AN ABSTRACT OF THE THESIS OF

Maria Fiorella for the degree of Master of Science in Forest Resources presented May 26, 1992.

Title: Forest and Wildlife Habitat Analysis Using Remote Sensing and Geographic Information Systems

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William J. Ripple

Forest and wildlife habitat analyses were conducted at the H.J. Andrews Experimental Forest in the Central Cascade Mountains of Oregon using remotely sensed data and a geographic information system (GIS). Landsat Thematic Mapper(TM) data were used to determine forest successional stages, and to analyze the structure of both old and young conifer forests. Two successional stage maps were developed. One was developed from six TM spectral bands alone, and the second was developed from six TM spectral bands and a relative sun incidence band. Including the sun incidence band in the classification improved the mapping accuracy in the two youngest successional stages, but did not improve overall accuracy or accuracy of the two oldest successional stages. Mean spectral values for old-growth and mature stands were compared in seven TM bands and seven band transformations. Differences between mature and old-growth successional stages were greatest for the band ratio of TM 4/5 ($P = 0.00005$) and the

multiband transformation of wetness (P = 0.00003). The age of young conifer stands had the highest correlation to TM 4/5 values (r = 0.9559) of any of the TM band or band transformations used. TM 4/5 ratio values of poorly regenerated conifer stands were significantly different from well regenerated conifer stands after age 15 (P = 0.0000). TM 4/5 was named a "Successional Stage Index" (SSI) because of its ability to distinguish forest successional stages.

The forest successional stage map was used as input into a vertebrate richness model using GIS. The three variables of 1) successional stage, 2) elevation, and 3) site moisture were used in the GIS to predict the spatial occurrence of small mammal, amphibian, and reptile species based on primary and secondary habitat requirements. These occurrence or habitat maps were overlayed to tally the predicted number of vertebrate at any given point in the study area. Overall, sixty-three and sixty-seven percent of the model predictions for vertebrate occurrence matched the vertebrates that were trapped in the field in eight forested stands. Of the three model variables, site moisture appeared to have the greatest influence on the pattern of high vertebrate richness in all vertebrate classes.

Forest and Wildlife Habitat Analysis Using Remote Sensing and Geographic Information Systems

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CHAPTER I

INTRODUCTION

Background

Forest management in the Pacific northwest has become very controversial. The demand on public lands to provide recreation, timber, and wildlife resources continues to rise while the total land base used to meet those demands has remained constant. Management goals are often in conflict, and developing forest plans that meet all management objectives is difficult. New technology for spatial analysis could provide information and methods for developing forest plans and for evaluating management alternatives.

Remotely sensed data from satellites can provide current and historical information on the distribution of older forest stands. These data can also be used to monitor changes in young forest development. A geographic information system (GIS) can link remotely sensed data to other environmental data, and provide a method to spatially model the effects of management plans on the wildlife component of the landscape. Together, satellite remote sensing and GIS, offer forest and wildlife managers another method to develop management alternatives, and offer scientists a technology to model forest and landscape processes.

Researchers have found Landsat TM data are useful in mapping forest structural features (Franklin, 1986; Horler and Ahern, 1986). Recent studies in western Oregon and Washington have employed TM data to map old-growth forests (Green and Congalton, 1990), to relate stand structural attributes of young, mature, and old-growth stands to the TM Tassled Cap indices (Cohen and Spies, in press), and to measure stand volume and basal area (Ripple, et al, 1991). Classifying forests in dissected mountainous terrain is difficult because of shadowing caused by steep slopes. Eby (1987) used the Landsat Multispectral Scanner near infrared band 4 and sun incidence angle to identify old-growth forest stands.

Information on young conifer stands is also vital for evaluating wildlife habitat and timber resources. Young conifer plantations now occupy extensive areas within the Cascade Mountains. Conditions within these stands can change quickly. Satellite remote sensing data has potential for assessing forests regeneration and wildlife habitat because it provides coverage over large areas and on a regular basis. The thirty meter spatial resolution of Landsat TM provides more within stand information than Landsat Multispectral Scanner data. Previous studies have used TM data to monitor the age of 0 to 12 year old conifer plantations (Horler and Ahern, 1986); to identify clearcuts and different age groups of conifer regeneration (Matejek and Dubois, 1988); to identify forest disturbance classes in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco.) forests (Spanner, et al, 1989), and to evaluate the influence of forest understory vegetation on spectral data (Spanner, et al., 1990).

Habitat suitability models based on tabular databases of habitat characteristics are common. Raphael and Marcot (1986) predicted species richness and abundance from seral stage information for mixed evergreen forests in northwestern California. Scott, et al (1987) proposed using a GIS to predict regional patterns of species diversity and to identify areas of high species richness which were not already protected. Miller (1989) used vegetation and soils data in a GIS to analyze rare bird species distributions in Tanzania to high light important habitat areas for preservation.

In this analysis, Landsat TM data were used to map forest successional stages, and to analyze the structure of both old and young forests in the H.J. Andrews forest in the central Oregon Cascade mountains. The successional stage map, along with elevation, and site moisture were used as variables in GIS model to predict the occurrence and richness of vertebrates.

Thesis Objectives and Organization:

The four main objectives of this thesis were:

1) to use Landsat TM data to develop a forest successional stage classification that could be used in a GIS vertebrate richness model,

2) to compare the spectral characteristics of mature and old-growth forests,

3) to describe the relationship of TM spectral data to the age and condition of young conifer plantations, and

4) to develop a GIS methodology for modelling vertebrate richness from potential habitat maps of individual vertebrate species.

This thesis is composed of five chapters and is written in manuscript format. Chapter 2 describes the methods used in both developing the successional stage classification and in comparing spectral values of old-growth and mature forests. Chapter 3 illustrates relationships between stand age and TM spectral values in young conifer forests. Differences in spectral values of well regenerated and poorly regenerated conifer stands are also described in Chapter 3. Chapter 4 presents a GIS methodology for modelling potential vertebrate richness and evaluates the method with vertebrate data collected in the field. Finally, Chapter five presents overall conclusions and suggests future areas of study.

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CHAPTER II

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 Mountains 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 band 1, 2, 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 ($P \leq 0.034$). The Tasseled Cap features, brightness, greenness, and wetness, also had significantly lower old-growth values as compared to mature forest values ($P \leq 0.010$). Wetness, and the TM 4/5 and 4/7 band ratios all had low correlations to relative

sun incidence ($r^2 \leq 0.163$). The TM 4/5 band ratio was named the "successional stage index" (SSI) because of its ability to distinguish between mature and old-growth forests and its simplicity.

INTRODUCTION

The identification of successional stages in Northwest conifer forests 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. 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 such as 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 stand structural attributes of young, mature, and old-growth stands to the TM Tasseled Cap indices (Cohen and Spies, in press), and to measure stand volume and basal area (Ripple, et al, 1991).

Identifying old-growth from mature forests is difficult because both successional stages tend to have large trees, and high basal areas and leaf areas. Most forest stand parameters such as biomass, leaf area index, volume, and in general, vegetation amount, show asymptotic relationships to spectral data beginning at moderate to high levels of these stand parameters (Ripple et al, 1991, Spanner, et al, 1990; 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 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 and Franklin, 1991; Spies, et al, 1990). In general, old-growth canopy gaps tend to be larger ($85m^2$ versus $19m^2$), but less numerous than those characteristic in mature stands (Spies, et al, 1990). Old-growth forests also have a greater range of tree sizes. Both of these features create dark shadows in the old-growth forest canopies which contrast sharply with sun lit tree crowns.

Identifying forest successional stages in dissected mountainous terrain is complicated because of dark shadowing caused by steep slopes. Eby (1987) used the Landsat MSS near infrared band 4 and sun incidence angle to identify old-growth forest stands with eighty percent accuracy. 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 Mountains 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 (Leprieur, et al., 1988; Pinter, et al., 1985; and Conese, et al., 1988), and plant architecture or canopy structure influenced measured reflectance (Pinter, et al., 1985; Williams, 1991).

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 on spectral signatures. The usefulness of sun incidence data in mapping forest successional stage was evaluated, as well as the appropriateness of using a Lambertian model for different conifer successional stages.

METHODS

Study Site

The H.J. Andrews Experimental Forest study site is located in the Central Cascade Mountains of Oregon. Elevations range from 414 to 1630 meters 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 meters, 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), but there are some small areas where western red cedar (Thuja plicata Donn.) dominates.

Timber harvesting in the Experimental Forest began in 1950. These replanted, managed stands represent approximately twenty-five 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 have been more susceptible to wildfires than have north facing slopes (Teensma, 1987).

Computer-assisted Classification and Mapping

An area including the H.J. Andrews Experimental Forest was extracted from a July 30, 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. 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. A previous study indicated that the use of sun incidence angle could reduce confusion between mature and old-growth forests due to topography (Eby, 1987). Relative sun incidence was calculated from a 1:250,000 scale digital elevation model (DEM) data using the ERDAS RELIEF program (Figure II.1). This program calculates direct

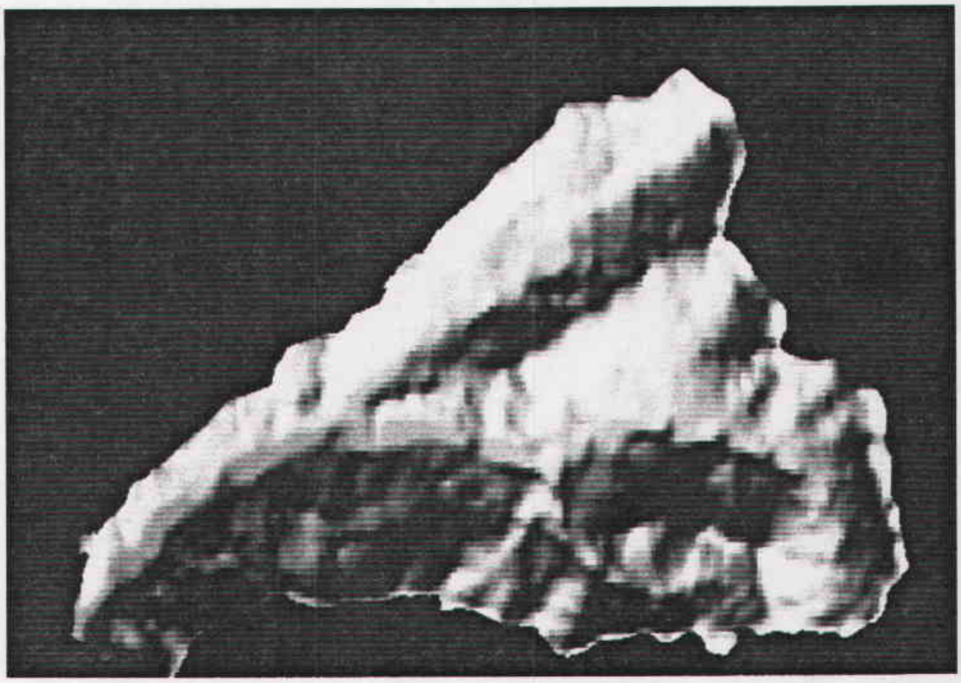

Figure II.1: Shaded relief map for the H.J. Andrews. Dark areas represent low incident light levels, and light areas represent high incident light levels.

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 30 x 30 meter cell size using a nearest neighbor resampling method to match the TM data. These data represented the relative amount of incident sun light to a surface based on sun azimuth and sun elevation at the time of the satellite overpass, but do 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) algorithm was used to develop 99 spectral classes (ERDAS, 1990). 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 3x3 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 II.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 small classes and forty pixels were selected for large classes. 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 per successional stage, and were also limited to coverage of the 1988, 1:12,000 scale photographs. The

Table II.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 feet tall Conifer closure < 30% Soil, Rock 0 - 10 years old (± 5 years)
Open Sapling-Pole	Trees > 10 feet tall Canopy closure 30-60% Trees ≥ 1 inch 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 average DBH ≥ 21+ Trees ≥ 100 feet tall 1 or 2 story stands Crown cover < 100% 90-200 (± 20 years) years old
Old-growth	Tree average DBH ≥ 26+ 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.

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

Spectral Characteristics of Old-Growth and Mature Forest

Mean spectral values of a 3x3 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 mean old-growth and mature forest values for the seven TM spectral band, four band transformations, the three TM Tasseled Cap indices (Crist, and Cicone, 1984), and relative sun incidence, was used to identify which single TM band or TM band transformation provided the best separation between old-growth and 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 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 ($r^2 = 0.7789$) 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 II.2 and II.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).

Table II.2: Error matrix for the classification with six TM bands (1,2,3,4,5,7).

TM DATA	REFERENCE 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

Table II.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 Commission 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

Overal Percent Correct = 78.3

Kappa = 0.718

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 II.4). The nonparametric test (Wilcoxon Rank Sum, Table II.4) for the difference in mean old-growth and mature forest stand band values shows 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 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 ($r = 0.163$, 0.143, and 0.103 respectively) than those to any other band or band transformation ($r = 0.490$ to 0.802; and $r = .710$, .779, .671, and .688 for TM 3, TM 4, NDVI, and TM 4/3 ratio respectively).

Sun Incidence

The mean TM band 4 band values for old-growth, mature, and young forest stands are shown under various relative incident light levels (Figures II.2, II.3, and II.4 respectively). Mature forest stands had a higher

Table II.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 7 TM spectral bands, 7 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 (.45 - .52μm)	60.03 (0.348)	59.02 (0.331)	0.0341
TM 2 (.52 - .60μm)	21.00 (0.252)	20.20 (0.127)	0.0103
TM 3 (.63 - .69μm)	16.84 (0.217)	16.47 (0.149)	0.2597
TM 4 (.76 - .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	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

correlation ($r^2 = .739$) with relative incident light than old growth forest stands ($r^2 = .387$) or young stands ($r^2 = 0.320$). 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., 1990). 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 an unequal response of young, mature, and old-growth forest stands to incident solar radiation.

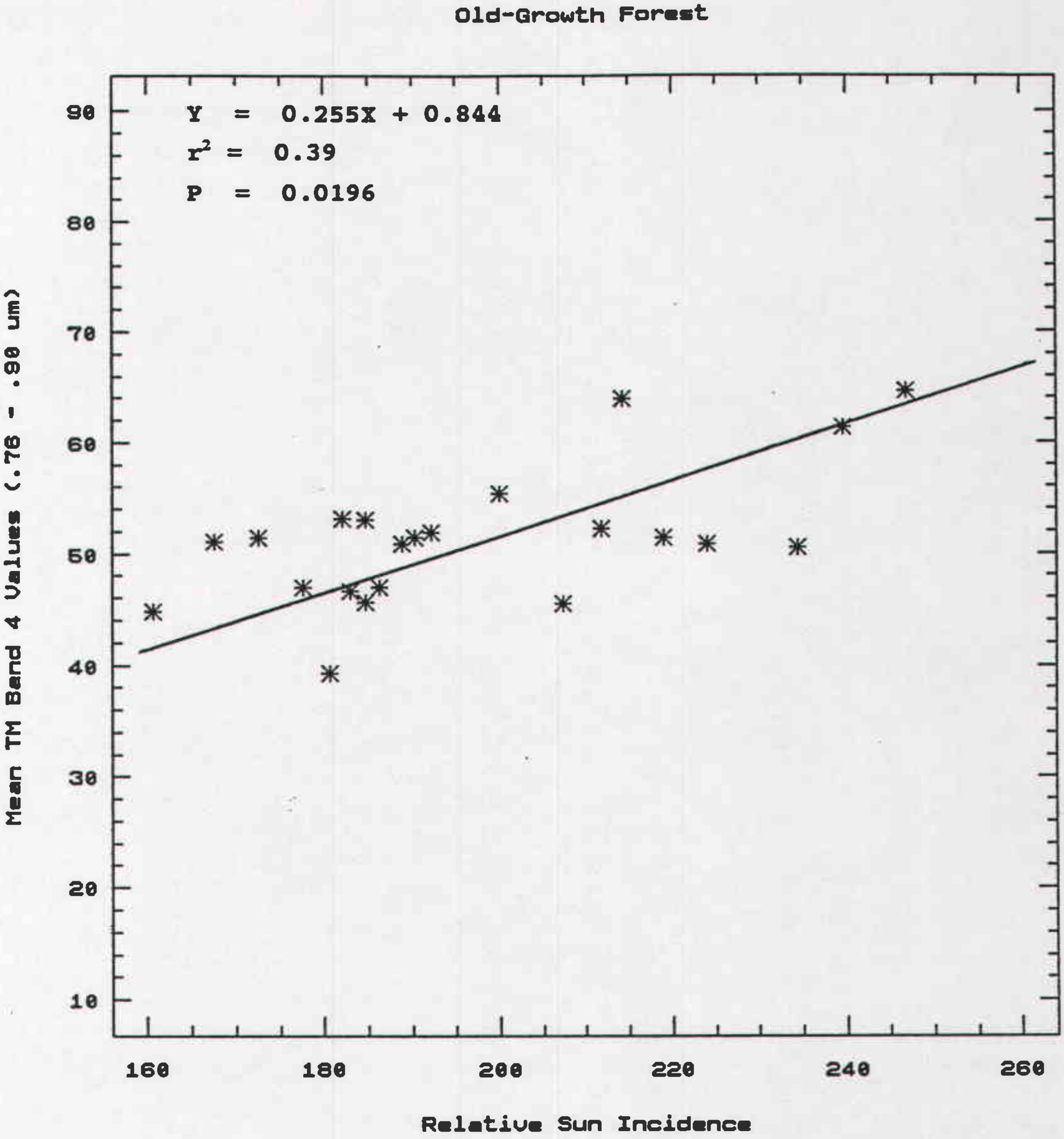

Figure II.2: Relationship between mean near infrared old-growth band values and the relative incident sun light on those forest stands. Higher sun incidence values indicate higher illumination levels (n = 22).
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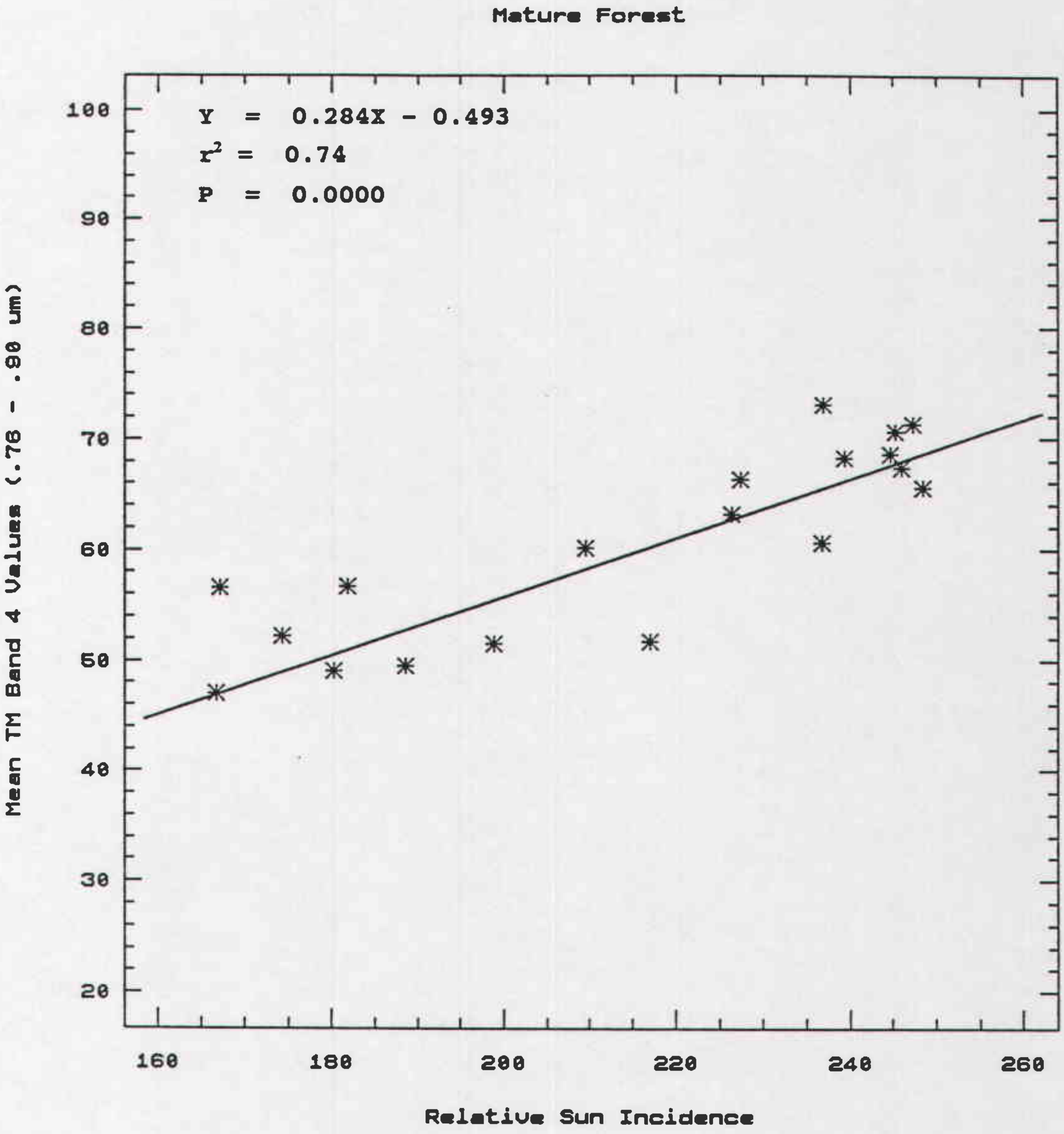

Figure II.3: Relationship between mean near infrared mature band values and the relative incident sun light on those forest stands. Higher sun incidence values indicate higher illumination levels (n = 19).

