Analysis of Conifer Forest Regeneration 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 analyses 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. TM bands 1, 2, 3, 5, 6, and 7 were inversely correlated with the age ($r \geq -0.80$) of well regenerated Douglas-fir stands. Overall, the "structural index" (TM 4/5 ratio) had the highest correlation to age of Douglas-fir stands ($r = 0.96$). Poorly regenerated stands were spectrally distinct from well regenerated Douglas-fir stands after the stands reached an age of approximately 15 years.

Introduction

Standard forestry practices require that harvested timber areas 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 (Ripple *et al.*, 1991a). 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 60 percent canopy closure (Brown, 1985). At 60 percent canopy closure, light to understory vegetation is limited and changes in understory species composition typically occur. These successional stage changes also 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 U.S. Forest Service land average 10 to 20 hectares (110 to 220 TM pixels). Landsat Thematic Mapper (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 photointerpreted 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, and (2) determine whether poorly regenerated stands could be separated from well regenerated stands.

Study Area

The research was conducted at the H.J. Andrews Experimental Forest located in the western Cascade Mountains of Oregon. Elevations range from 414 to 1630 metres above mean sea level. 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 metres (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 pre-

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Maria Fiorell
William J. Ri
Environmental Remote Sensing Applications Lab.
(ERSAL), Department of Forest Resources, Or
University, Corvallis OR

pare 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 25 percent of the forest landscape.

Methods

Data Development

An area representing the H.J. Andrews Experimental Forest was extracted from a 30 July 1988 TM quarter scene (scene ID Y5161218271). The TM data were rectified to a Universal Transverse Mercator (UTM) grid using a nearest neighbor resampling method. A 3 by 3 area of pixels was extracted from the TM data for well regenerated Douglas-fir stands within the study area. 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, 1:12,000-scale color aerial photographs, were used to assess the success of stand regeneration. Multiple samples from each stand were typically used in large stands to account for topographic or stand level variability. A total of 61 samples were taken from 45 stands.

A 3 by 3 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 and (2) shrubs. These two categories of poorly regenerated stands will be referred to as herb stands and shrub stands in the following text. There were 21 samples taken from 20 different herb stands and another 21 samples taken from 16 different shrub stands. 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.).

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 and TM 4/7 band ratios), the structural index (SI), and the three TM Tasseled Cap features of brightness, greenness, and wetness were included in the analysis. The SI is simply the TM 4/5 band ratio (Fiorella and Ripple, 1993). 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 SI - see results). These data were fit with a regression line with a 95 percent 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 SI values for the two subgroups of poorly regenerated stands were plotted against stand age and with the 95 percent prediction intervals from the well regenerated stands. The percentage of points which fell outside the 95 percent prediction intervals was computed for both graphs.

SI values for young well regenerated conifers, shrub stands, and herb stands were divided into two age groups: (1) 5 to 14 years old and (2) 15 to 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 SI 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. 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).

Results

Correlations between stand age and individual TM band values were highest with the log-linear relationship (Table 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 ($r = -0.01$) had high correlations with stand age ($r = -0.95$ to -0.87). Overall, the log-log relationships of stand age with SI ($r = 0.96$) and stand age with TM 4/7 ($r = 0.95$) had the highest correlations. Among the Tasseled Cap features, the log-linear relationship of stand age with wetness had the highest correlation ($r = 0.95$). NDVI and TM 4/3 had lower correlations to stand age ($r \leq 0.84$) than all single bands except for TM 4 and TM 5.

The SI had a direct curvilinear relationship to stand age in well regenerated stands (Figure 1). TM bands 1, 2, 3, 5, 6, and 7 had inverse curvilinear relationships to stand age. The relationship between SI values and age for the poorly regenerated stand subgroups (1) herb stands and (2) shrubs stands are shown (Figures 2 and 3, respectively). Fifty-two percent of the poorly regenerated stands with a herb understory fell outside the prediction intervals, and 57 percent of the poorly regenerated stands with a shrub understory fell outside the

