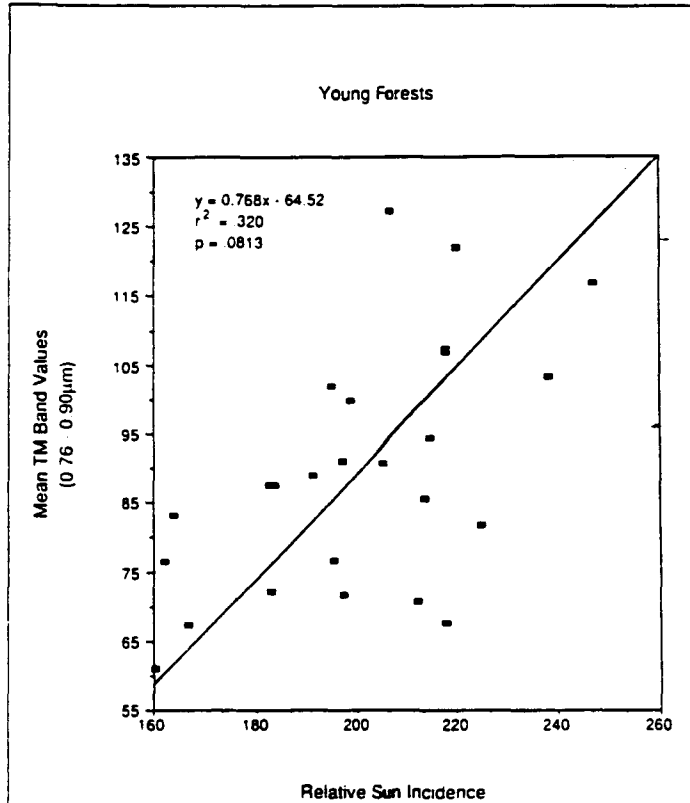

Figure 4. Relationship between mean near-infrared band values for young closed canopy forests and the relative incident sunlight on those stands. Higher sun incidence values indicate higher illumination levels ($n = 25$).
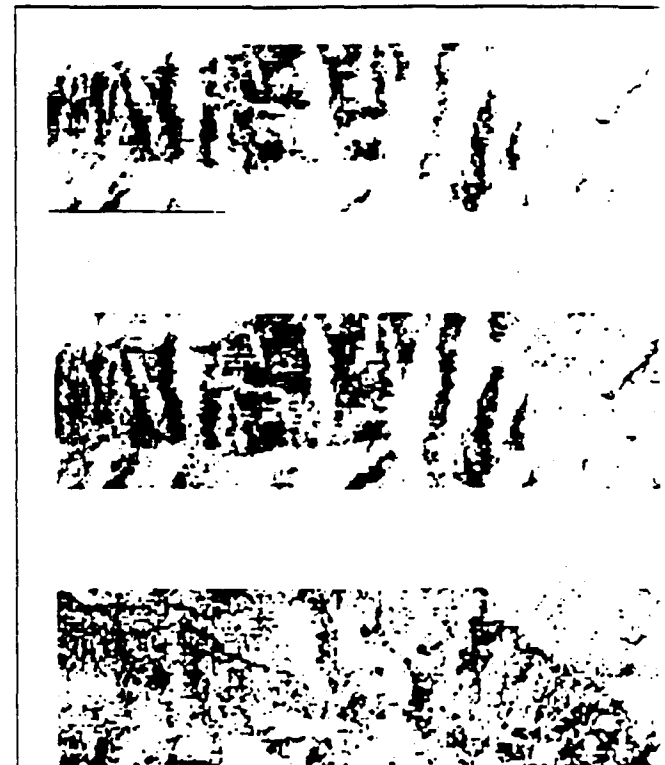

Figure 5. TM 4 (top), TM 5 (middle), and TM 4/5 ratio, the structural index (SI) (bottom), for a 1650-metre by 6000-metre natural forest area adjacent to the H.J. Andrews forest in the Three Sisters Wilderness.

had a different response, as measured by slope, to increased incident light.

There was a general decrease in regression slopes between relative sun incidence and TM band 4 values from young to old-growth forests. These differences could be due to changes in canopy structure. The relatively minor change in regression slope between old-growth and mature successional stages is reasonable, because these successional stages represent a continuum of forest development, where old-growth overstory structure is much closer to mature forests than mature forests are to young forests. In young closed canopy forests there are many tiny crowns packed tightly together, and few, if any, large gaps. More incident light to these canopies results in higher TM band 4 values.

As the stand matures, tree crowns get larger, and spaces between crowns become more pronounced. In old-growth forests the canopy gaps and uneven canopy structure trap much of the incident light, and old-growth forest canopies appear dark whether or not they are highly illuminated. While a Lambertian model may be appropriate for young stands, old-growth canopies as well as mature canopies may require a non-Lambertian model which accommodates canopy gap structure. Further research should be conducted to determine the best model.

The second observation that indicates forest canopy response differs between successional stages is that the r^2 values between TM band 4 and relative sun incidence values for the three successional stages were not equal. TM 4 values from old-growth had low correlations with sun incidence due to the heterogeneous nature of their canopies and because they are dark regardless of the illumination angle. As discussed previously, old-growth forest band values do not always respond evenly to increases in incident light. Mature forests have gaps which are much smaller than the size of a pixel, and generally have even canopies. Because mature forest canopy variability is low, the response to incident sunlight was more predictable. One would also expect young, closed canopy stands to have a high correlation with incident light. While all these stands have at least 95 percent canopy closure, they are plantations and may have been managed differently (different planting densities, thinned versus unthinned, competition with shrubs).

Eby (1987) found that correlations between sun incidence angle (angle normal to the surface) and MSS infrared band 4 were highest for old-growth stands ($r = -0.82$), and that the correlations decreased with younger stands (mature, $r = -0.77$; small sawtimber, $r = -0.44$). He hypothesized that the contrast caused by the complex structure of older stands would be enhanced on slopes with higher sun angles. The difference in spatial resolution between MSS and TM data may account in part for these dissimilar results.

Conclusions

TM data were useful in mapping successional stages. Other conclusions from this study are

- The mean TM band value for all old-growth stands was lower than the mean value for all mature stands due to (a) the many large dark canopy gaps and shadows in old-growth stand, and (b) fire history which shows that mature forests are more likely to be found on south facing slopes which are highly illuminated during the Landsat overpass.
- Including relative sun incidence only improved the classification accuracy of successional stages with minimal or no conifer canopy, probably because the Lambertian model was more appropriate for the understory vegetation.
- Conifer vegetation structure affected the response to incident light. Younger forest successional stages tend to respond more like a Lambertian surface than do older forest canopies.
- A reflectance model that accounts for different vegetation re-

sponses may be more appropriate than a pure Lambertian model.
- Band transformations that contrast near-infrared values with middle infrared values such as SI (structural index = TM 4/5) and wetness appear to decrease topographic shadowing and thereby permit the detection of spectral differences between old-growth and mature forest types.

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