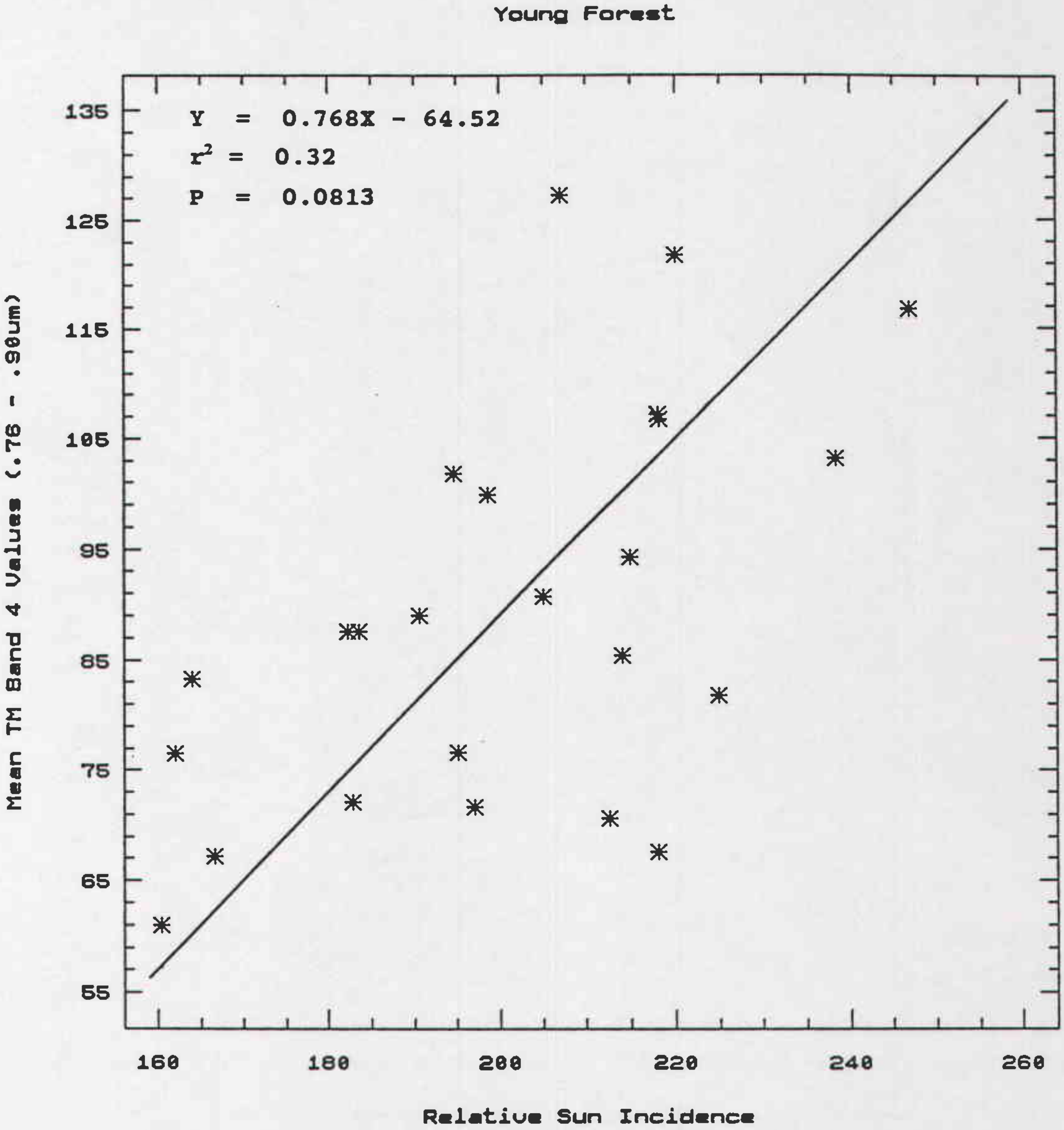

Figure II.4: Relationship between mean near infrared young, closed canopy band values and the relative incident sun light on those forest stands. Higher sun incidence values indicate higher illuminations levels (n = 25).

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 do erectile canopies, and may more likely fit the Lambertian reflectance model (Pinter, et al., 1985). Deciduous canopies tend to be more planophile than conifers. Since 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 sun lit tree crowns. Spectral bands which accentuate the high contrast between shadows and gaps from tree crowns are likely to best distinguish old-growth and mature forests.

While not all bands significantly differentiated between old-growth and mature forests, old-growth mean values were always lower than those for mature forests. 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). Higher leaf areas and live biomass could account for lower band values for old-growth forests in absorption bands (bands 1, 2, 3, 5, and 7) as compared with mature forest values. Lower old-growth values could also be due to the large number and size of canopy gaps in old-growth which could lower overall mean band values. Finally, fire history of the study area indicates that the majority of the wild fires of the 1800’s 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. Since 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 differences in relative sun incidence on old-growth and mature forests supports this theory ($P = 0.0917$).

Rank sum results indicate that TM bands 1, 2, and 4 showed significant differences between old-growth and mature forests, where as 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.,1990; 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 contrast between gaps and forest. 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). In a similar way, dark canopy gaps and sun lit 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 sun lit 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 (in press) found that wetness was the best Tasseled Cap feature for distinguishing old-growth from mature forest stands. In this study, wetness was also better than all other single 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 ($r^2 = 0.971$). 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 much simpler to calculate and interpret. The TM 4/5 was named the "successional stage index" (SSI) 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 SSI and stand age (r = 0.96, n = 61) were higher than all individual bands and six multiband transformations including the Tasseled Cap indices (Fiorella, Chapter III). Figure II.5 shows the response of TM 4, TM 5, and SSI on a natural forest in the Three Sisters Wilderness, an area adjacent to the H.J. Andrews forest. This figure illustrates how much of the topographic shadowing effect is removed with the SSI.

Wetness, SSI, and TM 4/7 band ratios all had low correlations with relative sun incidence. Leprieur, et al. (1988) found that topographic effect increased with band wavelength. Cohen and Spies (in press) found that the topographic effect was minimized in wetness, and it appears that this is also the case for SSI and TM 4/7 based on correlations of these band ratios to relative sun incidence. In a previous study, a near infrared (NIR) to middle infrared (MIR) band ratio was used as moisture stress indicator and was found to be sensitive to changes in plant water stress (Rock, et al., 1985). In both this study and the Cohen and Spies (in press) study, old-growth forests had lower mean wetness values than did mature forests. Cohen and Spies (in press) found that lichen, bark, and wood all have lower wetness values than Douglas-fir, western hemlock, and western red cedar. They

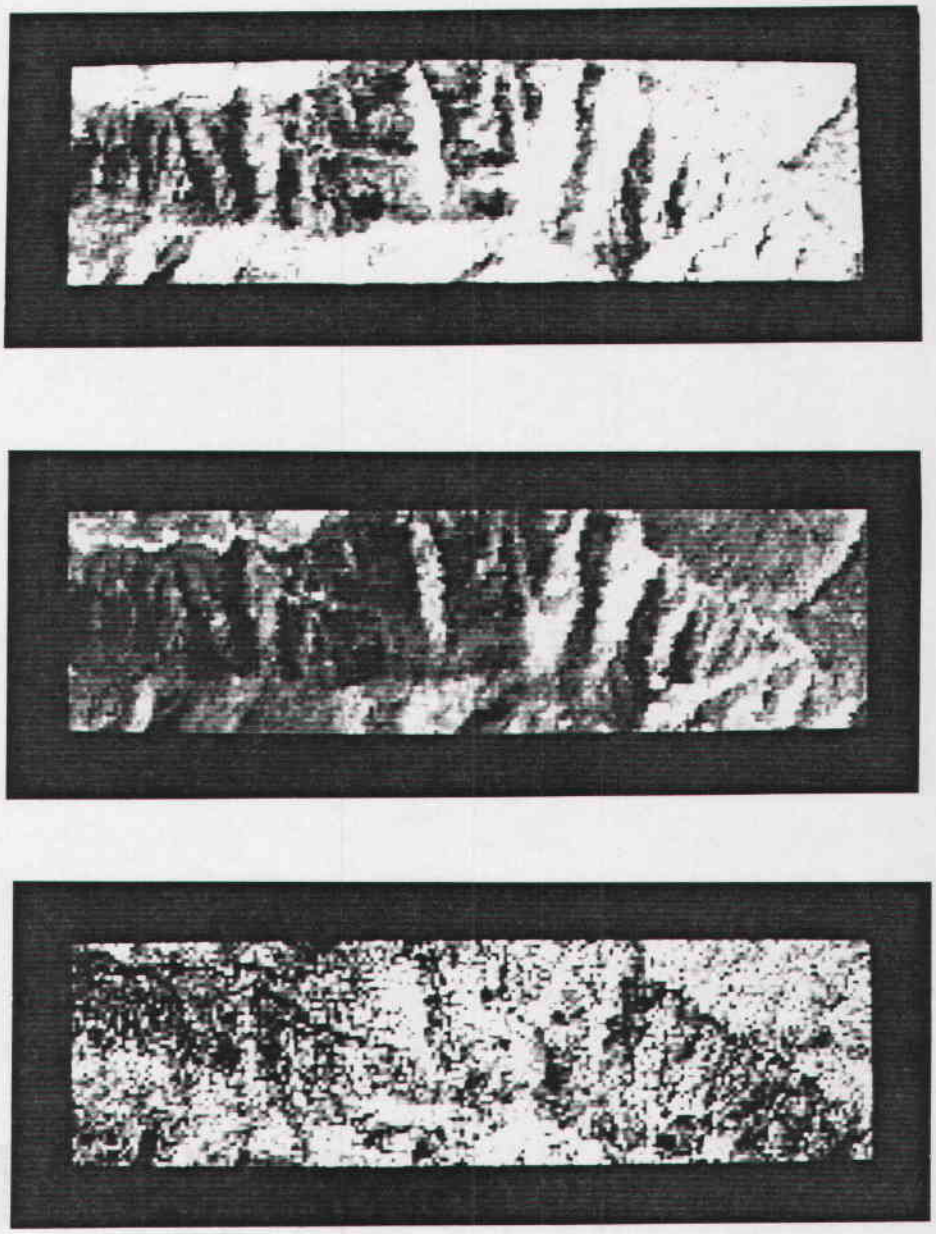

Figure II.5: TM 4 (top), TM 5 (middle), and TM 4/5 ratio, the successional stage index (bottom), for a 1650 meter by 6000 meter natural forest area adjacent to the H.J. Andrews Experimental forest in the Three Sisters Wilderness.

hypothesized that the lower wetness values for old-growth forests is due to the increase of lichen, snags, and broken topped trees in old-growth as 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 forests. One explanation for the decreased accuracy observed in the case of older stands is that the level of Lambertian response from older forests was different than that for younger forests.

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, since these successional stages represent a continuum of forest development, where old-growth overstory structure is much closer to mature forests than 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 forests 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.

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. Old-growth forests had low correlations due to the heterogeneous nature of its canopy. 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. Since mature forest canopy variability is low, the response to incident sun light is 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). Also, since they are younger, they may still reflect site variability that may be masked once trees are taller and have larger diameters.

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 ($r = -.81855$), and that the correlations decreased with younger stands (mature, $r = -.77470$; small sawtimber, $r = -0.43922$). 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 for these dissimilar results.

CONCLUSIONS

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

1. TM forest band values for old-growth forests were lower than those for mature forests due to a number of possible factors: (a) Old-growth has higher live biomass and leaf area, (b) Old-growth has many large dark canopy gaps, and shadows, and (c) Fire history shows that mature forests are more likely to be found on south facing slopes

which are highly illuminated during the Landsat overpass.

2. 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.

3. Conifer vegetation structure affected the response to incident light. Younger successional stages tend to respond more like a Lambertian surface than do older forest canopies.

4. A reflectance model that accounts for different vegetation responses may be more appropriate than a pure Lambertian model.

5. Band transformations that contrast near-infrared values with middle infrared values such as SSI (Successional Stage Index = TM 4/5) and wetness appear to decrease topographic shadowing and thereby enhance spectral differences between old-growth and mature forest types.

ACKNOWLEDGEMENTS

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CHAPTER III

ANALYSIS OF YOUNG CONIFER FORESTS USING LANDSAT THEMATIC MAPPER DATA

ABSTRACT

Landsat Thematic Mapper (TM) data were used to evaluate young conifer stands in the Western Cascade Mountains of Oregon. Regression and correlation analysis were used to describe the relationships between TM band values and age of young Douglas-fir stands (2 to 35 years old). Spectral data from well regenerated Douglas-fir stands were compared to those of poorly regenerated conifer stands and to those of common understory species. TM bands 1, 2, 3, 5, 6, and 7 were inversely correlated with the age ($r \geq -0.7963$) of well regenerated Douglas-fir stands. Overall, a TM 4/5 ratio had the highest correlation to age of Douglas-fir stands ($r = 0.9559$). The TM 4/5 ratio was named a "successional stage index" (SSI) because of its ability to distinguish among successional stages. Poorly regenerated stands were spectrally distinct from well regenerated Douglas-fir stands after the stands reached an age of approximately 15 years. Spectral signatures of four common understory types were described and were found to be significantly

different than the spectral signature of young Douglas-fir stands in TM bands 3, 4, 5, and TM 4/5 ratio.

INTRODUCTION

Standard forestry practices require harvested timber areas to be reforested. Once a site is replanted, the stand needs continual monitoring to determine how reforestation is progressing. Information on stand condition is needed to manage forests for both timber and wildlife habitat objectives. Forest variables that are traditionally monitored are tree density, distribution, and quality, understory vegetation, seedling growth rate, and stand composition (Cleary, et al., 1978).

The western Cascade Mountains of Oregon are dominated by stands of Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco.). Extensive areas of these natural forests have been harvested and replanted. Newly replanted conifer stands usually progress from a herbaceous stage to one dominated by shrubs and conifer seedlings and saplings (Dyrness, 1973). Typically, these stands develop into a closed canopy condition where conifers dominate the site. In this study, well regenerated stands were defined as stands which were progressing to canopy closure at an expected rate and were not dominated by hardwood trees and shrubs. These stands also had a relatively even tree size and spatial distribution. A closed canopy stand condition was defined to have at least sixty percent canopy closure (Brown, 1985). At sixty percent canopy closure, light to understory vegetation is limited and changes in understory species composition typically occur. These successional stage changes influence wildlife species abundance and diversity (Brown, 1985, Harris, 1984, Hansen, et al, 1991).

Recent emphasis on landscape and regional analyses necessitates monitoring forest regeneration over large areas. Conditions within regenerating stands change quickly and therefore stand condition information must be updated periodically. Analysis of remotely sensed data from satellites has potential for assessing forest regeneration and wildlife habitat because it provides coverage over large geographic areas on a regular basis. Harvested areas on US Forest Service land average 10 to 20 hectares (110 to 220 TM pixels). TM data may be suitable to monitor within stand condition because of the increased spatial and spectral resolution as compared to Multispectral Scanner (MSS) data.

In the past, radar data have been used with some success to identify clearcut stage by a photo interpreted method (Hardy, 1981) and by digital texture analysis (Edwards, et al., 1988). Thematic Mapper (TM) data have been used to update stand boundaries (Pilon and Wiart, 1990, Smith, 1988) and to monitor age of 0 to 12 year old conifer plantations (Horler and Ahern, 1986). Matejek and Dubois (1988) found a TM band 3, 4, 5 composite image useful in identifying young clearcuts and different age groups of conifer regeneration in Ontario, Canada. Spanner, et al (1989) used TM data to identify forest disturbance classes for a portion of this study area. Other related studies have used TM data to assess the influence of forest understory vegetation on satellite spectral data values (Spanner, et al., 1990; Stenback and Congalton, 1990) and to measure canopy closure with satellite data (Butera, 1986; Spanner, et al, 1990).

Objectives of this study were to use TM data to: (1) describe the relationships between spectral data and age of young Douglas-fir forests, (2) determine whether poorly regenerated stands could be separated from well regenerated stands, and (3) describe the spectral signatures of common understory vegetation associated with young conifer stands.

STUDY AREA

The research was conducted at H.J. Andrews Experimental Forest located in the western Cascade Mountains of Oregon. Elevations range from 414 to 1630 meters above mean sea level (MSL). The majority of the study area falls within the Western Hemlock (*Tsuga heterophylla*) zone (Franklin and Dyrness, 1973). 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. The remaining portion of the study area falls into the Silver fir (*Abies amabilis*) zone occurring above 1100 to 1200 meters (MSL) (Franklin and Dyrness, 1973). Most of these higher elevations are dominated by noble fir (*Abies procera* Rehd.) or Pacific silver fir (*Abies amabilis* (Dougl.) Forbes). The study area is representative of western Cascade Mountain forests managed by the U.S. Forest Service.

The traditional harvest method for Forest Service lands in this region included harvesting all trees in 10 to 20 hectare units. The harvested areas were usually burned to prepare the site for planting and to control brush (Cleary et al., 1978). One to three year old seedlings were planted within two years of burning. Planting densities and species composition have varied, although the dominate species planted has been Douglas-fir. Stands which had high seedling mortality may have been replanted. Timber harvest in the experimental forest began in 1950, and these replanted managed stands represent approximately twenty-five percent of the forest landscape.

METHODS

Data Development

An area representing the H.J. Andrews Experimental Forest was extracted from a July 30, 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. A 3x3 area of pixels was extracted from the TM data for well regenerated Douglas-fir stands within the study area (n=61). Well regenerated stands were defined as stands that were replanted to Douglas-fir (Pseudotsuga menziesii), were completely replanted within a two year period, and were progressing to canopy closure at an expected rate. These stands had relatively even tree size and spatial distributions and were not overgrown with hardwood trees and shrubs. Stand age ranged from 2 to 35 years. Ancillary data, such as tree densities from field stand examinations (when available), and 1988, 12,000 color aerial photographs, were used to assess the success of stand regeneration. Multiple samples from each stand were used to account for topographic or stand level variability.

A 3x3 area of pixels was sampled from Douglas-fir stands that did not meet the criteria for well regenerated stands in the aerial photograph evaluation. These stands were dominated by shrubs, and deciduous trees, or herbaceous vegetation, and had few, sparsely distributed conifers. Based on the criteria for conifer regeneration, these stands were considered to be poorly regenerated. Age for poorly regenerated stands was determined from the last date in which the entire area had been planted or replanted. The 1988 color aerial photographs were used to estimate conifer canopy closure for all stands.

The aerial photographs were also used to describe understory vegetation in open stands and assign poorly regenerated stands to two different categories based on understory composition: 1) herbs (n=21), and 2) shrubs (n=21). Theses two categories of poorly regenerated stands will be referred to as herb stands and shrub stands in the following text. The herb category included stands in which two-thirds or more of the non-conifer vegetation was low growing grasses, ferns, or other herbaceous plants. The shrub category included stands in which two-thirds or more of the non-conifer vegetation was shrubs or deciduous trees. Conifer canopy closure ranged from 0 to 45 percent (average 10 percent) in the herb stands and from 0 to 30 percent (average 11 percent) in the shrub stands. Common shrubs and deciduous tree species included the following: sitka alder (Alnus sinuata (Reg.) Rydb.), red alder (Alnus rubra Bong.), mountain alder (Alnus tenuifolia Nutt.), vine maple (Acer cincinatum Pursh), big leaf maple (Acer macrophyllum Pursh), and snowbrush ceanothus (Ceanothus velutinus Dougl.). More than one sample from each stand was typically selected to account for topographic or understory vegetation differences.

Data Analysis

Correlation analysis was used to determine the relationship between stand age and TM band values of well regenerated conifer stands. Seven TM bands, four band transformations (normalized difference vegetation index (NDVI) [(TM 4 - TM 3)/(TM 4 + TM 3)], and TM 4/3, TM 4/5, and TM 4/7 band ratios), and the three TM Tasseled Cap features of brightness, greenness, and wetness were included in the analysis. The TM Tasseled Cap features are a linear transformation of TM bands 1, 2, 3, 4, 5, and 7 (Crist and Cicone, 1984). Correlations for linear, log-linear, and log-log relationships of stand age with band values were computed. The log-linear relationship was the correlation of the log of stand age with the TM data.

The band or band transformation with the highest correlation with stand age was then regressed against stand age (this was the TM 4/5 ratio - see results). These data were fit with a regression line with a 95% prediction interval. This prediction interval represented the range of possible values for a new observation from the population of well regenerated conifer stands. For comparison purposes, the mean TM 4/5 ratio values for the two subgroups of poorly regenerated stands were plotted against stand age and with the 95% prediction intervals from the well regenerated stands. The percentage of points which fell outside the 95% prediction intervals was computed for both graphs.