TABLE 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 ARE SIGNIFICANT AT 0.0000 EXCEPT WHERE NOTED (A = 0.2734, B = 0.9206, C = 0.9949, D = 0.1728, E = 0.0083). INCLUDED ARE BOTH 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)	−0.82	−0.90	−0.89
TM 2 (0.52 − 0.60 μm)	−0.85	−0.86	−0.85
TM 3 (0.63 − 0.69 μm)	−0.86	−0.95	−0.93
TM 4 (0.76 − 0.90 μm)	−0.14[a]	−0.01[b]	−0.00[c]
TM 5 (1.55 − 1.75 μm)	−0.84	−0.87	−0.80
TM 6 (10.4 − 12.5 μm)	−0.80	−0.89	−0.89
TM 7 (2.08 − 2.35 μm)	−0.86	−0.93	−0.89
NDVI [(TM 4−3)/(TM 4+3)]	0.67	0.83	0.84
TM 4/3	0.61	0.72	0.80
Structural Index (TM 4/5)	0.90	0.93	0.96
TM 4/7	0.90	0.91	0.95
Brightness	−0.71	−0.68	------
Greenness	0.17[d]	0.34[e]	------
Wetness	0.86	0.95	------

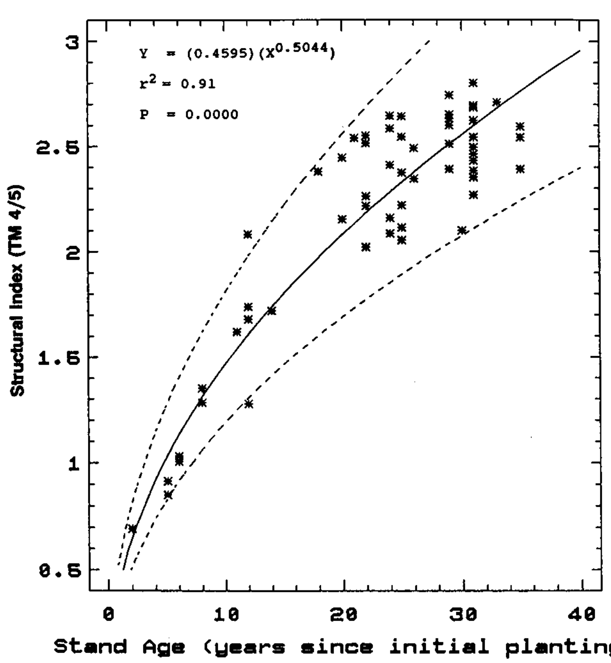

Figure 1. The relationship between the Structural Index, SI (TM 4/5 ratio) and young well regenerated Douglas-fir (*Pseudotsuga menziesii*) stands (n = 61 from 45 stands). A prediction interval (95 percent) for new observations is also shown

prediction intervals. Ninety-one percent of the herb stand observations which were greater than 12 years old fell outside the prediction intervals for well regenerated stands. Seventy-five percent of the shrub stands observations which were

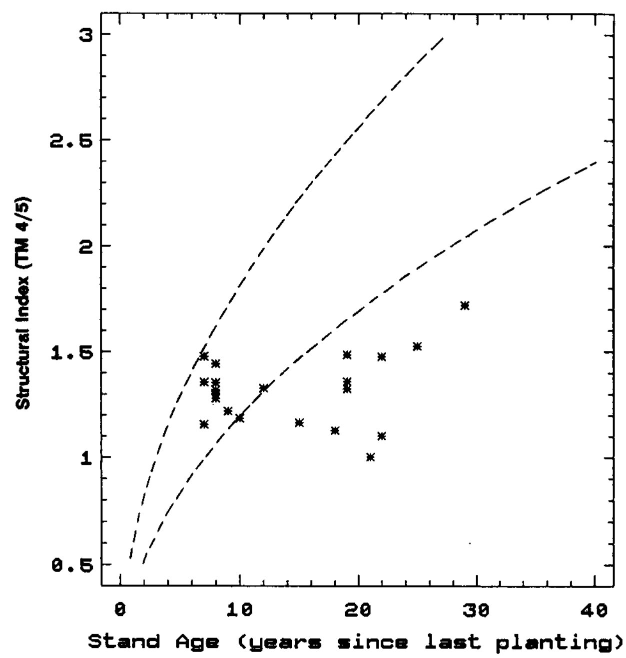

Figure 2. The relationship between the Structural Index, SI (TM 4/5 ratio) and the age of poorly regenerated conifer stands where the understory is predominately herbs (herb stands) (n = 21 from 20 stands). The prediction interval from the regression of well regenerated stands (Figure 1) is included to illustrate the differences between herb stands and well regenerated stands. Age is determined from the most recent planting date.

