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Estimating the age and structure of forests in a multi-ownership landscape of western Oregon, U.S.A.

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Abstract. Forests of the Pacific Northwest region of the U.S.A. are part of an ongoing political debate that focuses on the trade-offs between commodity and non-commodity values. A key issue in this debate is the location and extent of closed canopy mature and old-growth forest remaining in the region. Remote sensing can play a major part in locating mature and old-growth forests, but several challenges must be overcome to do so with acceptable accuracy. Conifer forests of the region have high leaf area indices. Thus, most incident solar energy is absorbed, making these forests difficult targets for discrimination of classes. Additionally, spectral characteristics can be affected more by the effects of steep topography than condition of the closed canopy forest.

Experimenting with a number of techniques, we estimated and mapped forest age and structure in 1988 over a 1 237 482 ha area on the west side of the Oregon Cascade Range with an overall accuracy of 82 per cent. Unsupervised classification enabled several forest classes to be defined in terms of per cent cover: open (0–30 per cent), semi-open (30–85 per cent), closed mix (>85 per cent, of which at least 10 per cent is comprised of non-conifer species), and closed conifer (>85 per cent, of which less than 10 per cent is non-conifer). These classes represented nearly distinct spectral groups. Within the closed canopy conifer class, between two and three age and structural classes could be distinguished using regression analysis (e.g., young, mature, and old-growth). Defining more classes seriously degraded map accuracies. The Tasseled Cap wetness index was not sensitive to topography, and yielded more accurate results in closed canopy conifer stands than Tasseled Cap brightness or greenness, even when regression models using these indices were based on solar incidence angle stratification.

The multi-ownership study area consisted of 76 per cent forestland. Of the total forestland, 70 per cent was closed canopy conifer, with 42 per cent being in a mature or old-growth state. Forests administered by the USDI Bureau of Land Management (BLM) and the USDA Forest Service, but protected by congressional and administrative mandates from harvest, were 10 per cent of the total forestland. Of the protected category, only 60 per cent was mature and old-growth forest. Unprotected BLM and Forest Service lands accounted for 53 per cent of the forestland in this study (8 and 45 per cent, respectively). Of the unprotected category, the BLM had 63 per cent, and the Forest Service had 49 per cent, respectively, of their holdings in a pre-canopy closure and young conifer condition. Thirty-five per cent of the forestland was privately owned, and consisted of 73 per cent pre-canopy closure and young conifer forest stands. Of all mature and old-growth forest, 22 per cent was found on private land, 7 per cent on unprotected BLM land, 55 per cent on unprotected Forest Service land, and 15 per cent on protected land.

1. Introduction

Closed canopy mature and old-growth conifer-dominated forests of the Pacific Northwest (PNW) region of the United States have high ecological, commodity and non-commodity values and, not surprisingly, their conservation and management have been extremely controversial. A major contributor to the controversy has been lack of information about the amount and distribution of these ecosystems over the landscape. Remote sensing, particularly with the use of satellite images, holds considerable promise to assist in mapping the distribution of forest conditions in the region and resolve controversies about the conservation and management of old forest ecosystems. Recognizing this, both public land management agencies and conservation groups have recently used satellite imagery to estimate the amount, and map the locations, of old forest systems on public lands in the PNW region (Morrison *et al.* 1991, Congalton *et al.* 1993). Although these independent efforts demonstrated the potential value of remote sensing as a management tool in the PNW, and may have narrowed the uncertainty about the amount of mature and old forest in the region, the estimates differ by as much as over 100 per cent depending on the definition used and the public planning unit surveyed (Table 1). These differences in estimates are partially due to differences in definitions, with the remainder probably a result of major differences in data sources and methodologies used. While these application experiences are valuable to help define the role of remote sensing in management of PNW ecosystems, a strong research component is needed to test, compare, and explore potentially useful data sources and methods, and to provide detailed descriptions of methods and accuracy in the scientific literature. Even more fundamentally, research can help bring about an understanding of the basic reflectance characteristics of ecosystems in the region, and how these characteristics change with forest structure and composition. Such directed research can also help identify important limitations in the application of different types of current satellite data and methods of analysis.

1.1. *Important problems*

As closed canopy conifer forests mature, from young to old-growth, a large number of structural and compositional canopy attributes change, including tree

Table 1. Acres of old-growth (Congalton *et al.* 1993) and ancient forest (Morrison *et al.* 1991) on nine National Forests in the Pacific Northwest, as determined from remote sensing.

National forest	Congalton *et al.* (1993)[a]	Morrison *et al.* (1991)[b]
Olympic	147 650	189 500
Mt. Baker-Snoqualmie	725 280	585 700
Gifford Pinchot	447 150	341 900
Mt. Hood	363 250	334 500
Willamette	783 550	605 000
Siuslaw	91 860	133 700
Umpqua	619 340	306 300
Rogue	267 950	150 100
Siskiyou	277 890	332 400
Total	3,723 920	2,979 100

[a] Definition used was designed to mimic the canopy characteristics of old-growth, as described in USDA Forest Service, 1986, Research Note PNW-447.

[b] Definition used was broader than that of Congalton *et al.* Included are forests meeting the Congalton *et al.* standards, plus some young and mature forests with residual old trees. For differences in methodologies and data see sources of these studies.

size, variation in tree size, tree density, tree species, crown vigour, and cover of canopy lichen (Spies and Franklin 1991). Many of these vegetation changes are associated with habitat changes for vertebrate and invertebrate organisms (Ruggiero *et al.* 1991, Schowalter 1989). Consequently, maps of closed canopy forests that will be useful for conservation and ecosystem management should contain several classes of age and structural attributes to make them useful in habitat analysis and planning. However, as the number of classes of an attribute increases, the accuracy associated with that classification and map is expected to decline. No published information is available to indicate the remote sensing classification error per centages for different numbers of attribute classes from PNW forest types.