TM 4/5 ratio values for young well regenerated conifers, shrub stands, and herb stands were divided into two age groups: 1) 5-14 years old, and 2) 15-24 years old. A one way analysis of variance and the protected least significant difference (LSD) were used to test for significant differences in mean TM 4/5 values between each of the three stand types (conifers, shrub stands, and herb stands) in each of the two age groups.

Stepwise multiple regression was used to examine which band combinations were useful in predicting the age of well regenerated Douglas-fir stands. Canopy closure for well regenerated stands was plotted against stand age. TM band 4 values were also plotted against the stand age of well regenerated conifer stands because previous investigations had reported that the near infrared was sensitive to changes in forest age and biomass (Horler and Ahern, 1986, Ripple, et al, 1991).

In a separate analysis, the spectral signatures of four common understory vegetation types found in young conifer stands were obtained from the TM data. These were snowbrush ceanothus (Ceanothus velutinus Dougl.) (n = 11 pixels), Sitka alder (Alnus sinuata (Reg.) Rydb.) (n = 8 pixels), bracken fern (Pteridium aquilinum (L.) Kuhn)(n = 6 pixels), and herbs (which included a large amount of bear grass (Xerophyllum tenax (Pursh) Nutt.)) (n = 15). Vine maple (Acer circinatum Pursh) was also a common understory species, but was not sampled because we found no large pure stands of it. Mean spectral values for each understory species and closed canopy Douglas-fir (22 years old) were plotted using TM bands 3, 4, 5, and a TM 4/5 ratio. Ninety-five percent confidence intervals were included on the graphs with each mean value. A one way analysis of variance and the protected least significant difference (LSD) were used to test for significant differences between the mean spectral values of these five vegetation types.

RESULTS

Correlations between stand age and individual TM band values were highest were highest with the log-linear relationship (Table III.1). Conversely, the TM band ratios and NDVI had their highest correlations to stand age with the log-log relationship. All single bands with the exception of TM band 4 ($r = -.0130$) had high correlations with stand age ($r = -.9453$ to $-.8649$). Overall, the log-log relationships of stand age with TM 4/5 ($r = 0.9559$) and stand age with TM 4/7 ($r = 0.9537$) had the highest correlations. Among the Tasseled Cap features, the log-linear relationship of stand age with wetness had the highest correlation ($r = 0.9474$). NDVI and TM 4/3 had lower correlations to stand age ($r \leq 0.8362$) than did all single bands except for TM 4 and TM 5.

TM 4/5 ratio had a direct curvilinear relationship to stand age in well regenerated stands (Figure III.1). TM bands 1, 2, 3, 5, 6, and 7 had inverse curvilinear relationships to stand age. The relationship between TM 4/5 ratio values and age for the poorly regenerated stand subgroups 1) herb stands, and 2) shrubs stands are shown (Figures III.2 and III.3 respectively). Fifty-two percent of the poorly regenerated stands with a herb understory fell outside the prediction intervals, and fifty-seven

Table III.1: Summary of the relationship between the age of well regenerated Douglas-fir (Pseudotsuga menziesii) stands, and 7 TM bands, and 7 band transformations. All P-values were significant at 0.0000 except where noted (a = 0.2734, b = 0.9206, c = 0.9949, d = 0.1728, e = 0.0083). Included are linear, log-linear, and log-log correlations between stand age and band values. The log-linear relationship is the log of stand age versus band values. Log refers to the natural logarithm.

TM Band or Band Transformation	Correlation Coefficient (r) linear	Correlation Coefficient (r) log-linear	Correlation Coefficient (r) log-log
TM 1 (0.45 - 0.52 μm)	-0.8233	-0.8990	-0.8898
TM 2 (0.52 - 0.60 μm)	-0.8540	-0.8649	-0.8463
TM 3 (0.63 - 0.69 μm)	-0.8613	-0.9453	-0.9300
TM 4 (0.76 - 0.90 μm)	-0.1425[a]	-0.0130[b]	-0.0008[c]
TM 5 (1.55 - 1.75 μm)	-0.8392	-0.8676	-0.8042
TM 6 (10.4 - 12.5 μm)	-0.7963	-0.8937	-0.8885
TM 7 (2.08 - 2.35 μm)	-0.8561	-0.9328	-0.8908
NDVI [(TM 4-3)/(TM 4+3)]	0.6675	0.8275	0.8362
TM 4/3	0.6085	0.7245	0.8000
TM 4/5	0.8953	0.9277	0.9559
TM 4/7	0.9003	0.9138	0.9537
Brightness	-0.7071	-0.6829	------
Greenness	0.1728[d]	0.3353[e]	------
Wetness	0.8570	0.9474	------

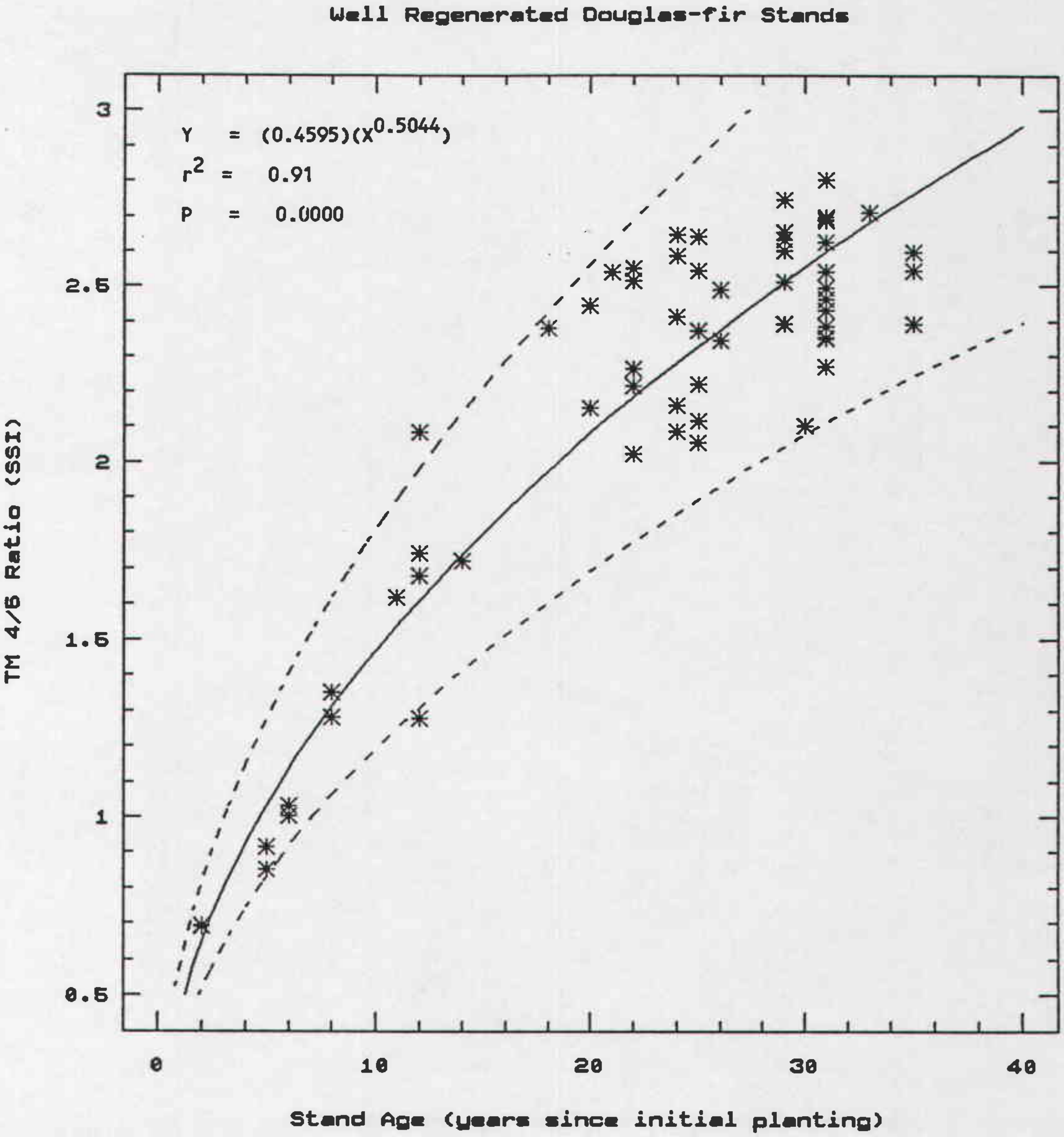

Figure III.1: The relationship between the TM 4/5 ratio (successional stage index - SSI) and the age of young Douglas-fir (Pseudotsuga menziesii) stands (n = 61). A prediction interval (95%) for new observations is shown.

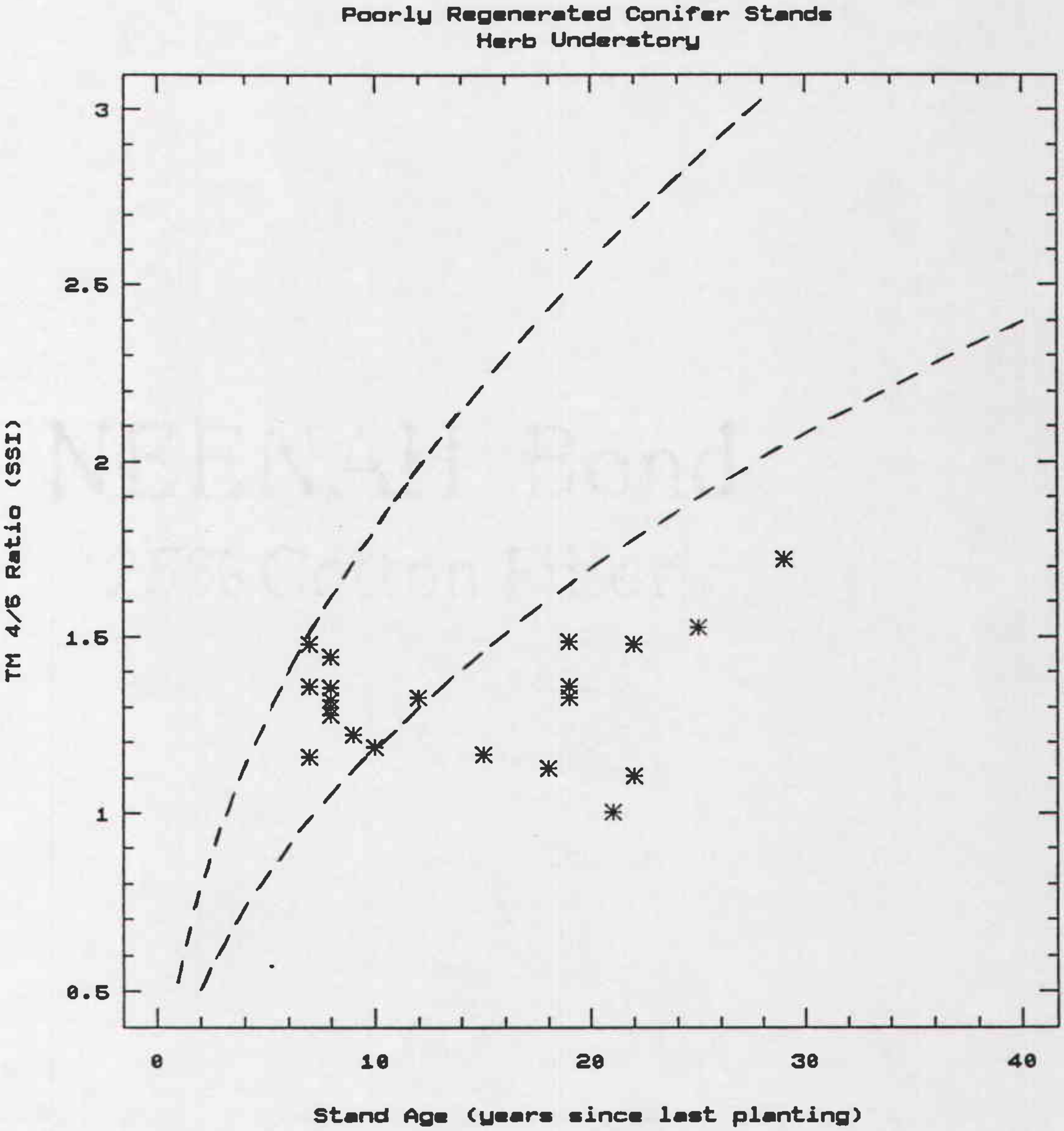

Figure III.2: The relationship between TM 4/5 ratio (successional stage index - SSI), and the age of poorly regenerated conifer stands where the understory was dominated by herbs (herb stands)(n = 21). The prediction interval from the regression of well regenerated stands (Figure III.1) is included to illustrate the difference between herb stands and well regenerated stands. Age is determined from the most recent planting date.

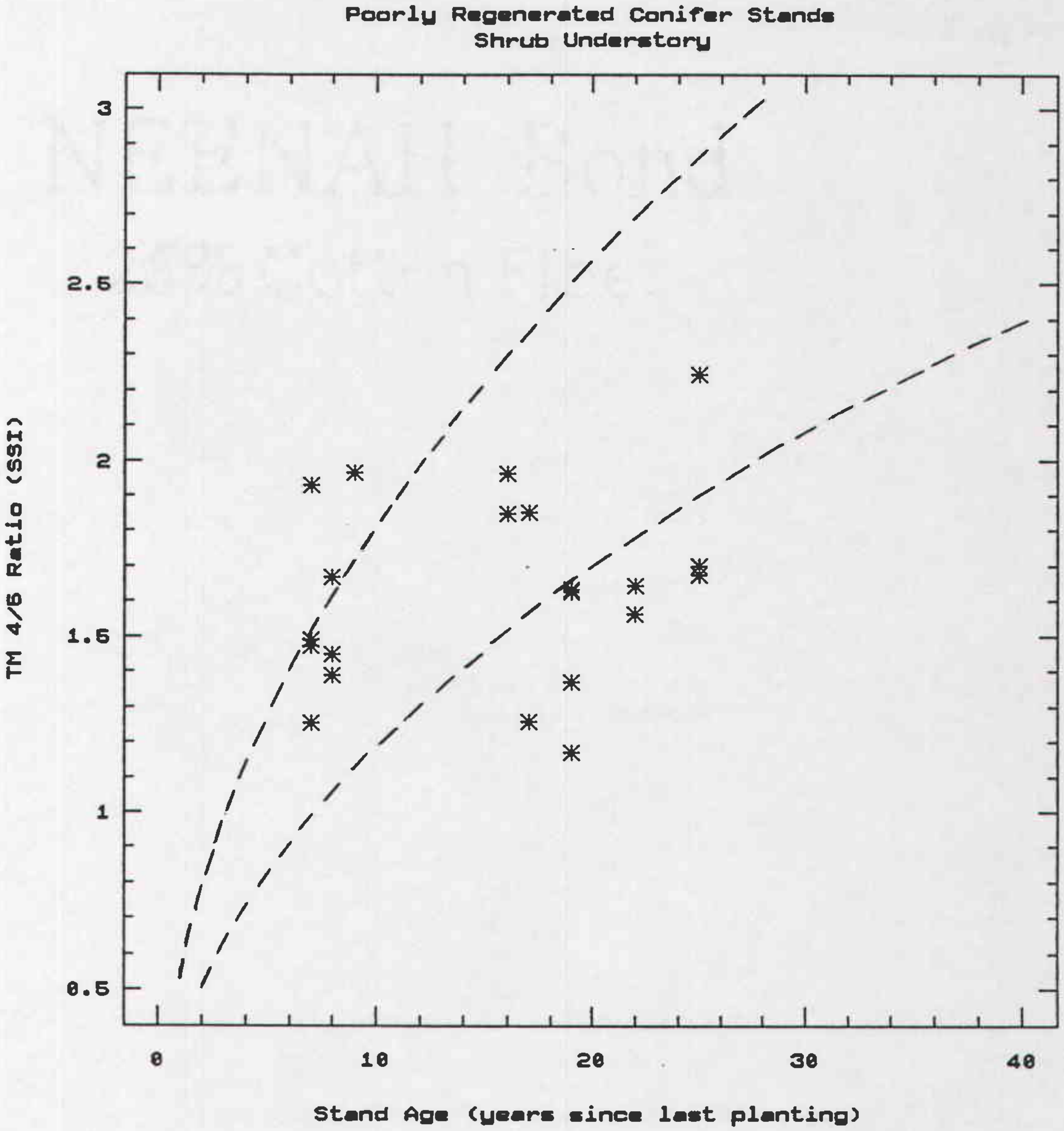

Figure III.3: The relationship between TM 4/5 ratio (successional stage index - SSI), and the age of poorly regenerated conifer stands where the understory was dominated by shrubs and/or deciduous trees (shrub stands)(n = 21). The prediction interval from the regression of well regenerated stands (Figure III.1) is included to illustrate the difference between shrub stands and well regenerated stands. Age is determined from the most recent planting date.

percent of the poorly regenerated stands with a shrub understory fell outside the prediction intervals. Ninety-one percent of the herb stand observations which were greater than twelve years old fell outside the prediction intervals for well regenerated stands. Seventy-five percent of the shrub stands observations which were greater than sixteen years old fell outside the prediction intervals for well regenerated stands.

The one way analysis of variance results showed that there were no significant differences in TM 4/5 values among well regenerated conifer stands, shrub stands, and herb stands in the 5-14 year age group ($P = 0.1376$), but that there were significant differences among these stand types in the 15-24 year age group ($P = 0.0000$). The results from protected LSD method for the comparison of means showed that all three stand types were significantly different in the 15-24 year age group ($\alpha = 0.05$).

In the stepwise multiple regression of the original TM band values and log of stand age, TM 3 and TM 4 were the only two independent variables included in the model (Adjusted $r^2 = 0.91$). The simple regression of TM 3 on log of stand age explained slightly less variance (Adjusted $r^2 = 0.89$). In the stepwise multiple regression of the log of individual TM bands on the log of stand age, TM 3, 4, and 5 were all included in the model (adjusted

$r^2 = 0.92$). The simple regression of the log of TM 4/5 on log of stand age explained approximately the same amount of variance (Adjusted $r^2 = 0.91$).

A scatter plot of TM band 4 band values and stand age of well regenerated stands indicated that before the stands reach age 18, TM band 4 had a direct linear relationship with stand age ($r^2 = 0.54$) (Figure III.4). After age 18, TM band 4 had little relationship with stand age ($r^2 = 0.02$). Stand age was highly correlated to conifer canopy closure in well regenerated Douglas-fir ($r^2 = 0.78$) (Figure III.5). Well regenerated stands reached sixty percent canopy closure approximately eighteen years after planting.

The mean spectral values for four understory species and closed canopy Douglas-fir in TM bands 3, 4, 5 and 4/5 ratio are shown (Figure III.6). Analysis of variance showed that there were significant differences among the spectral means of vegetation types in TM 3, TM 4, TM 5, and TM 4/5 ($P = 0.0000$). The protected LSD method for the comparison of spectral means found significant differences between means ($\alpha = 0.05$) of all vegetation types in all bands except between snowbrush ceanothus and sitka alder in TM 3, and between bracken fern and sitka alder in TM 4 and TM 4/5. A reciprocal transformation was used on TM 4/5 and TM 3 to equalize the variances between vegetation

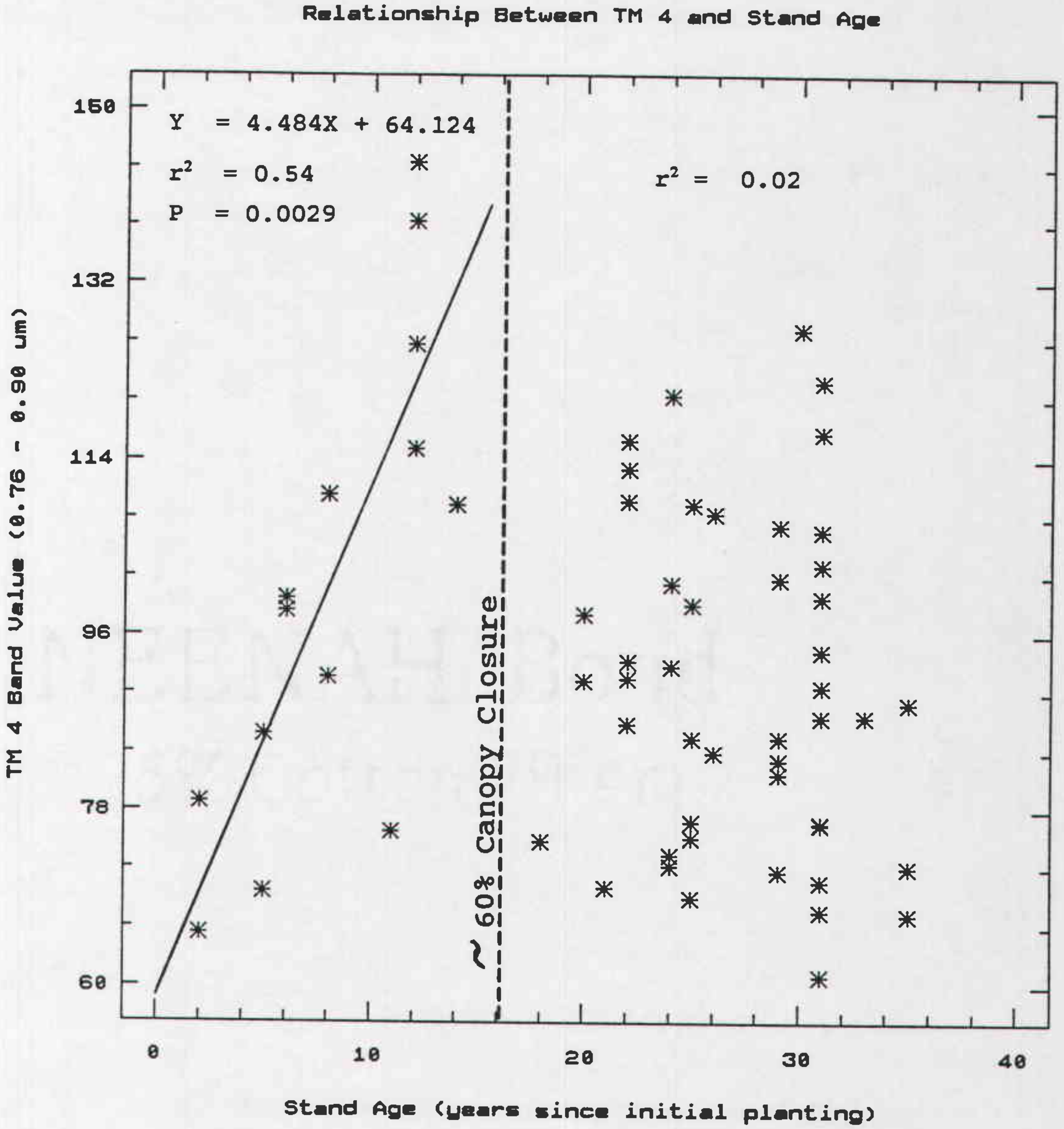

Figure III.4: The relationship between TM band 4 and stand age for well regenerated Douglas-fir stands (n = 61). Prior to age 18, TM band 4 had a direct linear relationship with stand age ($r^2 = 0.54$). After age 18, TM band 4 had little relationship with stand age ($r^2 = 0.02$).