greater than 16 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 SI values among well regenerated conifer stands, shrub stands, and herb stands in the 5 to 14 year age group (P = 0.1376), but that there were significant differences among these stand types in the 15 to 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 to 24 year age group (α = 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 SI 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 4). After age 18, TM band 4 had little relationship with stand age (r^2 = 0.02). Well regenerated stands reached 60 percent canopy closure approximately 18 years after planting.

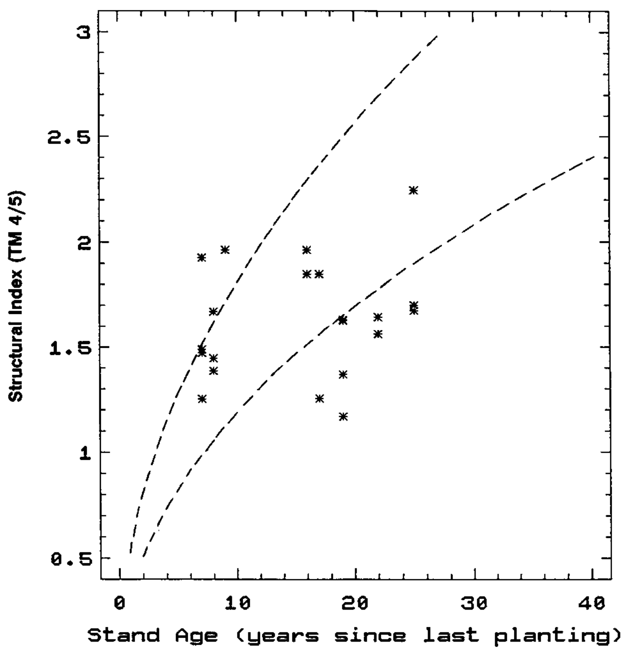

Figure 3. The relationship between the Structural Index, SI (TM 4/5 ratio) and the age of poorly regenerated conifer stands where the understory is predominately shrubs and/or deciduous trees (shrub stands) ($n = 21$ from 16 stands). The prediction interval from the regression of well regenerated stands (Figure 1) is included to illustrate the differences between shrub stands and well regenerated stands. Age is determined from the most recent planting date.

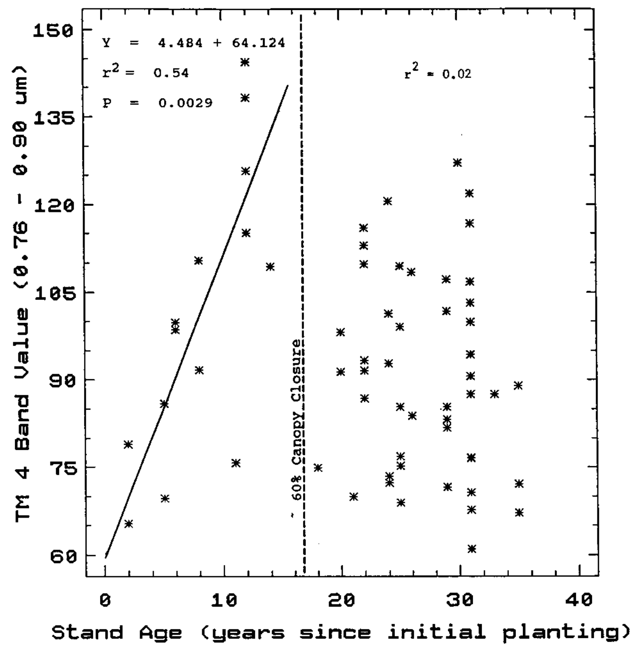

Figure 4. The relationship between TM band 4 and stand age for well regenerated Douglas-fir stands ($n = 61$ from 45 stands). Prior to age 18 and 60 percent canopy closure, TM band 4 had a direct linear relationship with stand age ($r^2 = 0.54$). After age 18 and at greater than 60 percent canopy closure, TM band 4 had little relationship with stand age ($r^2 = 0.02$).