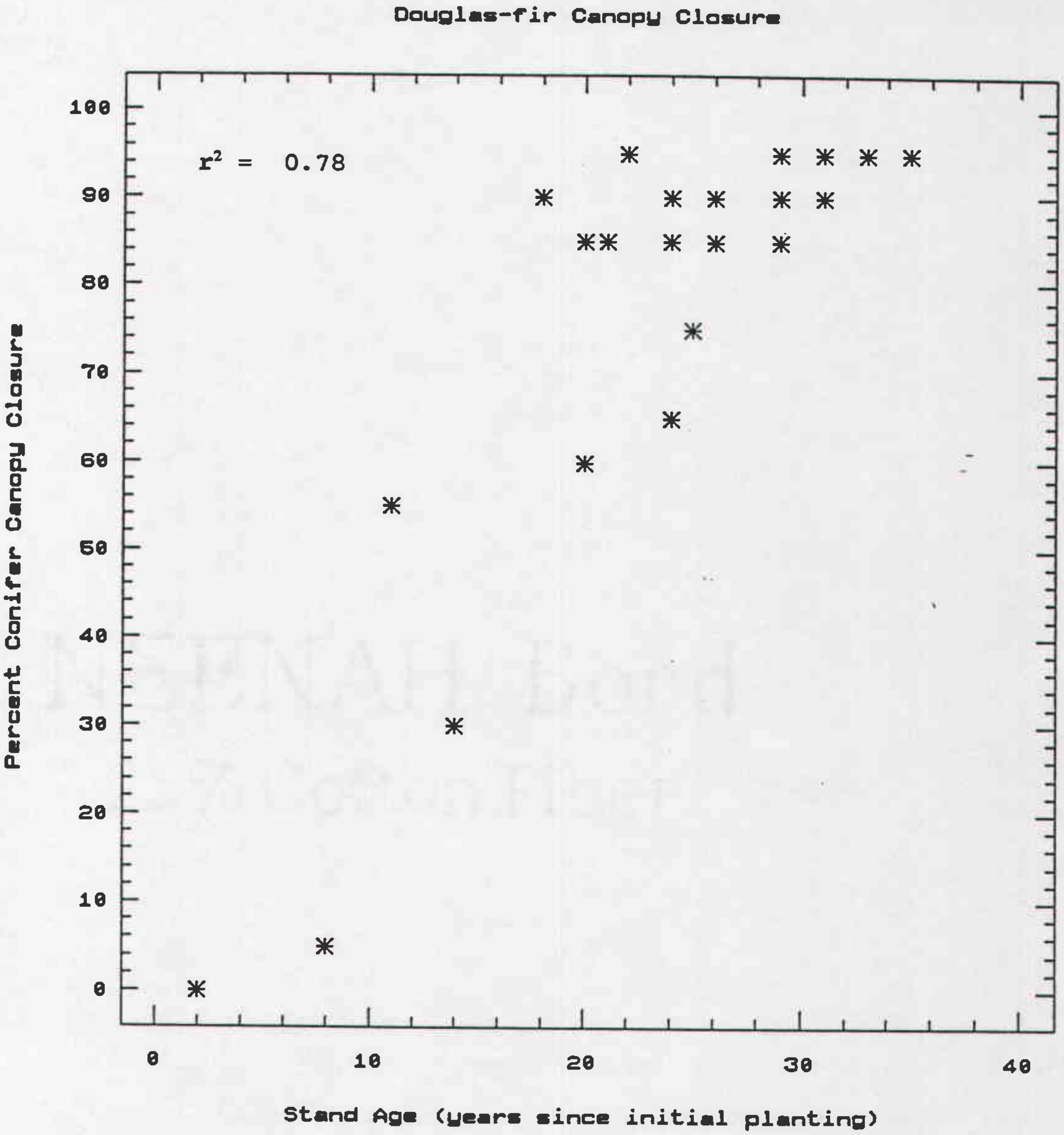

Figure III.5: The relationship between canopy closure and the age of well regenerated Douglas-fir stands (n = 35).

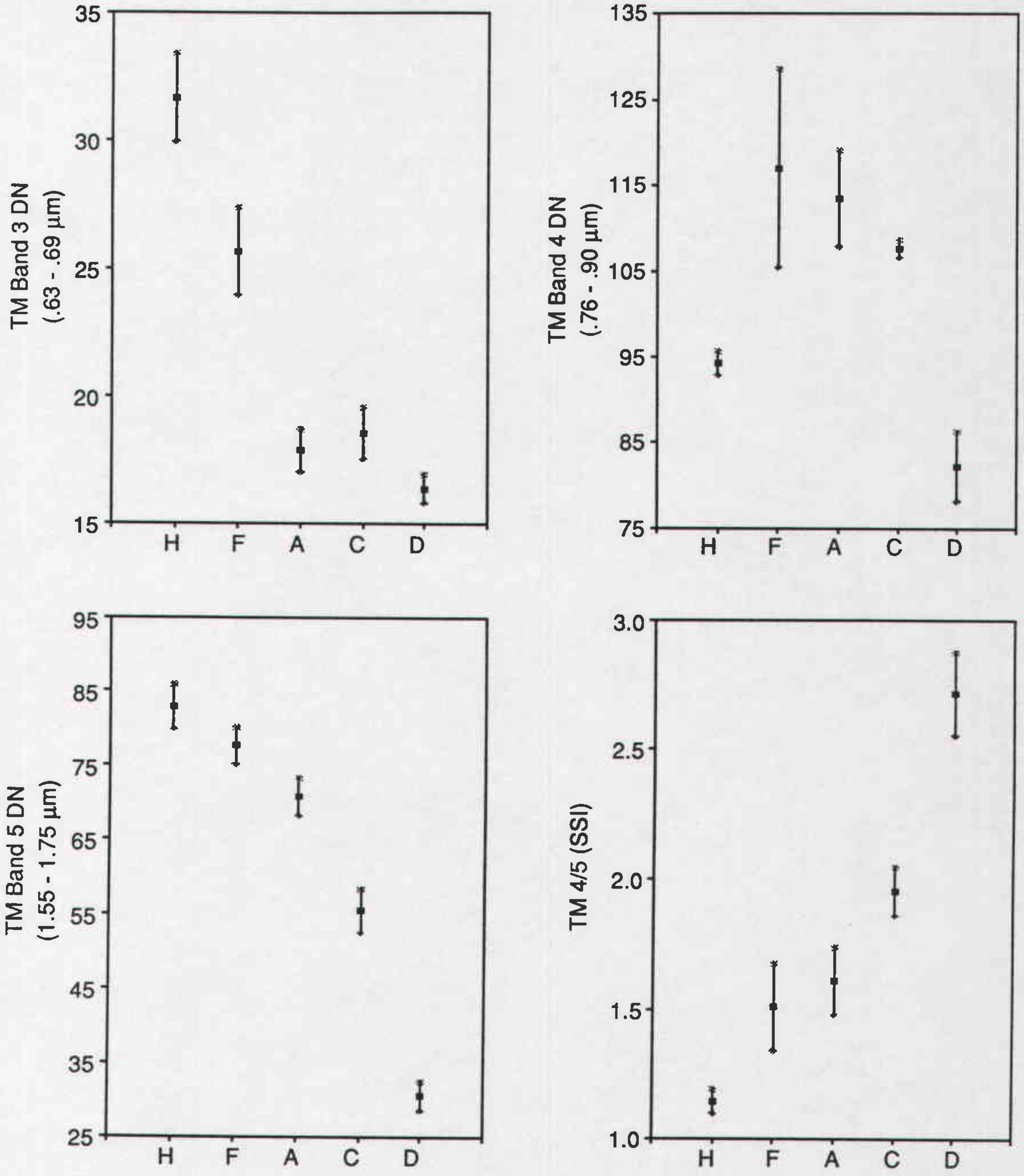

Figure III.6: The mean TM band 3, 4, 5, and TM 4/5 ratio (successional stage index - SSI) values for four understory plant species and Douglas-fir. Ninety-five percent confidence intervals for mean values are included. (H = Herbs, F = bracken fern, A = Sitka alder, C = snowbrush ceanothus, D = Douglas-fir).

types. The herb and snowbrush ceanothus vegetation types were not included in the analysis of variance of TM 4 data because they had significantly different variances even with a transformation.

DISCUSSION

With the exception of TM 4, all TM bands showed a strong inverse correlation with stand age. Since stand age was closely tied to canopy closure in well regenerated stands, it is not surprising that both the visible and middle infrared bands were well correlated with stand age. As leaf area and biomass increased with stand age, the absorption of energy by plant pigments and moisture also increased (Butera, 1986, Spanner, et al, 1989). Other important factors include the decrease in the amount of bright understory vegetation exposed to the sensor as the conifer canopy closes, and the increase in shadowing from the growing conifer crowns.

The correlation of TM 4/5 to stand age showed improvement over single bands and even over the TM 4/3 ratio and NDVI. The usefulness of TM 4/5 for estimating forest age is similar to the results by Spanner et al (1989) where forest age was described in terms of disturbance/successional stage classes. Fiorella (Chapter II) found that the TM 4/5 ratio and wetness, and Cohen and

Spies (in press) found that wetness were useful transformations for estimating structural attributes of older Douglas-fir stands, in separating mature from old-growth forests, and in reducing topographic or shadowing influences. From our studies and the work by Spanner et al (1989), the TM 4/5 ratio will be termed a "successional stage index" (SSI). It should be noted however, that SSI values for old-growth can be similar to young forests that have not reached canopy closure (Spanner et al, 1989, Fiorella and Ripple, unpublished data). With simple regression, the SSI accounted for approximately the same amount of variance in stand age as the results from stepwise multiple regression of individual spectral bands. The model developed for the relationship between stand age and TM 4/5 should be tested with an independent data set to determine if the model is as strong as it appears to be.

TM 4 had a weak relationship with stand age over the entire range of ages (2 to 35 years) in this study, but near-infrared bands have been found to have a strong relationship to structure in older forests (Ripple, et al., 1991, Eby, 1987). When TM 4 values were plotted against stand age, it became clear that TM 4 has two different relationships with stand age. Prior to canopy closure, TM band 4 values increased with age. This increase may be due to increased scattering of radiation with the increase in vegetation amount as succession proceeded from herbs, to shrubs, and finally to conifers (Spanner, et al., 1989). Horler and Ahern (1986) found similar results in Western Ontario, Canada in that TM band 4 values increased with age in 0 to 12 year old conifer plantations. After canopy closure, at greater than sixty percent closure, there was little relationship between TM 4 and stand age in our study. The variability in TM band 4 values after canopy closure may be due to offsetting influences of increasing biomass (increased brightness) and increasing conifer canopy shadowing (decreased brightness), and variability in the amount of broadleaf vegetation (Ripple, et al, 1991).

The results of our study indicate that differences in mean SSI values between poorly regenerated and well regenerated stands were significant after age fifteen. Although it would be difficult to use TM satellite data to assess regeneration in young Douglas-fir plantations less than 15 years old, the success in identifying poorly regenerated stands should be high after this initial period. The length of time required to find poorly regenerated stands may decrease if differences in site preparation, aspect, and planting density were accounted for.

TM satellite data could be very useful in identifying successional stage for wildlife habitat analysis. Herb and shrub successional stages are important habitat and forage areas for some wildlife species. Successful reforestation methods have reduced the time to reach a closed canopy condition, and consequently reduced the time a stand spends in herb and shrub stages. In a landscape context, these poorly regenerated stands can be important for enhancing wildlife and plant biodiversity.

TM 3, 4, 5 and SSI values for Douglas-fir were significantly different than those of all other understory vegetation types. The importance of the middle infrared (band 5) for analyzing young conifer stands was documented, since TM 5 showed significant differences among all understory vegetation types (Figure 6) and TM 5 was one of the bands in the SSI. Ripple, et al (1986) also found that two middle infrared radiometer bands (1.55 - 1.75 μm and 2.08 - 2.35 μm) were useful in separating vine maple and snowbrush ceanothus from young Douglas-fir forests. It should be noted that for this part of the study, all vegetation types have small sample sizes and variability within types would be expected to increase with a larger sample sizes.

CONCLUSIONS

Based on the results of this study, we make the following conclusions:

1) With the exception of TM 4, all bands showed a strong inverse correlation with age of young Douglas-fir stands (2-35 years old). This was attributed to decreasing amounts of the bright understory exposed to the sensor, increased shadowing from the conifers, and increased absorption by pigments for the visible bands and moisture for the middle infrared bands.

2) The near-infrared band, TM 4, showed a direct relationship to stand age before canopy closure (2-18 years) and a weak relationship to stand age after canopy closure (18-35 years). This weak relationship was attributed to the variability in offsetting influences of increasing biomass, increasing shadowing, and variability in the understory.

3) The TM 4/5 ratio had a very strong relationship with stand age and was named the successional stage index (SSI).

4) TM spectral data from poorly regenerated stands were significantly different from well regenerated stands only after the plantations reached an age of approximately fifteen years.

5) TM spectral data for common understory species were characterized and spectral means were found to be significantly different from young Douglas-fir conifers. The middle infrared band (TM 5) was particularly useful in spectrally separating all five vegetation types.

6) The analysis of within stand conditions of young conifer forests has applications for timber production by quantifying conifer regeneration success.

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CHAPTER IV

MODELLING VERTEBRATE RICHNESS IN THE CASCADE MOUNTAINS OF OREGON USING A GEOGRAPHIC INFORMATION SYSTEM

ABSTRACT

A technique for modelling vertebrate richness in the western Cascade mountains of Oregon was tested using a geographic information system (GIS). Vertebrate species occurrence was predicted using three variables: 1) forest successional stage, 2) elevation, and 3) site moisture. The GIS was used to map the spatial distribution of amphibian, reptile, and small mammal from published primary and secondary habitat requirements. Occurrence maps were overlayed to count the predicted number of vertebrates at any given point in the study area. The percentage of matches between GIS species predictions and field based species occurrence data was computed (match percentage) as a means of model assessment. Of all vertebrate classes studied, reptiles had both the highest match percentage (88%) when using primary habitat requirements and the lowest match percentage (54%) when using secondary habitat requirements. Overall vertebrate richness match percentage was sixty-seven percent when both primary and secondary habitat requirements were used. Site moisture appeared to have the greatest influence on

the patterns of high vertebrate richness for all vertebrate classes.

INTRODUCTION

Maintaining species diversity is an important policy consideration and management goal on public forest land. Diversity is believed to be one indicator of landscape and forest stability, and sustainability (Forman, 1990, Franklin, et al., 1989). In the Pacific northwest, there is concern that the conversion of mature and old-growth forest to young, evenaged stands of Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco.), and the fragmentation of the remaining old-growth forest will adversely affect the population of vertebrate species. In particular, biologists believe that these forest changes may cause a decline in species that require areas of mature and old-growth forest habitat (Harris, 1984; Rosenberg and Raphael, 1986). Conversely, young successional stages provide habitat for a high number of species, particularly when snags and down logs are present (Hansen, et al., 1991). The species found in young successional stages add to overall landscape diversity because many of these species are not found in closed canopy forests.

One approach to the analysis of species richness on the forested landscape is to develop a model that can be used to predict the occurrence of vertebrate species from habitat characteristics (Berry, 1986, Farmer, 1982). Raphael and Marcot (1986) tested the reliability of a wildlife-habitat-relationships model in predicting species richness and abundance for four seral stages of mixed-evergreen forest in northwestern California. They found that eleven percent of the species were predicted but not observed and fourteen percent were observed but not predicted. Harris (1984) proposed a model for vertebrate species occurrence in the Western Cascade mountains. Natural history information was used to identify key habitat characteristics which influenced species presence and absence. Harris (1984) found that elevation, forest successional stage, and site moisture and/or presence of absence of water determined mammal, amphibian, and reptile presence and richness. Two trends in species richness that he noted were 1) that as elevation increased, species richness decreased ($r^2 = 0.99$), and 2) that species richness tended to be highest in both early and late successional stages.

Based on these results, we hypothesized that a geographic information system (GIS) could be used to spatially illustrate potential species richness using forest successional stage, elevation, and site moisture. The strength of a GIS is its ability to spatially integrate these three habitat variables, and elucidate the patterns of species richness of a landscape. Areas of high species richness based the three spatial variables may be different than predictions based on one variable such as successional stage. Lancia, et al (1986) used a spatial species habitat model to predict the occurrence of three bird species based on a habitat quality index. Miller (1989) used vegetation and soils data in a GIS to analyze rare bird species distributions in Tanzania in order to identify other important habitat areas for preservation.

The objective of this study was to develop a GIS methodology for modelling species vertebrate based on mapping potential habitat for individual vertebrate species. Areas of high or low species richness will be described. The model will be evaluated by comparing the predictions of species occurrence at specific sites to the species occurrence data that were collected in the field.

STUDY AREA

The H.J. Andrews Experimental Forest was chosen as the study site. It is located in the Central Cascade Mountains of Oregon. Elevations range from 414 meters near the Blue River Reservoir to 1630 meters at Lookout Mountain, and mean elevation was 979 meters 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 meters, 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 twenty-five percent of the forest landscape. In general, the fauna of the Cascade region is comprised of a high number of mammals and birds, and a low number of amphibians and reptiles (Harris, 1984).

METHODS

Three site characteristics of forest successional stage, elevation, and site moisture were used to map potential species occurrence and richness in the H.J. Andrews Experimental Forest using a GIS. Both potential primary, and primary and secondary habitats were mapped for small mammals, amphibians, and reptile species (Table IV.3). Primary habitat was defined as the areas which meet all the life history functions of a species (Harris, 1984). Life history functions are defined as breeding, foraging, and resting. Secondary habitat was defined as all areas that a species utilizes in its lifetime. In the following discussion, the term primary will refer to primary habitat only, and the term secondary will refer to both primary and secondary habitats. The data layers for site characteristics were derived from both digital and analog map sources.

Data Development

An unsupervised classification technique of a 1988 Thematic Mapper (TM) satellite image (30 meter resolution) was used to map the forest into five successional stages 1) grass-forb, shrub, 2) open sapling-pole, 3) closed sapling-pole, small sawtimber, 4) mature, large sawtimber, and 5) old-growth (Table IV.1; Figure IV.1). A stratified random sample of pixels from these five successional stage categories was used to assess map accuracy (Fiorella, Chapter II). Selected pixels were located on aerial photographs and the successional stage was interpreted by a forest ecologist who was very familiar with the area.

Table IV.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 feet tall Conifer closure < 30% Soil, Rock 0 - 10 years old (± 5 years)
Open Sapling-Pole	Trees > 10 feet tall Canopy closure 30-60% Trees ≥ 1 inch 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 average DBH ≥ 21+ Trees ≥ 100 feet tall 1 or 2 story stands Crown cover < 100% 90-200 (± 20 years) years old
Old-growth	Tree average DBH ≥ 26+ 2 or 3 story stands Crown cover < 100% Large amounts of snags and down woody debris 200+ years old (± 30 years)

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[1] Ages adapted for study area.

Accuracy percentages were computed for each of the five successional stages.

The elevational data were derived from a 1:250,000 scale digital elevation model (DEM). The DEM was recoded into 500 foot (152.4 meter) contour intervals to match the elevation classes presented by Harris (1984). The DEM data were resampled to 30 meter pixels to match the resolution of the TM satellite imagery.

The site moisture variable was modelled by overlaying soil, stream and pond, aspect, and slope gradient data layers. Criteria for the four moisture classes, 1) very wet, 2) wet, 3) dry, and 4) very dry, were based on descriptions outlined by Harris (1984). Very wet areas included ponds and perennial streams. Wet sites consisted of northwest, north, and northeast slopes, and riparian zones. Riparian zones were defined as areas within thirty meters of perennial streams and sixty meters of ponds. In addition, riparian zones also included areas within 150 meters of perennial streams which had 0 to 10 percent slope. Very dry areas consisted of areas with south and southwest aspects which had coarse or talus soils (Willamette National Forest soil resource inventory map (scale 1:62,500)) and/or had greater than sixty percent slope. Dry sites consisted of all remaining portions of east, southeast, south, southwest, west, and flat slopes that were not already characterized as very wet, wet, or very dry.

Habitat and Species Richness Modelling

The vertebrate species chosen for the analysis were both listed in Harris (1984) and trapped in the field at one of the sites in or adjacent to the H.J. Andrews Experimental Forest (Corn et al, 1988, and Bury and Corn, 1988, in 1983; Gilbert and Allwine, 1991a, and Gilbert and Allwine, 1991b, in 1984 and 1985). Amphibians and reptiles were sampled with pitfall traps, drift fences, and time constrained searches (Bury and Corn 1988, Gilbert and Allwine, 1991b). Mammals were sampled with pitfall traps, snap traps, and variable circular plots (Corn el al, 1988, Gilbert and Allwine, 1991a, U.S. Forest Service unpublished data). A total of thirty-seven species were used in the analysis. The species included nineteen mammal, twelve amphibian, and six reptile species (Table 2). The combined field studies included sites in both natural forest and managed forest stands and the stands ranged in age from 5 to 450 years.

Forest successional stage, elevation and site moisture digital maps were overlayed to generate maps of primary and secondary habitat for each vertebrate species. Primary habitat were defined as areas that met the primary habitat requirements of a species in all three variables. Secondary habitat consisted of all areas that met either the primary or secondary habitat requirements of a species in all three variables. Primary habitat in each variable was coded to a value of 1 and all other areas to a value of 0. The three maps were added together to create a primary habitat map for each species. Primary habitat had a value of three in the output map. The same procedure was used to create secondary habitat maps.

The primary habitat map for each vertebrate species was used as input to the vertebrate richness model. Primary habitat in each individual species map was coded to a value as 1, and all remaining areas to a value of 0. A GIS overlay function was then used to add the values between the maps together. Areas with high potential vertebrate richness had high values, and areas of low potential vertebrate richness had low values. The maximum value possible in each map was equal to the number of species included in the vertebrate richness model. Vertebrate richness maps were created for small mammals, amphibians, reptiles, and all vertebrates. Richness maps based on secondary habitat were created with the same overlay procedure. The mean vertebrate richness for the study area was summarized by the nine elevation, four site moisture, and five successional stage categories. Spatial patterns in amphibian, reptile, mammal, and all vertebrate richness maps were described.

Model Evaluation

The GIS habitat and species richness maps were evaluated by comparing the primary and secondary habitat maps for each species to data collected in field studies by Corn et al (1988), Bury and Corn (1988), and the U.S. Forest Service (unpublished data). Eight stands found within the study area were used in the comparison. All eight stands were sampled in 1984 and 1985 by the Forest Service, and five of the eight were sampled in 1983 by Corn et al (1988), and Bury and Corn (1988). Two stands were 130 years old and six stands were 450 years old. The five year difference in the dates between vertebrate sampling (1983-85) and the TM satellite image (1988) was not considered significant because only older stands were used in the comparison.

The number of matches, both positive and negative, between field data and predicted primary habitat maps, and field data and predicted secondary habitat maps were totaled. A positive match occurred when a species was predicted to occur in a stand and was actually trapped in the stand; a negative match occurred when a species was not predicted to occur in a stand and was not trapped in the stand. The number of matches was divided by the number of species being considered. This ratio was termed a match percentage and was computed for each species, for each vertebrate class, and for all vertebrate species considered. Finally, the number of times a species was predicted to occur and did not (commission), and the number of times a species occurred and was not predicted (omission) were computed for each vertebrate class, and for all vertebrates.

RESULTS

Digital Map Data

Forest successional stage areas were calculated using the GIS successional stage map (Figure IV.1). Old-growth comprised the largest land area (3562 hectares) and open sapling pole the smallest land area (343 hectares). The overall accuracy of the successional stage map was 78.3 percent. Class accuracy ranged from 69 percent in the mature category to 85 percent in the grass-forb, shrub category (Chapter II). The study area contained nine 500 foot elevation contour intervals beginning with the 1001-1500 foot interval and ending with the 5001-5500 foot interval (Figure IV.2). The wet and dry categories (93.6 percent of total area) dominated the site moisture map and had relatively equal areas (3088 and 2946 hectares respectively) (Figure IV.3).

Primary Habitat and Species Richness Modelling

In the amphibian richness map, the highest species richness was found on very wet and wet sites at low elevations independent of successional stage (Figure IV.4). In contrast, the highest reptile richness was found in early successional stages on dry sites, and particularly in the grass-forb, shrub stage (Figure IV.5). The highest mammal richness occurred on wet sites in older forests (Figure IV.6). Within a moisture class, closed canopy forests had the lowest mammal richness. Young successional stages on wet sites at high elevations (4500 to 5500 feet) also had high richness values.

The highest overall vertebrate richness occurred in grass-forb, shrub stands at low elevations on wet sites (Figure IV.7). In general, successional stages on wet areas had higher species richness than similar successional stages on dry sites. Within a given moisture class, closed canopy forests had the lowest vertebrate richness of any successional stage.

Mean vertebrate richness decreased with increasing elevation (Table IV.2). Of all moisture classes, wet sites had the highest, and very dry sites had the lowest mean vertebrate richness. Mean vertebrate richness for the study area was high in grass-forb, shrub (11.60), open sapling-pole (11.00), and old-growth (10.00), and low in closed canopy (5.30) and mature (6.86).

Secondary Habitat and Species Richness Modelling

The highest amphibian richness occurred on very wet and wet areas at low elevations, regardless of successional stage (Figure IV.8). Reptile richness was highest in young successional stages at low elevations on dry sites (Figure IV.9), but was low on very wet sites, and in closed canopy, mature, and old-growth forests at high elevations.

The highest mammal richness occurred in older forests on wet sites and at high elevations (4500 to 5500 feet)(Figure IV.10). Grass-forb, shrub, and open sapling-pole stands had lower species richness than closed canopy, mature, and old-growth areas with similar site moisture.

Vertebrate richness was highest at low elevations and on wet sites (Figure IV.11). Richness decreased with elevation on wet sites. Dry sites had lower richness than wet sites, and very dry sites had the lowest richness. The successional stage pattern was not noticeable in the vertebrate richness map. Older forests on wet sites and at high elevations (4500 to 5500 feet) had higher

Table IV.2: The predicted mean and range of vertebrate richness in each variable category. Mean and range values were summarized from primary and secondary vertebrate richness maps. These maps were generated using successional stage, elevation, and site moisture variables. Also included are the number of species that would have been predicted if only one variable (elevation only, or successional stage only, or site moisture only) had been used. (closed canopy = closed sapling-pole, small sawtimber; mature = mature, large sawtimber).

VARIABLE CATEGORY	PRIMARY HABITAT		SECONDARY HABITAT	
	Vertebrate Mean (range) Richness 3 Variables	Vertebrate Richness 1 Variable	Vertebrate Mean (range) Richness 3 Variables	Vertebrate Habitat 1 Variable
ELEVATION				
1001 - 1500 Feet	10.89 (0 to 21)	33	22.50 (11 to 27)	33
1501 - 2000 Feet	10.45 (0 to 20)	33	23.60 (0 to 27)	32
2001 - 2500 Feet	9.62 (0 to 20)	30	23.84 (9 to 27)	32
2501 - 3000 Feet	9.54 (0 to 20)	31	24.09 (9 to 27)	31
3001 - 3500 Feet	9.31 (0 to 19)	29	23.22 (9 to 26)	29
3501 - 4000 Feet	8.94 (0 to 18)	27	22.22 (7 to 24)	27
4001 - 4500 Feet	8.91 (0 to 19)	28	22.02 (7 to 25)	28
4501 - 5000 Feet	7.19 (0 to 19)	27	20.29 (8 to 24)	27
5001 - 5500 Feet	4.59 (0 to 13)	20	15.04 (7 to 18)	20

Table IV.2: (continued)

VARIABLE CATEGORY	PRIMARY HABITAT		SECONDARY HABITAT	
	Vertebrate Mean (range) Richness 3 Variables	Vertebrate Richness 1 Variable	Vertebrate Mean (range) Richness 3 Variables	Vertebrate Habitat 1 Variable
SITE MOISTURE				
Very Wet	9.34 (6 to 11)	15	10.16 (7 to 12)	17
Wet	14.48 (4 to 21)	27	25.62 (17 to 27)	34
Dry	4.42 (0 to 7)	11	22.00 (14 to 24)	28
Very Dry	1.03 (0 to 3)	3	9.40 (7 to 11)	14
SUCCESSIONAL STAGE				
Grass-forb, shrub	11.59 (1 to 21)	33	22.30 (7 to 27)	34
Open sapling-pole	11.00 (1 to 16)	26	22.12 (7 to 25)	31
Closed canopy	5.30 (0 to 10)	17	23.25 (7 to 27)	31
Mature	6.86 (1 to 16)	24	21.74 (7 to 27)	32
Old-growth	10.00 (0 to 16)	24	23.41 (0 to 27)	32

vertebrate richness than similar areas at slightly lower elevations.

Mean vertebrate richness for the study area increased with elevation up to the 2500-3000 foot interval and then decreased with increasing elevation (Table IV.2). Wet sites had the highest mean vertebrate richness (25.62), and dry sites had slightly lower richness (22.00). Mean vertebrate richness for each of the successional stages were approximately equal (21.74 to 23.25).

Model Evaluation

Primary reptile richness had the highest match percentage (88%) of any vertebrate class or all vertebrates considered (Table IV.3). The match percentage for reptiles decreased to 54% in secondary habitat maps. Both mammal (54% to 77%), and all species (63% to 67%) match percentage increased when secondary habitat was included in the analysis. Amphibian match percentage (57%) was the same for both primary and secondary habitat maps. In all cases, percent omission decreased and percent commission increased when secondary habitats was included in the analysis.

The northern water shrew, heather vole, western fence lizard, western skink, and rubber boa all had a one

Table IV.3: Match percentage for each species, all mammals, all amphibians, all reptiles, and all vertebrates in primary and secondary habitat maps. Percent omission and percent commission for all mammals, all amphibians, all reptiles, and all vertebrates in primary and secondary habitat maps. Match percentage is the ratio of correctly predicted species to all species being considered. Percent omission is the percent of species that were not predicted to occur but which did occur in the field. Percent commission is the percent of species that were predicted to occur but did not occur in the field.

	MATCH PERCENTAGE	
REPTILE SPECIES	Primary Habitat	Secondary Habitat
Northern Alligator Lizard (Gerrhonotus coeruleus)	88	13
Western Fence Lizard (Sceloporus occidentalis)	100	100
Western Skink (Eumeces skiltonianus)	100	100
Rubber Boa (Charina bottae)	100	0
Northwestern Garter Snake (Thamnophis ordiniodes)	75	75
Common Garter Snake (Thamnophis sirtalis)	63	38
ALL REPTILES	88	54
	% Omission 12 % Commission 0	% Omission 4 % Commission 42

Table IV.3: (continued)

MAMMAL SPECIES	MATCH PERCENTAGE	
	Primary Habitat	Secondary Habitat
Marsh Shrew (*Sorex bendirii*)	38	75
Northern Water Shrew (*Sorex palustris*)	100	100
Pacific Shrew (*Sorex pacificus*)	0	0
Dusky Shrew (*Sorex monticolus*)	63	63
Wandering Shrew (*Sorex vagrans*)	25	75
Trowbridge Shrew (*Sorex trowbridgii*)	50	100
Richardson Vole (*Microtus richardsoni*)	88	88
Townsend Vole (*Microtus townsendi*)	88	88
California Red-Backed Vole (*Clethrionomys californicus*)	88	88
Heather Vole (*Phenacomys intermedius*)	100	100
Oregon Vole (*Microtus oregoni*)	50	50
Red Tree Vole (*Arborimus longicaudus*)	63	63
Deer Mouse (*Peromyscus maniculatus*)	88	88
Pacific Jumping Mouse (*Zapus trinotatus*)	25	75
Coast Mole (*Scapanus orarius*)	38	88
Shrew-Mole (*Neurotrichus gibbsii*)	38	88
Chickaree (*Tamiasciurus douglasi*)	38	88
Townsend Chipmunk (*Tamias townsendi*)	50	75
Mazama Pocket Gopher (*Thomomys mazama*)	75	75
ALL MAMMALS	58	77
	% Omission 35 % Commission 7	% Omission 9 % Commission 14

Table IV.3: (continued)

	MATCH PERCENTAGE	
AMPHIBIAN SPECIES	Primary Habitat	Secondary Habitat
Pacific Giant Salamander (Dicamptodon ensatus)	63	63
Olympic Salamander (Rhyacotriton olympicus)	63	63
Western Red-Backed Salamander (Plethodon vehiculum)	63	63
Oregon Salamander (Ensatina eschscholtzi)	13	100
Oregon Slender Salamander (Batrachoseps wrighti)	63	63
Rough-Skinned Newt (Taricha granulosa)	75	75
Clouded Salamander (Aneides ferreus)	75	50
Dunn's Salamander (Plethodon dunni)	88	88
Northwestern Salamander (Ambystoma gracile)	38	13
Tailed Frog (Ascaphus truei)	25	63
Pacific Treefrog (Hyla regilla)	25	25
Red-legged Frog (Rana aurora)	63	25
ALL AMPHIBIANS	57	57
	% Omission 25 % Commission 18	% Omission 7 % Commission 36
ALL VERTEBRATES	Match % 63 % Omission 28 % Commission 9	Match % 67 % Omission 8 % Commission 25

hundred percent match percentage. Other species with high match percentages were the deer mouse and western red backed vole. The greatest change in match percentage between primary and secondary habitat maps occurred for the Oregon salamander (13 to 100 percent). The Pacific shrew had a zero percent match percentage in both primary and secondary habitat maps. The northwestern salamander (38% and 13%) and the Pacific treefrog (25% and 25%) both had low match percentages in both primary and secondary habitat maps.

DISCUSSION

Habitat and Richness Modelling

With the exception of reptiles, vertebrate richness was always higher on wet sites relative to other moisture classes. Forest successional stage appeared to influence reptiles richness, mammal richness, and primary vertebrate richness. The only distinguishing variables which appeared to influence amphibian richness and secondary vertebrate richness were site moisture and elevation.

Wet sites at very high elevations (4500 to 5500 feet) had unexpectedly high mammal and all vertebrate richness. Overall vertebrate richness should decrease with increasing elevation (Harris, 1984). This elevation range is a transition area from the western hemlock vegetation zone to the Pacific silver fir zone. This transition zone therefore includes mammals species from both lower and higher elevation zones, and has higher vertebrate richness than would be predicted if only elevation was used.

Model Evaluation

Match percentages indicate that overall, mammals and all vertebrates were best predicted by including secondary habitat requirements, while reptiles were best predicted using only primary habitat requirements. Since the model match percentage for amphibians did not change from primary to secondary habitat, either set of habitat requirements could probably be used for amphibians. The choice of using primary or primary and secondary habitat requirements may also be influenced by omission and commission error. If excluding species that might be found in an area is undesirable, then omission error should be minimized by using both primary and secondary habitat requirements. If including species that are not likely to be found in an area is undesirable, then percent commission should be minimized by using only primary habitat requirements.

Species with high match percentages tended to fall into one of three categories 1) they were rare in older forests and/or difficult to trap and the model did not predict their occurrence (heather vole, western fence lizard, western skink and rubber boa, northern water shrew (Bury and Corn, 1988), 2) they were very common and had broad habitat requirements (deer mouse) and the model predicted their occurrence, or 3) had a high affinity for older forest stages (California red-backed vole (Taylor, et al, 1988) and the model predicted their occurrence. Species with low match percentages tended to fall into one of two categories 1) they were common and the model did not predict their occurrence (Pacific treefrog and Pacific shrew), and 2) they were uncommon in older forests, or difficult to trap and model predicted that they were common to those older stands (northwestern salamander). Match percentage might increase if field data had been sampled from a wider range of successional stages, or if the model had been applied to a wider elevation range.

The mean vertebrate richness values reported here were based on vertebrate richness maps developed using three variables to predict species occurrence. Harris (1984) described the trend in species richness for each single variable. In both cases, vertebrate richness decreased with increasing elevation; wet sites tended to have higher richness than dry sites; early and late successional stages had high vertebrate richness in the primary habitat maps; and all successional stages had approximately equal vertebrate richness in the secondary habitat maps. One difference between richness maps and Harris descriptions, was that the mature successional stage in the primary habitat map had lower mean richness than one would expect if only considering successional stage. This was most likely due to the co-occurrence of mature forests on dry south and southwest slopes due to fire history of the area (Teensma, 1987). Dry sites had lower vertebrate richness, and consequently, mature forests had lower than expected vertebrate richness.

Evaluation of Method

Overall, the GIS modelling technique is spatially oriented and highly automated. It would be impossible to accomplish this analysis manually. Since the technique is automated and digital, the model can be used for retrospective studies which provide a perspective of changes in the landscape. Similarly, the technique can be used to simulate future changes. Landsat data can be used as input to show changes in successional stage distribution over time. Summary statistics which show frequency distributions of vertebrate richness can be computed. These results can be compared between dates and for different management alternatives.

The influence of each variable on the distribution of mean richness across the study area is readily evaluated. Once identified, model variables can then be modified or eliminated based on the results of the evaluation. The species being modelled can be changed and can be selected based on project objectives. Patch and matrix patterns such as edge and interior forest habitat can be easily produced and used in the model if needed (Ripple, et al, 1991). Also, habitat definitions for individual species can be evaluated. For example, the elevation range for the Pacific shrew was reported to be from 0 to 1000 feet (0 to 304.8 meters) above sea level (Harris, 1984). It was not predicted to occur in the study area, but was found in each of the eight stands.

The GIS modelling technique is but one of many ways to assess animal habitat relationships. Prediction accuracy will change depending on the model and approach selected. One limitation of models which predict species richness (this model included) is that species occurrence does not imply that a species prefers that location. Animal abundance data can be more useful then species occurrence when evaluating habitat preference (Raphael, 1991). Final maps do not necessarily indicate which species are present, and therefore "threatened" and common species receive equal weight.

Since there can be many species in the model and the model is spatially oriented, it is difficult to find or collect species presence and absence data to validate the model. Along with this is the lack of good natural history information for most species to use as input to the model. It is difficult to develop one model that can be used on such a wide range of species. Relationships between species and habitat variables can be very different, and species that require unique habitats may be difficult to map.

The site moisture variable should be evaluated. It appeared to influence richness in all maps, and yet it is the most poorly defined variable. Additional research should be conducted to determine if site moisture influences species presence and absence to the extent the model predicts, and if it does, the definition of the four classes should be refined. More field studies are needed, particularly studies that evaluate animal assemblages in younger successional stages. Modelling changes in species richness over time, under different management regimes, and between patches are some other areas that can utilize this technique.

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Figure IV.1: Five class successional stage map developed from 1988 Landsat Thematic Mapper data (1:70,000).