Discussion

With the exception of TM 4, all TM bands showed a strong inverse correlation with stand age. Because 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 closed, and the increase in shadowing from the growing conifer crowns.

The correlation of SI to stand age showed improvement over single bands and even over the TM 4/3 ratio and NDVI. The usefulness of the SI for estimating forest age is similar to the results obtained by Spanner *et al.* (1989) where forest age was described in terms of disturbance/successional stage classes. Fiorella and Ripple (1993) found that the SI and wetness, and Cohen and Spies (1992) 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), it appears that the SI has very good potential for estimating structural characteristics and successional stages in both young and old conifer forests by reducing topographic effects. It should be noted, however, that SI values for old-growth can be similar to young forests that have not reached canopy closure (Spanner *et al.*, 1989; Fiorella and Ripple, 1992, unpublished data). With simple regression, the SI 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 SI 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.*, 1991b; 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 rise in TM 4 values may be due to increased scattering of radiation with the increase in vegetation amount as succession proceeded from herbs to shrubs (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 60 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.*, 1991b).

The results of our study indicate that differences in mean SI 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 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. This length of time will also be dependent upon site productivity and how long it takes the conifer canopy to develop and dominate a site.

TM satellite data may also 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.

Conclusions

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

- With the exception of TM 4, all bands showed a strong inverse correlation with age of young Douglas-fir stands (2 to 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 of radiation by pigments for the visible bands and moisture for the middle infrared bands.
- The near-infrared band, TM 4, showed a direct relationship to stand age before canopy closure (2 to 18 years) and a weak relationship to stand age after canopy closure (18 to 35 years). This weak relationship was attributed to the variability in offsetting influences of increasing biomass, increasing shadowing, and variability in the understory.
- The SI had a very strong relationship with stand age and should be tested in future studies involving the analysis of vegetation structure.
- TM spectral data from poorly regenerated stands were significantly different from well regenerated stands only after the plantations reached an age of approximately 15 years in the Cascade Mountains of Oregon. This length of time (15 years) would be shorter in areas of higher site productivity and longer in areas of lower site productivity and related to the rate of development of the young conifer crowns.

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References

Brown, E.R. (editor), 1985. *Management of Wildlife and Fish Habitats in forests of Western Oregon and Washington.* Pacific Northwest Region, Forest Service, USDA, Portland, Oregon, No.:R6-F&WL-192-1985.

Butera, M.K., 1986. A correlation and regression analysis of percent canopy closure versus TMS spectral response for selected forest sites in the San Juan National Forest, Colorado. *IEEE Transactions on Geoscience and Remote Sensing,* GE-24 (1):122–129.

Cleary, B.D., R.D. Graves, and R.K. Hermann (editors), 1978. *Regenerating Oregon's Forests.* Oregon State University Extension Service, School of Forestry, 287 p.

Cohen, W.B., and T.A. Spies, 1992. Estimating attributes of Douglas-fir/Western hemlock forest stands from satellite imagery. *Remote Sensing of Environment,* 4(1):1–18.

Crist, E.P., and R.C. Cicone, 1984. A physically-based transformation of Thematic Mapper - The TM tasseled cap. *IEEE Transactions on Geoscience and Remote Sensing,* GE-22(3):256–263.

Dyrness, C.T., 1973. Early stages of plant succession following logging and burning in the Western Cascades of Oregon. *Ecology,* 54(1):57–69.

Eby, J.R., 1987. The use of sun incidence angle and infrared reflectance levels in mapping old-growth coniferous forests. *Proceedings, American Society for Photogrammetry and Remote Sensing, Fall Convention.* Reno, Nevada, pp. 36–44.

Edwards, G., R. Landry, and K.P.B. Thompson, 1988. Texture analysis of forest regeneration sites in high-resolution SAR imagery. *International Geosciences and Remote Sensing Symposium,* Edinburgh, Scotland, 13-16 Sept., pp. 1355–1360.