Class Name	Hectares
Grass-Forb, Shrub	877
Open Sapling-Pole	343
Closed Sapling-Pole-Small Sawtimber (Closed Canopy)	1084
Mature, Large Sawtimber	594
Old-growth	3562

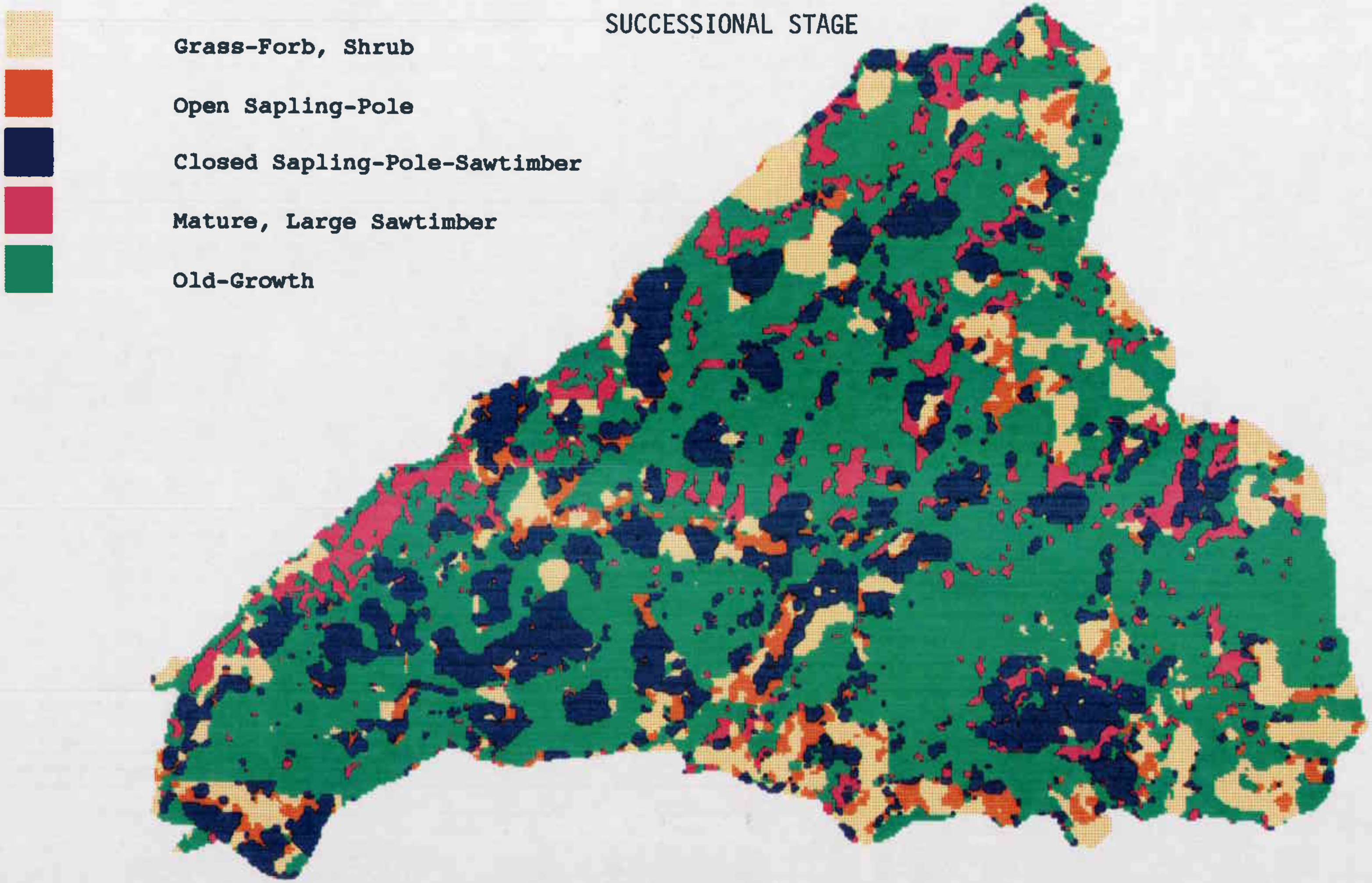
SUCCESSIONAL STAGE
Grass-Forb, Shrub
Open Sapling-Pole
Closed Sapling-Pole-Sawtimber
Mature, Large Sawtimber
Old-Growth

Figure IV.1:

Figure IV.2: Elevation in 500 foot contour intervals derived from 1:250,000 digital elevation model (1:70,000).

Class Number	Elevation Class	Hectare
3	1001-1500 feet	41
4	1501-2000 feet	476
5	2001-2500 feet	1061
6	2501-3000 feet	1330
7	3001-3500 feet	1032
8	3501-4000 feet	1065
9	4001-4500 feet	923
10	4501-5000 feet	486
11	5001-5500 feet	46

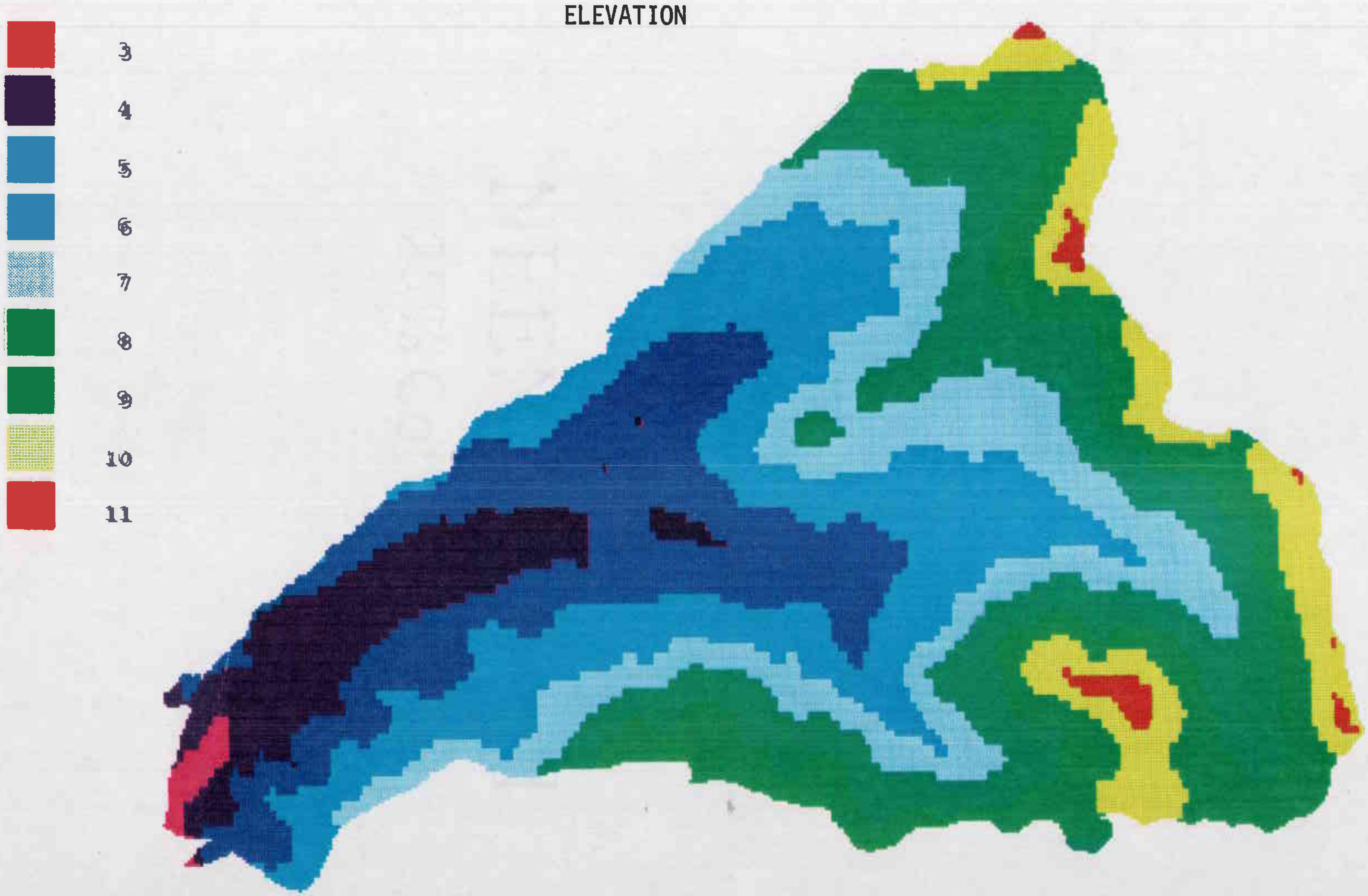

Figure IV.2:

Figure IV.3: Four class site moisture map (1:70,000).

Class Name	Hectares
very wet	147
wet	3088
dry	2946
very dry	280

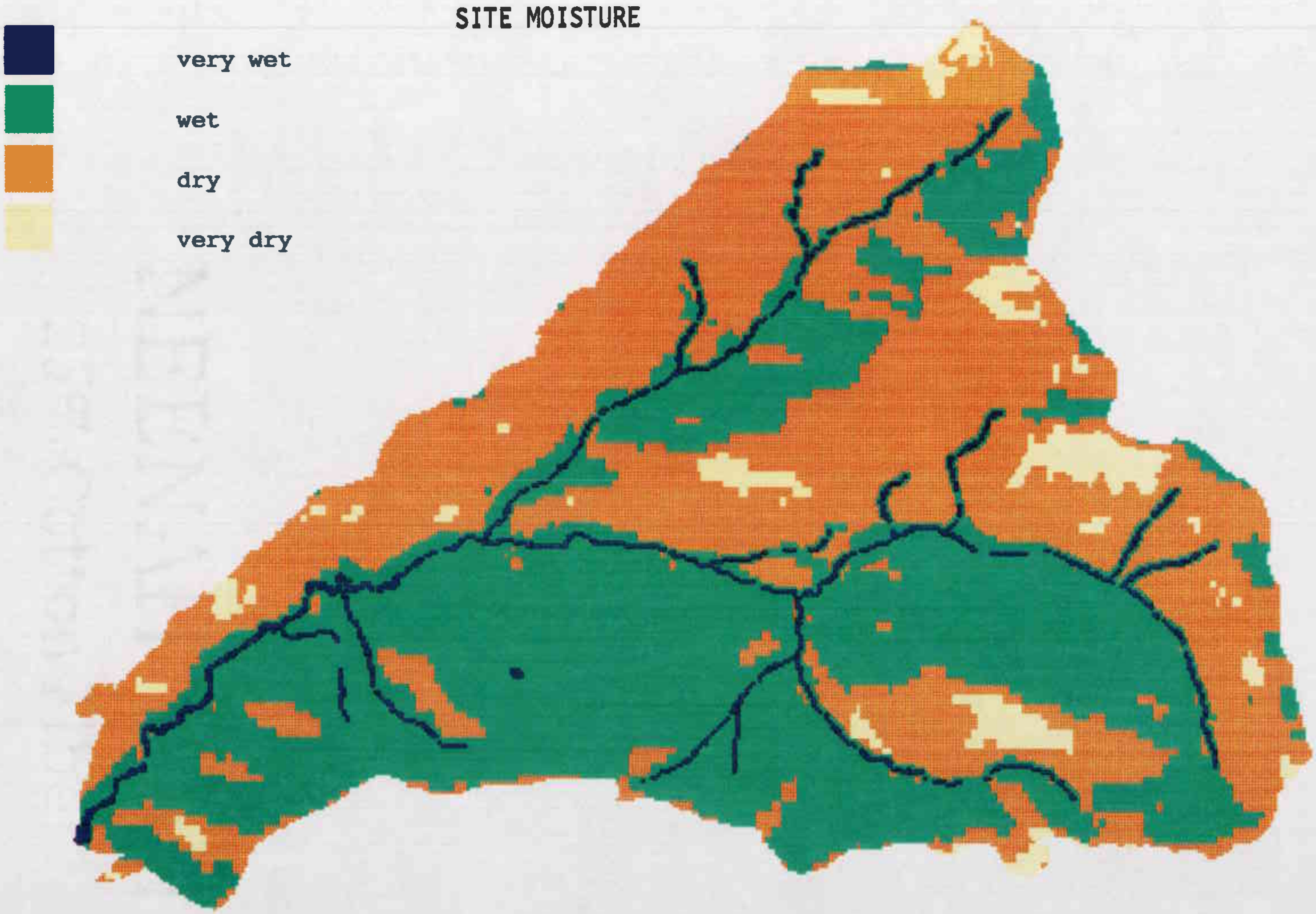

Figure IV.3:

Figure IV.4: Amphibian richness map based on primary habitat requirements for twelve species (1:70,000). Legend numbers refer to the number of species predicted at a given point (i.e. 5 equals five species, 9 equals nine species). Amphibian richness ranged from 0 to 9 species (1:70,000).

Figure IV.4:

Figure IV.5: Reptile richness map based on primary habitat requirements for six species (1:70,000). Legend numbers refer to the number of species predicted at a given point (i.e. 2 equals two species, 3 equals three species). Reptile richness ranged from 0 to 3 species (1:70,000).

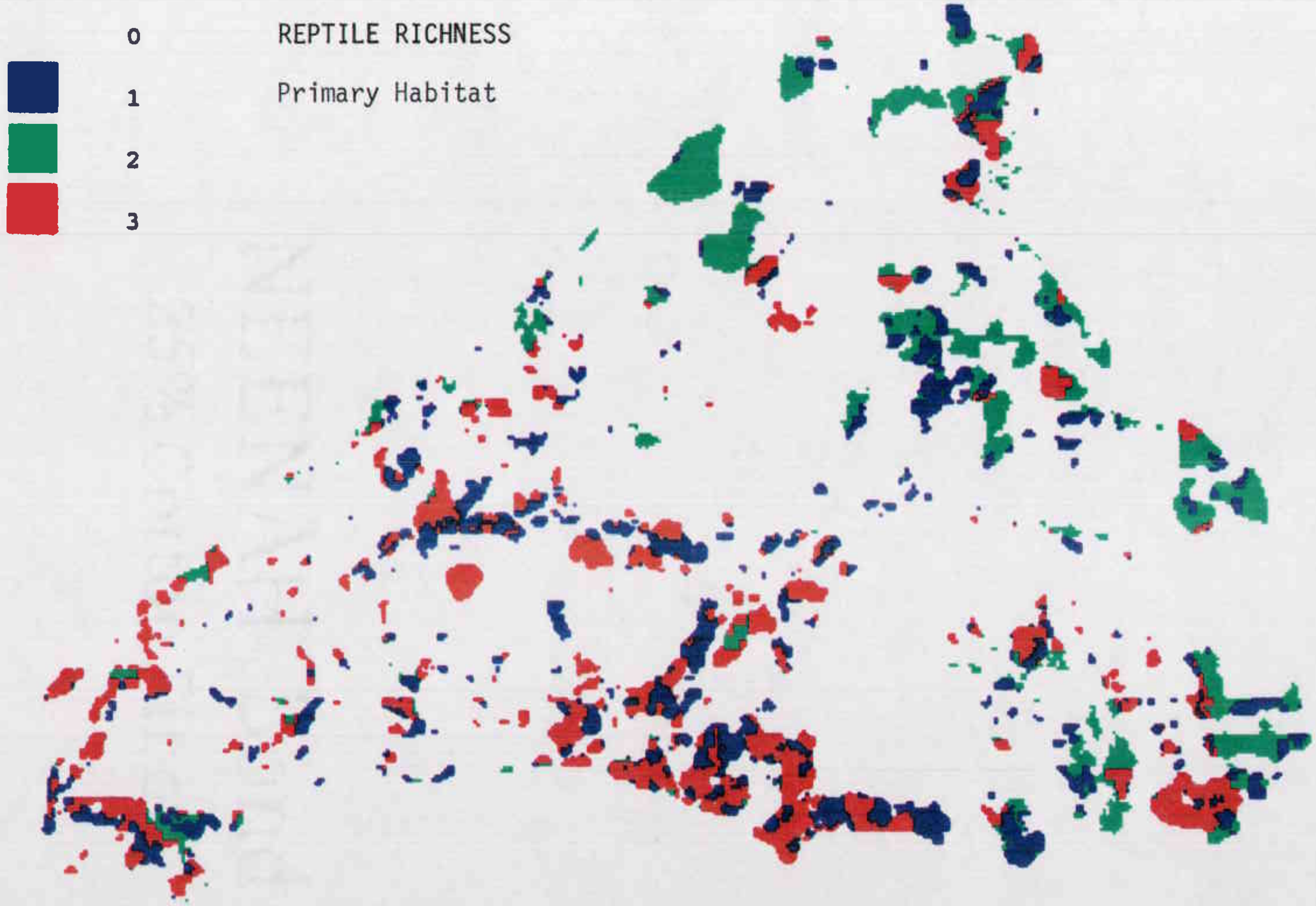

Figure IV.5:

Figure IV.6: Mammal richness map based on primary habitat requirements for nineteen species (1:70,000). Legend numbers refer to the number of species predicted at a given point (i.e. 5 equals five species, 7 equals seven species). Mammal richness ranged from 0 to 10 species.

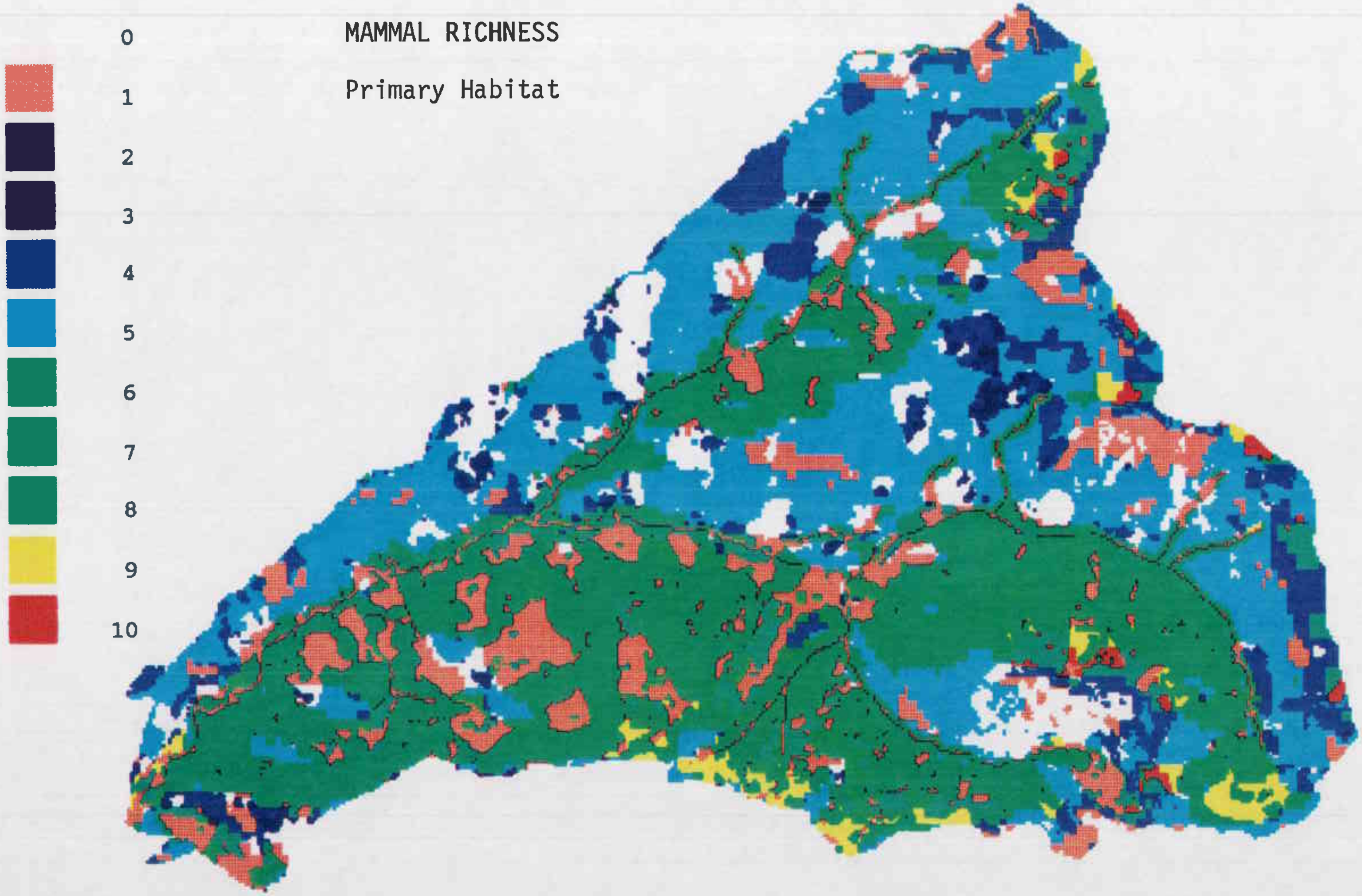

Figure IV.6:

Figure IV.7: Vertebrate richness map based on primary habitat requirements for thirty-seven species (1:70,000). Legend numbers refer to the number of mammals predicted at a given point (i.e. 6 equals six species, 18 refers to eighteen species). Vertebrate richness ranged from 0 to 21.

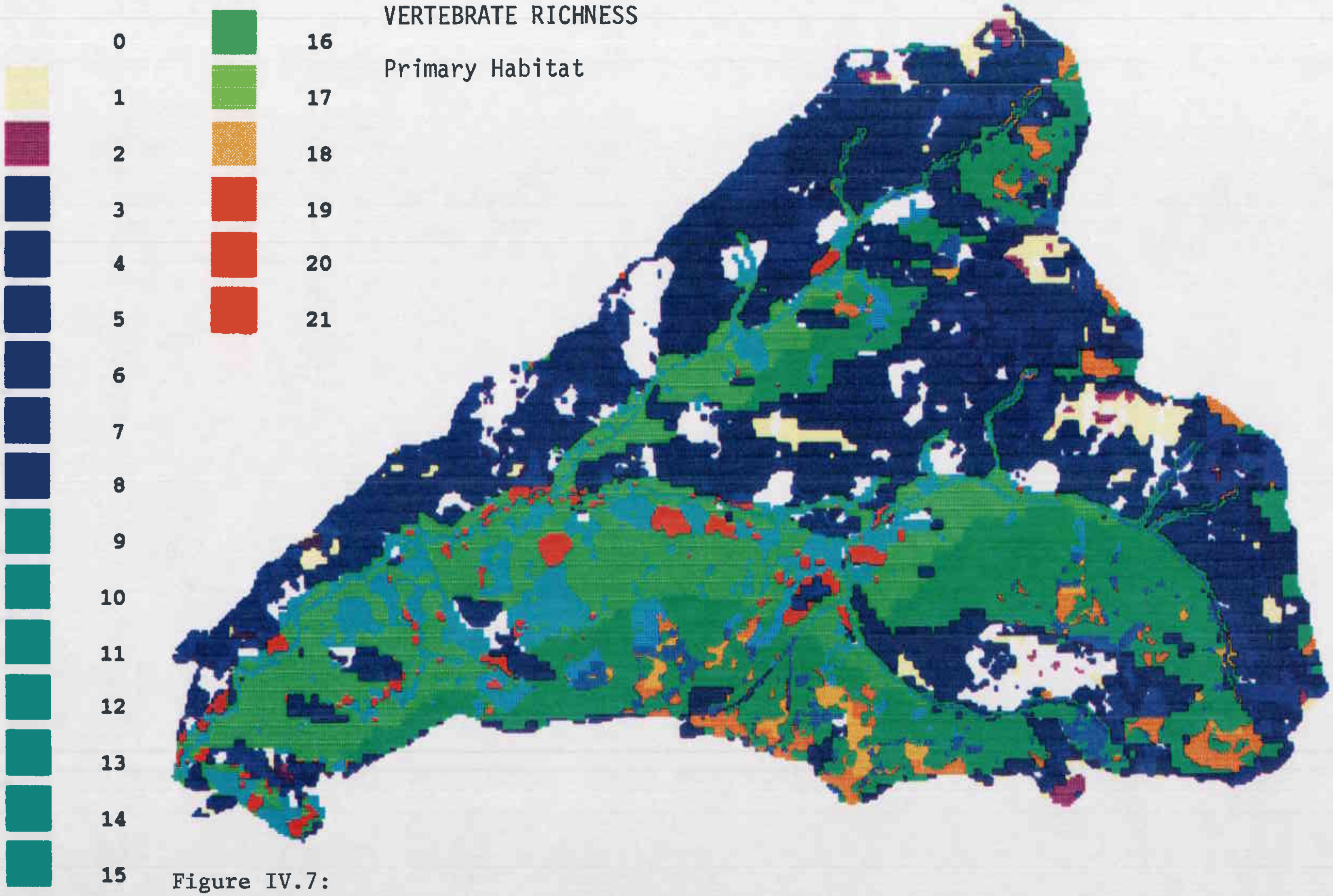
VERTEBRATE RICHNESS
Primary Habitat
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21

Figure IV.7:

Figure IV.8: Amphibian richness map based on secondary habitat requirements for twelve species (1:70,000). Legend numbers refer to the number of species predicted at a given point (i.e. 2 equals two species, 8 equals eight species). Amphibian richness ranged from 1 to 11 species.

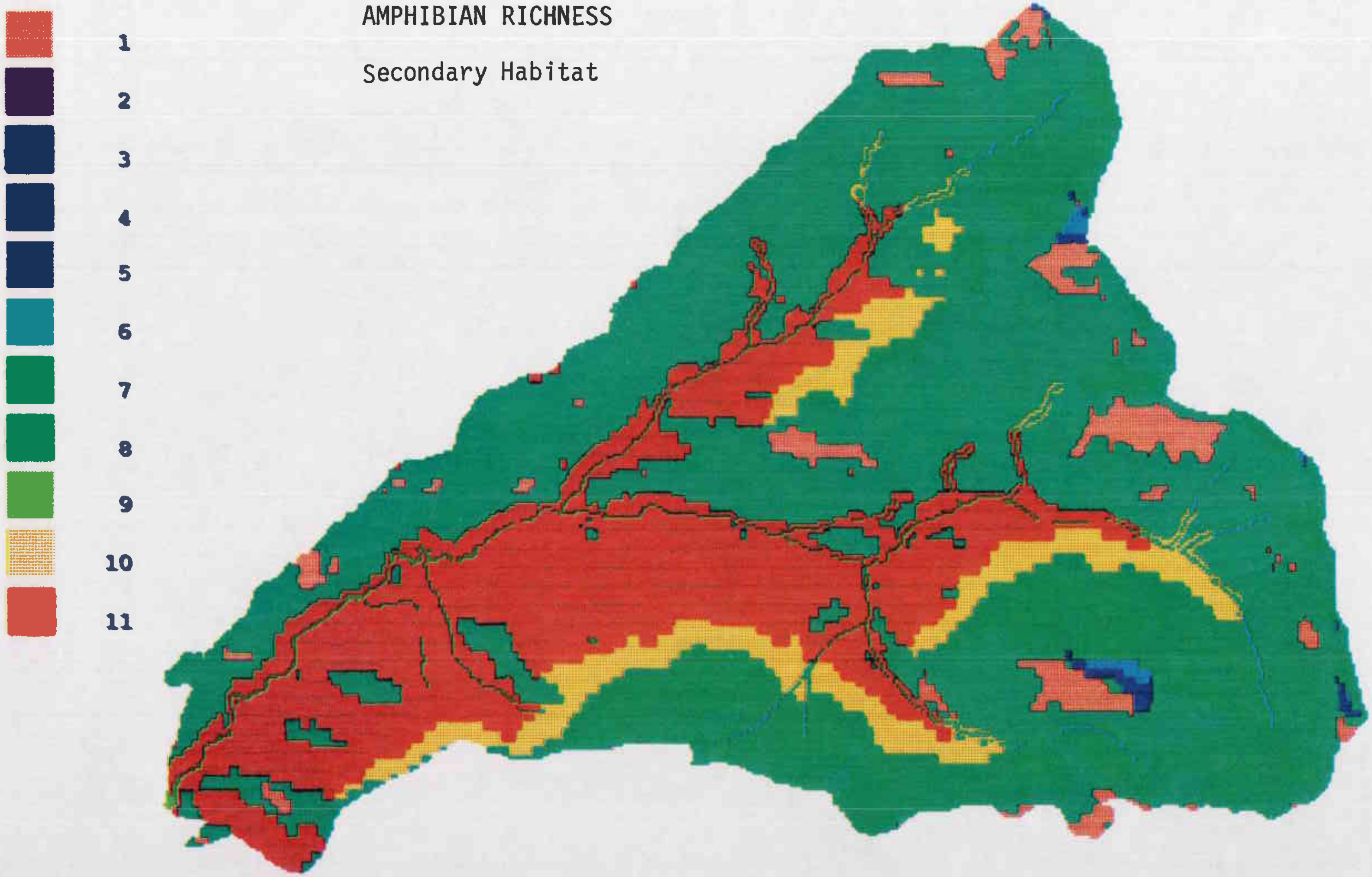

Figure IV.8:

Figure IV.9: Reptile richness map based on secondary habitat requirements for six species (1:70,000). Legend numbers refer to the number of species predicted at a given point (i.e. 2 equals two species, 4 equals four species). Reptile richness ranged from 1 to 6 species.

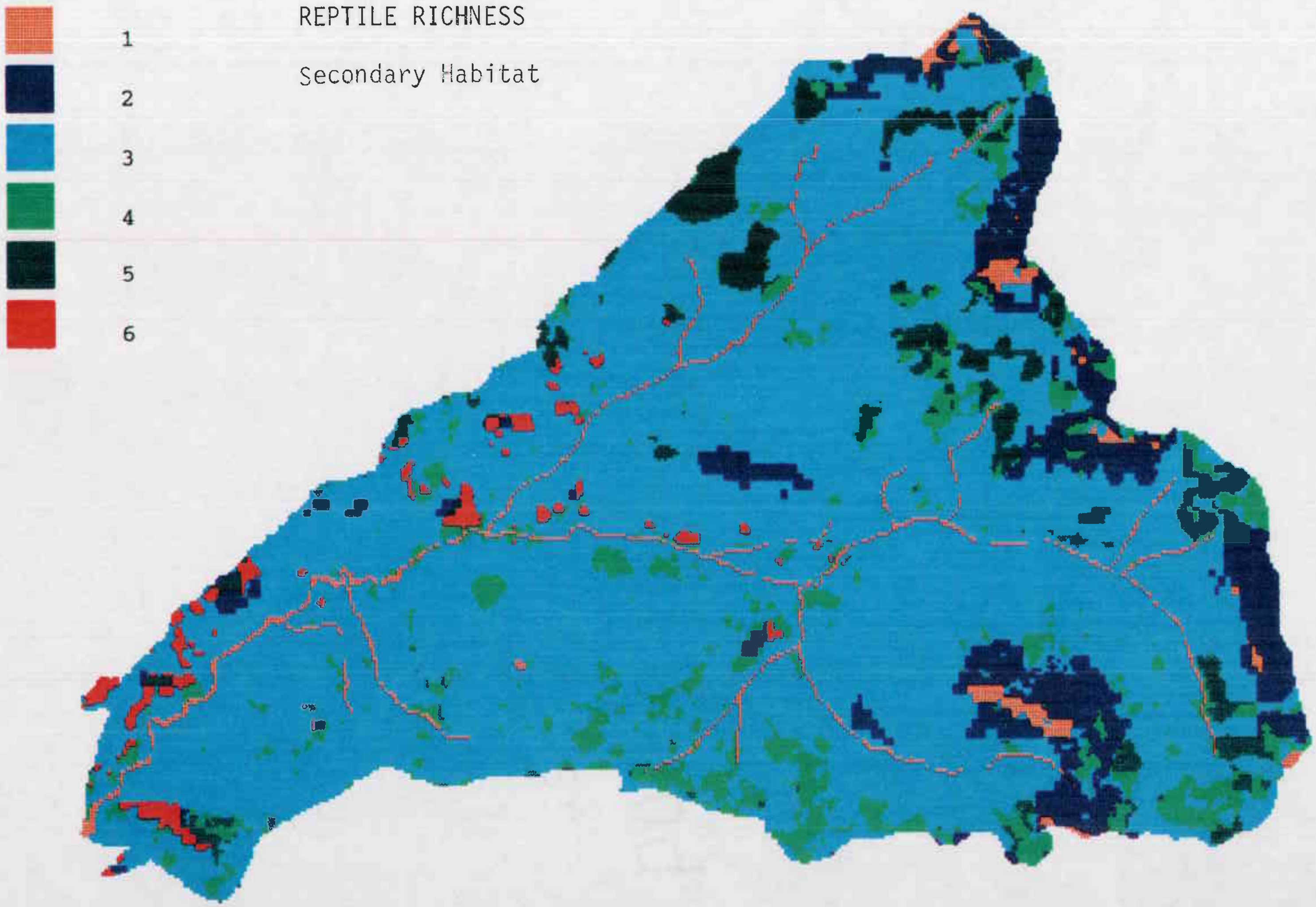

Figure IV.9:

Figure IV.10: Mammal richness map based on secondary habitat requirements for nineteen species (1:70,000). Legend numbers refer to the number of species predicted at a given point (i.e. 4 equals four species, 9 equals nine species. Mammal richness ranged from 1 to 14 species.

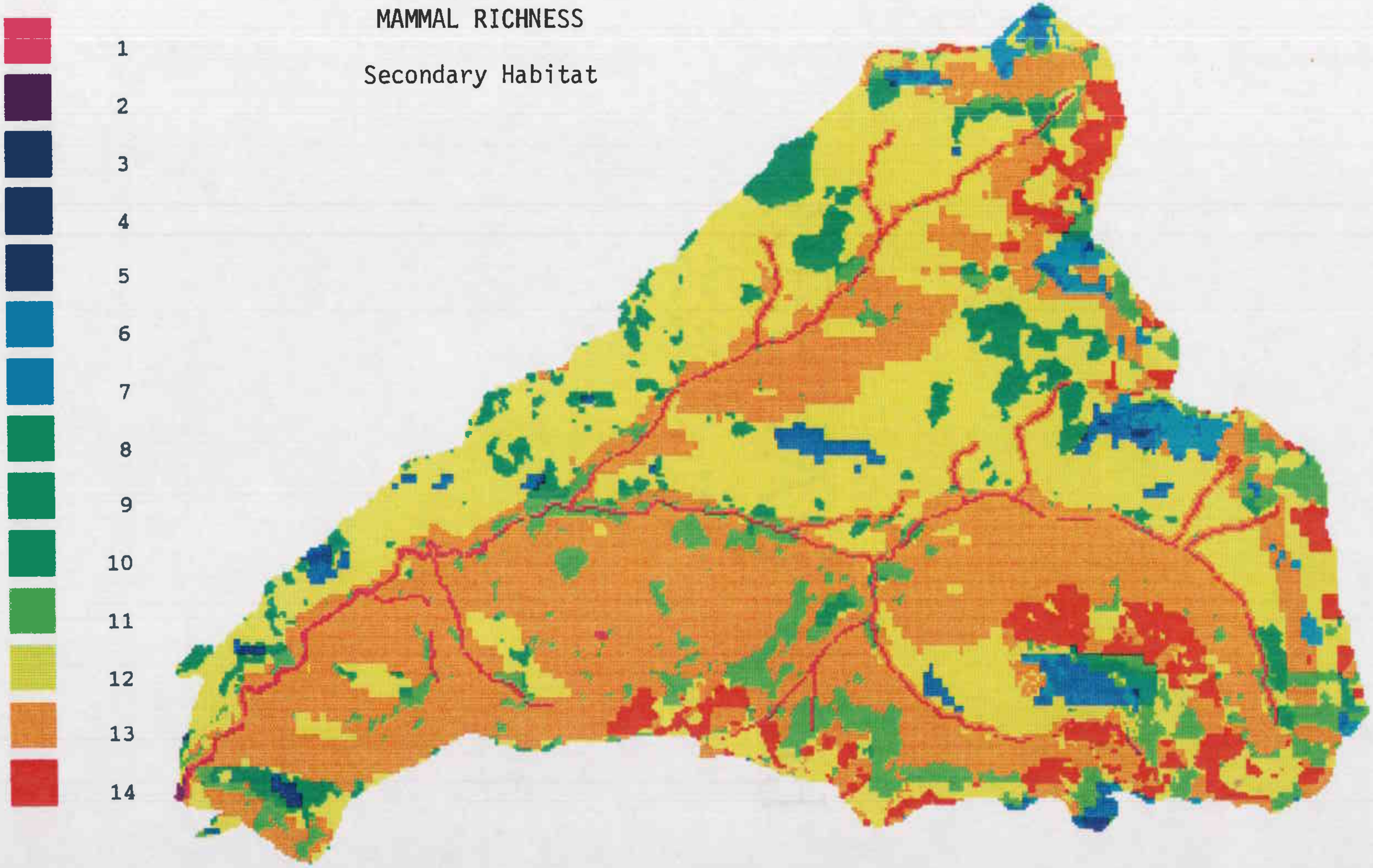

Figure IV.10:

Figure IV.11: Vertebrate richness map based on secondary habitat requirements for thirty-seven species (1:70,000). Legend numbers refer to the number of species predicted at a given point (i.e. 4 equals four species, 9 equals nine species). Vertebrate richness ranged from 7 to 27 species.

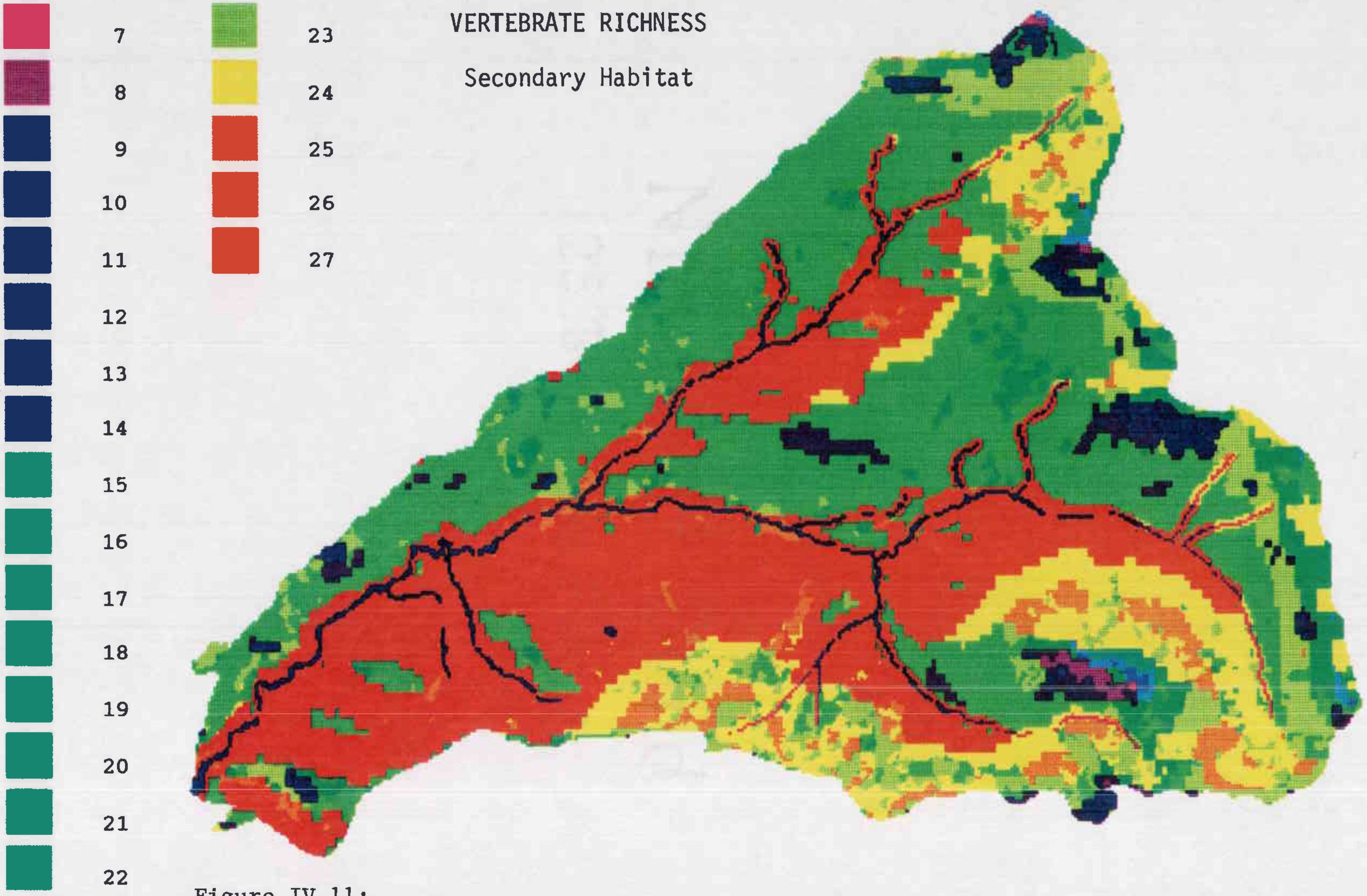
VERTEBRATE RICHNESS
Secondary Habitat
7
8
9
10
11
12
13
14
15
16
17
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Figure IV.11:

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CHAPTER V

CONCLUSIONS

Landsat Thematic Mapper (TM) data were useful in mapping forest successional stages, separating old-growth and mature forests, and in identifying the age of young conifer stands. Topography in this area greatly influenced forest spectral values, particularly in bands with long wavelengths. The TM 4/5 ratio was useful in separating mature forests from old-growth forests, in predicting the age of young conifer stands, and in reducing topographic variation in spectral values. For these reasons, TM 4/5 was named a successional stage index (SSI). Poorly regenerated conifer stands could be separated from well regenerated conifer stands after fifteen years. A GIS modelling technique was useful in providing a map of vertebrate richness based on model variables, and in evaluating the pattern of high and low vertebrate richness across a small landscape. Of the three model variables, site moisture appeared to have the greatest influence on the pattern of vertebrate richness for all vertebrate classes.

Future research efforts could evaluate the used of spectral texture to characterize the structure of both old and young forests. The inclusion of aspect, slope, or soils information may aide in distinguishing poorly regenerated conifer stands from well regenerated conifer stands. Mixture modelling might also be useful for monitoring conifer regeneration. This would be based on the modelling the percentage of vegetation types found within image pixels. Future vertebrate richness modelling should determine whether site moisture is as influential as indicated by vertebrate richness maps, and if it is, the definition of site moisture should be refined. The model could also include other variables such as edge and interior forest habitats. The spatial character of the species richness maps could be quantified using landscape indices.

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APPENDICES

Appendix II.1: Mean TM band and sun incidence (SUN) values for old-growth stands. Stand numbers (STDNUM) which are less than 100 are H.J. Andrews reference stands, and stand numbers greater than 100 are from the Forest Services old-growth study.