Fiorella, M., and W.J. Ripple, 1992. Unpublished data, Environmental Remote Sensing Laboratory (ERSAL), Oregon State University, Corvallis, Oregon.

———, 1993. Determining successional stages of temperate coniferous forests with Landsat satellite data. *Photogrammetric Engineering & Remote Sensing,* 59:(2):239–246.

Franklin, J., 1986. Thematic mapper analysis of coniferous Forest structure and composition. *International Journal of Remote Sensing,* 7(10):1287–1301.

Franklin, J.F., and C.T. Dyrness, 1973. *Natural Vegetation of Oregon and Washington.* Oregon State University Press, 452 p.

Hansen, A.J., T.A. Spies, F.J. Swanson, and J.L. Ohmann, 1991. Conserving biodiversity in managed forests, lessons from natural forests. *BioScience* 41:382–392.

Hardy, N.E., 1981. A photo interpretation approach to forest regrowth monitoring using side-looking radar - Grant County, Oregon. *International Journal of Remote Sensing,* 2(2):136–144.

Harris, L.D., 1984. *The Fragmented Forest. Island Biogeography Theory and the Preservation of Biotic Diversity.* University of Chicago Press, Chicago, 211 p.

Horler, D.N., and F.J. Ahern, 1986. Forestry information content of Thematic Mapper data. *International Journal of Remote Sensing,* 7(3):405–428.

Matejek, S., and J.M.M. Dubois, 1988. Determining the age of cutting areas by Landsat-5 TM (Quebec, Canada). *Photo Interpretation,* 27 (May-June):15–17,19,21–22.

Pilon, P.G., and R.J. Wiart, 1990. Operational forest inventory applications using Landsat TM data: The British Columbia Experience. *Geocarto International,* (1):25–30.

Ripple, W.J., G.A. Bradshaw, and T.A. Spies, 1991a. Measuring Forest Landscape Patterns in the Cascade Range of Oregon, USA. *Biological Conservation,* 57:73–88.

Ripple, W.J., S. Wang, D.L. Isaacson, and D.P. Paine, 1991b. A preliminary comparison of Landsat TM and SPOT-1 HRV multispectral data for estimating coniferous forest volume. *International Journal of Remote Sensing,* 12(9):1971–1977.

Smith, J.M., 1988. Landsat TM study of afforestation in northern Scotland and its impact on breeding bird populations. *International Geosciences and Remote Sensing Symposium (IGARSS),* Edinburgh, Scotland, 13–16 Sept., pp. 1369–1370.

Spanner, M.A., C.A. Hlavka, and L.L. Pierce, 1989. Analysis of forest disturbance using TM and AVHRR data. *International Geoscience and Remote Sensing Symposium IGARSS) 1989,* 12th Canadian Symposium on Remote Sensing, Vancouver, Canada, 10 July, pp 1387–1390.

Spanner, M.A., L.L. Pierce, D.L. Peterson, and S.W. Running, 1990. Remote sensing of temperate coniferous forest leaf area index. The influence of canopy closure, understory vegetation, and background reflectance. *International Journal of Remote Sensing*, 11(1):95–111.

Stenback, J.M., and R.G. Congalton, 1990. Using TM imagery to examine forest understory. *Photogrammetric Engineering & Remote Sensing*, 56(9):1285–90.

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Maria Fiorella
Maria Fiorella received the B.S. degree in natural resources from Cornell University in 1985, and the M.S. degree in forest resources, specializing in remote sensing and GIS, from Oregon State University in 1992. She is currently with the U.S. Forest Service where she is involved in using satellite data to analyze the 20-year change in forest structure and carbon in western Oregon and Washington. Other interests include using remote sensing and GIS for landscape and wildlife habitat analyses.

William J. Ripple
William J. Ripple is currently an Associate Professor in the Department of Forest Resources at Oregon State University (OSU). He serves as the Director of the Environmental Remote Sensing Applications Laboratory (ERSAL) which is also located in the College of Forestry at OSU. Dr. Ripple has 16-years experience in the research and applications of geographic information systems and remote sensing for the study of vegetation and other natural resources.