#	STDNUM	TM 1	TM 2	TM 3	TM 4	TM 5	TM 7	TM 6	SUN	STDAGE
1	2	60.778	20.111	16.556	46.556	24.778	7.000	135.778	183.000	460
2	3	57.444	20.222	16.333	46.889	26.000	8.111	133.000	186.333	460
3	4	55.778	19.222	16.000	45.556	20.778	6.000	129.778	184.667	460
4	5	57.778	20.444	16.000	51.111	27.333	7.778	134.000	167.556	460
5	7	59.889	19.889	15.667	45.444	22.111	6.556	135.000	207.333	460
6	12	60.222	21.000	17.222	63.889	32.333	9.222	130.000	214.222	---
7	15	58.222	19.556	16.222	44.778	23.556	5.444	132.667	160.667	---
8	16	61.000	21.000	17.111	46.889	27.667	8.444	133.889	177.667	---
9	17	61.778	20.556	17.222	50.889	26.556	7.778	136.222	188.889	---
10	22	58.333	20.889	17.889	50.556	27.889	8.333	133.889	234.444	450
11	23	58.222	20.444	16.778	52.222	27.444	8.222	134.000	211.778	---
12	27	59.778	20.111	16.667	50.889	27.667	8.444	137.333	224.000	450
13	28	57.000	19.667	16.111	51.444	26.778	7.333	133.889	219.000	450
14	29	57.667	18.889	14.444	39.222	20.778	5.889	134.000	180.667	---
15	30	59.000	20.333	16.667	53.000	27.000	7.778	136.000	184.667	---
16	31	57.667	20.778	17.111	61.333	29.444	7.333	136.667	239.667	450
17	34	58.889	19.778	16.333	55.333	28.778	8.333	134.222	200.000	---
18	102	60.333	19.889	16.444	51.444	27.000	7.444	134.000	190.333	450
19	103	59.667	20.000	16.333	51.889	24.222	7.778	134.000	192.222	450
20	105	58.778	20.111	16.000	53.111	26.111	7.667	133.000	182.111	450
21	124	58.667	20.111	16.222	51.444	26.222	7.444	134.000	172.667	450
22	133	61.667	21.333	17.111	64.556	33.000	9.111	137.000	246.778	200

Appendix II.2: Mean TM band and sun incidence (SUN) values for mature stands. Stand numbers (STDNUM) which are less than 100 are H.J. Andrews reference stands, stand numbers greater than 100 are from the Forest Services old-growth study, and stand numbers with an 'A' were sampled from aerial photographs.

#	STDNUM	TM 1	TM 2	TM 3	TM 4	TM 5	TM 7	TM 6	SUN	STDAGE
1	10	61.667	20.778	17.222	60.6667	28.556	8.111	137.000	236.667	---
2	18	60.444	21.000	16.556	68.3333	31.000	8.556	134.667	239.333	---
3	20	62.222	22.556	17.889	65.5556	36.778	10.333	140.222	248.333	110
4	26	59.556	21.444	17.556	68.6667	31.111	8.222	137.000	244.667	150
5	32	61.222	21.000	17.111	66.3333	31.222	8.444	137.889	227.333	145
6	33	58.667	20.222	15.889	56.6667	26.222	6.889	132.000	181.889	145
7	111	60.222	20.556	16.222	51.5556	25.889	6.000	134.000	198.778	130
8	136	58.667	20.556	16.222	56.5556	24.889	6.778	131.778	167.111	130
9	1A	60.889	21.778	17.000	67.4444	33.889	9.000	136.667	246.000	---
10	2A	61.778	23.333	19.111	71.3333	29.111	10.667	134.000	247.222	---
11	3A	60.889	21.556	17.111	63.2222	29.556	7.778	135.778	226.333	---
12	4A	59.333	19.444	16.111	52.2222	23.000	6.222	132.667	174.333	---
13	5A	59.444	20.444	17.000	60.2222	26.444	7.444	132.000	209.444	---
14	6A	61.222	21.444	17.556	70.6667	31.778	8.778	136.000	245.222	---
15	7A	60.889	23.000	17.778	73.1111	34.000	9.111	134.778	236.889	---
16	8A	57.778	19.444	14.889	47.0000	19.556	5.778	132.000	166.667	---
17	9A	60.444	20.333	16.333	49.0000	22.889	6.556	133.000	180.222	---
18	10A	59.000	20.333	16.556	51.7778	20.889	4.889	129.444	217.000	---
19	11A	56.222	19.778	15.778	49.4444	25.889	7.667	130.444	188.667	---

Appendix II.3: Mean TM band and sun incidence (SUN) values for young, closed canopy stands. Stand numbers (STDNUM) refer to harvest units on the H.J. Andrews. Stand age is years since initial planting.

#	STDNUM	STDAGE	TM 1	TM 2	TM 3	TM 4	TM 5	TM 7	TM 6	SUN
1	L102D	35	62.222	21.444	16.667	67.222	28.111	7.778	135.333	166.556
2	L102L	35	62.444	21.444	17.222	89.000	35.000	7.556	135.333	190.667
3	L105	35	60.111	20.444	16.556	72.111	27.778	7.222	137.000	182.778
4	L202	33	60.667	21.556	17.000	87.556	32.333	7.667	135.667	182.333
5	L201	31	61.778	21.000	16.667	87.556	34.444	7.889	134.555	183.556
6	L501	31	64.111	23.667	19.000	121.889	51.778	12.889	138.333	220.000
7	L109L	31	61.778	21.333	17.556	99.889	37.222	9.000	139.667	198.556
8	L109D	31	60.889	20.222	15.600	70.667	26.222	6.667	139.333	212.556
9	L103	31	61.000	20.889	16.222	76.667	29.222	7.444	137.000	195.111
10	L108	31	62.111	22.556	17.778	90.667	38.556	9.889	143.000	205.000
11	L231D	31	60.333	20.556	16.556	61.000	24.778	6.333	136.000	160.444
12	L231L	31	60.222	20.778	16.000	76.556	27.333	7.222	132.000	162.000
13	L301L	31	61.222	21.556	16.889	94.333	35.111	7.889	138.000	214.889
14	L301D	31	59.111	21.000	15.333	67.667	27.111	7.555	141.000	218.000
15	L403	31	64.556	24.111	19.111	116.778	51.444	12.111	141.444	246.889
16	L404	31	62.777	23.000	17.778	103.222	42.444	9.889	140.667	238.333
17	L404	31	61.556	23.556	17.000	106.778	44.778	10.667	137.111	218.111
18	L402	30	65.666	25.222	19.667	127.222	60.556	15.444	138.000	207.000
19	L505D	29	58.889	21.222	16.889	85.444	32.222	7.556	134.000	214.000
20	L521D	29	59.667	21.444	16.889	81.778	31.444	8.333	137.000	224.889
21	L521L	29	62.778	24.222	20.000	107.222	42.667	9.778	139.000	218.000
22	L204D	29	58.111	20.000	15.667	71.667	27.222	6.444	132.444	197.000
23	L204L	29	61.000	21.222	17.111	101.778	42.556	10.778	134.000	194.667
24	L203	29	59.556	20.444	16.111	83.222	30.333	8.000	135.111	164.000

Appendix III.1: Mean TM band and sun incidence values (SUN), and canopy closure (CANCLOS) estimates for well regenerated Douglas-fir (*Pseudotsuga menziesii*) stands. Stand age is years since initial planting (STDAGE). Stand numbers (STDNUM) refer to harvest unit numbers in the H.J. Andrews.

#	STDNUM	STDAGE	TM 1	TM 2	TM 3	TM 4	TM 5	TM 7	TM 6	SUN	CANCLOS
1	L102D	35	62.222	21.444	16.667	67.222	28.111	7.778	135.333	166.556	95
2	L102L	35	62.444	21.444	17.222	89.000	35.000	7.556	135.333	190.667	--
3	L105	35	60.111	20.444	16.556	72.111	27.778	7.222	137.000	182.778	95
4	L202	33	60.667	21.556	17.000	87.556	32.333	7.667	135.667	182.333	95
5	L201	31	61.778	21.000	16.667	87.556	34.444	7.889	134.555	183.556	90
6	L501	31	64.111	23.667	19.000	121.889	51.778	12.889	138.333	220.000	--
7	L109L	31	61.778	21.333	17.556	99.889	37.222	9.000	139.667	198.556	95
8	L109D	31	60.889	20.222	15.600	70.667	26.222	6.667	139.333	212.556	95
9	L103	31	61.000	20.889	16.222	76.667	29.222	7.444	137.000	195.111	90
10	L108	31	62.111	22.556	17.778	90.667	38.556	9.889	143.000	205.000	95
11	L231D	31	60.333	20.556	16.556	61.000	24.778	6.333	136.000	160.444	95
12	L231L	31	60.222	20.778	16.000	76.556	27.333	7.222	132.000	162.000	95
13	L301L	31	61.222	21.556	16.889	94.333	35.111	7.889	138.000	214.889	95
14	L301D	31	59.111	21.000	15.333	67.667	27.111	7.555	141.000	218.000	90
15	L403	31	64.556	24.111	19.111	116.778	51.444	12.111	141.444	246.889	--
16	L404	31	62.778	23.000	17.778	103.222	42.444	9.889	140.667	238.333	--
17	L404	31	61.556	23.556	17.000	106.778	44.778	10.667	137.111	218.111	--
18	L402	30	65.667	25.222	19.667	127.222	60.556	15.444	138.000	207.000	--
19	L505D	29	58.889	21.222	16.889	85.444	32.222	7.556	134.000	214.000	85
20	L521D	29	59.667	21.444	16.889	81.778	31.444	8.333	137.000	224.889	--
21	L521L	29	62.778	24.222	20.000	107.222	42.667	9.778	139.000	218.000	--
22	L204D	29	58.111	20.000	15.667	71.667	27.222	6.444	132.444	197.000	95
23	L204L	29	61.000	21.222	17.111	101.778	42.556	10.778	134.000	194.667	95
24	L203	29	59.556	20.444	16.111	83.222	30.333	8.000	135.111	164.000	90
25	L702	26	60.889	21.889	17.111	83.889	33.667	8.222	137.000	225.556	90

Appendix III.1: (continued)

#	STDNUM	STDAGE	TM 1	TM 2	TM 3	TM 4	TM 5	TM 7	TM 6	SUN	CANCLOS
26	L703	26	62.000	24.111	18.000	108.444	46.222	10.444	138.111	215.333	85
27	L405	25	61.333	22.222	17.222	99.111	44.667	11.000	137.777	222.778	--
28	L522	25	63.000	24.667	19.667	109.444	51.778	13.889	137.000	218.111	--
29	L304D	25	59.111	21.556	16.778	76.889	37.444	9.778	131.556	180.667	75
30	L601L	25	61.222	21.778	17.444	85.444	32.333	8.778	137.000	208.111	--
31	L601D	25	61.222	21.556	16.778	75.222	31.667	7.889	138.000	210.889	--
32	L602	25	58.778	20.444	16.444	69.000	27.111	7.889	135.222	168.000	--
33	L141L	24	63.778	22.667	17.444	101.330	48.556	12.222	136.667	181.556	85
34	L141D	24	60.778	21.333	16.556	73.443	30.444	8.444	135.000	175.444	85
35	L221	24	62.000	20.889	16.556	72.333	27.333	7.778	132.667	162.222	90
36	L211	24	61.000	25.222	19.222	120.556	55.778	14.333	134.556	178.222	65
37	L222	24	61.445	21.556	16.778	92.778	35.889	9.000	134.000	140.667	85
38	L405AD	22	62.889	24.667	19.222	113.000	55.889	14.333	138.111	224.111	--
39	L401L	22	63.444	23.333	18.222	93.333	41.222	10.000	140.667	229.000	95
40	L401D	22	61.778	22.111	17.111	86.889	34.556	9.111	139.000	229.778	95
41	L405AL	22	64.556	26.111	21.778	109.778	54.333	14.444	141.778	238.000	--
42	L402A	22	64.222	24.667	19.111	116.000	52.333	14.333	139.000	236.333	--
43	L402AD	22	61.556	21.556	17.222	91.556	35.889	9.111	137.222	217.667	--
44	L112	21	60.111	20.444	16.556	70.000	27.556	7.667	136.333	177.667	85
45	L109B1	20	61.111	22.556	17.222	91.333	37.333	9.111	140.444	194.222	85
46	L109B3	20	62.667	24.667	19.667	98.111	45.556	12.333	136.333	181.667	60
47	L109A	18	60.333	21.111	16.444	74.889	31.444	7.667	138.333	186.111	90
48	L201A	14	65.889	27.000	23.444	109.333	63.556	19.889	139.666	201.889	30
49	WS61	12	65.222	26.778	22.000	144.444	69.333	16.333	142.556	237.111	--
50	WS62	12	65.778	28.667	23.889	125.778	72.222	21.778	152.889	237.444	--

Appendix III.1: (continued)

#	STDNUM	STDAGE	TM 1	TM 2	TM 3	TM 4	TM 5	TM 7	TM 6	SUN	CANCLOS
51	WS71	12	69.889	30.889	29.444	115.111	90.111	33.222	154.111	237.333	--
52	WS72	12	67.556	28.889	25.333	138.333	82.333	24.778	149.444	229.333	--
53	WS10	11	63.333	23.889	20.111	75.778	46.778	13.444	136.778	237.667	55
54	L107B	8	68.444	28.444	26.111	91.667	67.889	22.111	149.667	182.778	5
55	L503A	8	69.556	29.889	28.111	110.444	86.111	29.111	146.222	224.556	--
56	L524	6	72.222	31.667	29.333	98.556	98.111	36.667	154.000	218.667	--
57	L524	6	73.111	31.667	33.444	99.778	96.667	35.111	156.000	219.111	--
58	L523	5	74.000	32.000	34.667	85.889	100.778	45.222	162.666	197.333	--
59	L523D	5	70.333	28.778	31.444	69.667	76.111	32.889	156.556	218.778	--
60	L114A	2	76.556	32.444	38.889	78.889	113.445	50.222	172.000	232.667	0
61	L115	2	75.333	31.556	38.778	65.333	94.667	43.889	163.000	179.667	0

Appendix III.2: Mean TM band and sun incidence values for grass stands. Stand age is given for years since initial planting (STDAGE) and for years since last replanting (REPAGE). Stand numbers (STDNUM) refer to harvest unit numbers in the H.J. Andrews.

#	STDNUM	TM 1	TM 2	TM 3	TM 4	TM 5	TM 6	TM 7	SUN	STDAGE	REPAGE
1	L207	65.667	28.222	25.889	115.444	67.111	143.000	21.556	184.667	29	29
2	L241S	65.111	26.000	24.111	86.333	56.556	139.000	17.778	194.667	28	25
3	L704	64.111	27.778	23.111	113.333	76.667	135.778	22.111	190.667	22	22
4	L707	70.444	32.111	33.333	94.333	85.444	148.333	31.667	224.333	22	22
5	L383	74.556	33.111	35.111	109.667	109.444	158.000	40.333	228.111	21	21
6	L306S	70.111	34.666	31.000	131.222	96.556	143.556	29.333	235.667	25	19
7	L307S	68.222	32.111	30.000	110.111	83.000	137.889	32.111	231.222	22	19
8	L112A	66.889	28.111	24.333	108.444	73.000	141.333	22.111	196.222	19	19
9	L708	71.111	34.111	35.111	96.889	85.889	147.111	31.222	221.889	22	18
10	FR10	71.222	33.889	33.333	125.778	108.000	150.111	39.778	183.000	20	15
11	L104BL	69.556	28.111	25.889	99.000	74.556	142.333	23.333	213.000	14	12
12	WS10	72.666	32.667	33.556	99.889	84.333	142.333	28.778	214.222	12	10
13	L381S	66.556	29.444	26.667	93.111	76.333	137.333	26.222	180.889	20	9
14	B133A	69.667	30.556	28.111	116.444	80.778	144.556	23.000	220.000	22	8
15	FC3S+	68.000	32.445	28.444	136.445	100.778	143.778	31.111	215.000	16	8
16	FC4PT	64.111	26.556	24.111	84.555	66.111	136.667	23.000	185.667	16	8
17	FC4S	63.889	27.444	25.222	89.445	68.889	135.556	22.889	188.889	16	8
18	FC5	67.000	30.333	28.778	102.333	77.556	145.667	26.667	196.000	16	8
19	FR8S	66.333	31.444	26.000	137.444	101.222	140.111	34.222	235.333	20	7
20	FR11S	70.444	31.000	32.111	97.444	84.222	143.556	31.222	236.000	17	7
21	L704AL	64.111	27.778	23.111	113.333	76.667	135.778	22.111	190.667	16	7

Appendix III.3: Mean TM band and sun incidence values for shrub stands. Stand age is given for years since initial planting (STDAGE) and for years since last replanting (REPAGE). Stand numbers (STDNUM) refer to harvest unit numbers in the H.J. Andrews.

#	STDNUM	TM 1	TM 2	TM 3	TM 4	TM 5	TM 6	TM 7	SUN	STDAGE	REPAGE
1	L241DC	63.889	24.444	19.556	122.778	54.667	137.444	15.444	187.000	28	25
2	L305	62.000	25.889	20.444	111.333	66.444	131.333	20.556	171.667	25	25
3	L209PT	64.556	28.778	23.111	136.000	80.000	142.556	22.556	214.556	25	25
4	L210D	62.000	24.111	18.333	113.556	69.111	131.667	19.444	151.556	25	22
5	L210L	62.445	25.667	21.222	128.778	82.333	134.778	24.556	166.667	25	22
6	L306DE	64.667	30.111	25.111	143.889	88.556	138.333	25.222	217.444	25	19
7	L307DE	67.778	31.556	30.111	135.444	83.000	137.778	28.667	226.111	22	19
8	L352SH	67.333	29.000	25.556	117.667	85.889	145.778	30.333	205.222	19	19
9	L374SH	64.333	27.222	25.778	105.667	90.333	138.111	28.667	194.111	19	19
10	WS1S	71.444	30.333	29.444	105.333	83.889	141.111	25.778	186.111	20	17
11	WS1DE	67.667	28.222	22.889	132.778	71.778	139.000	20.667	173.000	20	17
12	L383PT	63.222	25.889	22.444	124.889	67.556	139.667	19.667	229.000	20	16
13	L383SSH	63.222	26.889	23.222	132.444	67.444	141.333	20.333	214.000	20	16
14	L381PT	63.222	26.889	23.222	132.444	67.444	141.333	20.333	214.000	20	9
15	L212L	67.444	31.889	26.444	151.667	109.333	142.667	33.778	240.333	23	8
16	L212D	65.333	27.556	21.778	102.111	61.222	140.222	19.444	216.667	23	8
17	FC3PT	66.889	29.889	25.444	122.111	84.444	137.444	27.778	177.667	16	8
18	FR11SH	63.000	26.222	23.000	128.111	86.000	137.333	25.889	209.333	17	7
19	L704AD	56.556	23.222	18.778	102.778	53.333	132.444	14.333	171.667	16	7
20	L704CL	66.000	27.556	25.444	99.111	79.111	138.889	25.667	184.000	16	7
21	L704CD	64.556	28.111	23.889	124.333	84.556	137.667	25.111	189.667	16	7

Appendix III.4: TM band values and sun incidence values for five vegetation types: herbs, bracken fern, snowbrush ceanothus, Sitka alder, and Douglas-fir.

VEGTYPE	TM 1	TM 2	TM 3	TM 4	TM 5	TM 6	TM 7	SUN
Herbs	69	26	35	91	70	142	28	204
	71	32	32	91	83	149	31	213
	69	32	33	95	80	149	31	213
	69	32	31	97	80	149	24	218
	69	32	31	97	78	149	31	227
	69	32	33	95	87	149	33	223
	71	32	32	91	86	149	33	223
	68	27	26	95	82	142	23	215
	71	27	28	96	79	142	30	215
	72	32	33	91	90	149	30	223
	70	32	34	95	86	149	36	223
	70	31	33	95	79	149	29	227
	71	32	35	97	89	149	34	227
	71	34	36	91	90	149	34	223
	71	32	33	97	84	143	25	223
Bracken Fern	64	29	24	128	79	148	26	185
	64	29	24	130	75	148	24	185
	69	31	28	108	75	156	28	185
	64	29	26	119	79	148	23	181
	64	27	25	115	77	148	25	181
	66	30	27	102	81	148	28	181
Ceanothus	62	23	20	107	52	130	14	162
	57	22	17	111	60	130	16	162
	61	25	17	110	53	131	15	153
	59	26	20	107	63	134	20	146
	61	25	20	107	60	129	19	154
	61	26	20	108	58	129	19	154
	59	23	20	108	57	129	15	158
	61	23	17	108	54	130	16	158
	60	25	19	106	52	130	14	166
	61	22	17	107	51	130	12	166
	59	23	17	106	50	130	11	166

Appendix III.4: (continued)

VEGTYPE	TM 1	TM 2	TM 3	TM 4	TM 5	TM 6	TM 7	SUN
Sitka Alder	60	23	18	112	73	135	20	185
	59	23	20	121	65	133	17	185
	62	23	17	114	71	135	20	185
	59	25	18	124	69	135	18	183
	59	22	17	105	74	133	21	182
	59	22	17	116	70	133	19	181
	55	23	18	109	70	133	19	181
	62	23	18	107	74	133	21	182
Douglas-fir	62	21	17	90	30	134	9	162
	61	21	17	72	25	133	8	168
	57	20	17	72	26	133	7	168
	62	20	16	72	30	133	10	174
	59	19	15	72	29	133	5	182
	61	20	17	72	25	133	8	178
	62	21	14	91	31	133	8	178
	62	21	17	93	32	134	8	170
	63	21	17	89	33	134	10	170
	59	21	17	80	33	133	9	178
	58	20	14	85	33	133	8	178
	62	20	17	85	25	133	6	182
	60	20	16	87	32	133	8	182
	62	20	17	87	31	133	8	178
	59	21	17	80	37	133	9	178
	63	21	17	89	37	134	9	170