Using remote sensing to analyse map characteristics of closed canopy mature and old-growth conifer forests in the PNW region presents several challenges. Once canopy closure occurs, leaf area index (LAI) is relatively high (8 or more) and continued changes in LAI with succession are apparently small (Marshall and Waring 1986). Nonetheless, gradual but ecologically important changes in canopy structure and composition continue for at least 400 years (Spies and Franklin 1991). As mature canopies develop into old-growth, the proportion of shadow in the stands increases as a consequence of increasing area, depth, and size of gaps, and stands become virtual light traps. Thus, variation in reflectance as closed canopy forests mature is subtle. The situation is further complicated by the fact that the steep mountainous terrain of the region causes topographic influences to dominate the spectral signature of images (Walsh 1987, Cohen and Spies 1992).

Although reflectance changes in relation to variations in stand age and structure are subtle and influenced by topography, we recently demonstrated that certain spectral characteristics of stands in the western hemlock/Douglas-fir zone (the dominant forest zone in the region) predictably change in relation to age and structure (Cohen and Spies 1992, Cohen, in press). Likewise, at fine spatial scales the spatial distribution of reflectance in forest stands is related to age and structure (Cohen *et al.* 1990, Cohen and Spies 1992). Models developed to estimate forest age and structure from both SPOT HRV panchromatic and Landsat-TM imagery revealed that both the spectral properties of TM data and the spatial properties of HRV should enable accurate estimates of closed canopy conifer age and structural attributes. Refinement and use of these models would provide a test of this hypothesis.

Most of the interest in mature and old-growth forests in the PNW region has concentrated on public lands. However, there is growing recognition that ecological conditions on the public lands are influenced by forest conditions on adjacent private lands (FEMAT 1993). In a recent study of the structure and dynamics of closed canopy conifer forests, Spies *et al.* (1994) found large differences between public and private land in the rates and patterns of logging over a 16-year period in a relatively small (258 930 ha) PNW landscape. No studies in the region have characterized amounts and distributions of more than two forest classes for large multi-ownership landscapes.

1.2. *Objectives*

Our general objective in this study was to extend the modelling effort of Cohen and Spies (1992) to a larger study area and a broader range of pre- and post-canopy closure stands, and to develop a map for use in estimating forest age and structure across multiple ownerships. Specific objectives were to: (1) develop an empiricallybased Landsat-TM classification strategy for forest age and structure in pre- and post-canopy closure stands; (2) determine the accuracy associated with different numbers of classes of structural attributes; and (3) map and characterize the landscape cover conditions for a multi-ownership area in western Oregon.

2. Methods

2.1. *Study area*

This study encompasses a 1 237 482 ha area in west-central Oregon and consists of much of the Willamette National Forest, numerous tracts of other publicly owned forestland, large tracts of privately owned forestland, and agricultural land (figure 1). Many of the major forest types of the central and northern Cascade Range are represented, including the western hemlock/Douglas-fir, Pacific silver fir, and mountain hemlock forest zones (Franklin and Dyrness 1988). Western hemlock/Douglas-fir forests dominate the lower elevation range from the Willamette Valley fringe, at $\sim$315 m up to between 1100 m and 1250 m, with the other forest types dominating at higher elevations. Agricultural lands predominate below 315 m elevation.

2.2. *Reference data*

The primary emphasis of our research has thus far been on closed canopy conifer stands. In Cohen and Spies (1992), ground reference data from 41 closed canopy western hemlock/Douglas-fir stands from 5 ha to 25 ha in size were used to develop remote sensing models. For the present study, an additional set of 65 closed canopy conifer stands were sampled on the ground in the same manner as the original ground reference set (Spies and Franklin 1991). This second ground reference set came from stands that were well distributed across the forested portion of the study area (above 315 m elevation), and from all three major forest zones (figure 1). From these 106 ground reference stands, stand age and several structural attributes were calculated, including mean and standard deviation of three tree size measures (tree bole diameter at breast height, crown diameter and total height), tree density, basal area and a structural complexity index described by Cohen and Spies (1992). All stand summaries, except the standard deviation measures, were derived from dominant and codominant trees only, as reflectance from lower canopy layers is unlikely to reach the satellite sensor. To help with classification of the TM imagery into land cover classes we referenced a set of 1:60 000 colour-infrared aerial photographs obtained in July 1988. These photos were used both to help interpret spectral clusters derived from an unsupervised classification and to assess accuracy of cover class mapping.

2.3. *Image processing*

A single TM image acquired on 31 August 1988 (WRS 46/29) was used in this study. Prior to analyses, the image was resampled to a 25 m cell size using nearest neighbour rules and was transformed into the brightness, greenness, and wetness axes of the TM Tasseled Cap (Crist *et al.* 1986). The Tasseled Cap is a guided principal components analysis using a Gram-Schmidt orthogonalization procedure, which results in a standard, or fixed, transformation (Freiberger 1960, Kauth and Thomas 1976).

Previous work (Cohen and Spies 1992, Fiorella and Ripple 1993) showed that the wetness index was valuable for discrimination within the closed canopy forest condition. In addition, wetness is nearly insensitive to topographic variation.

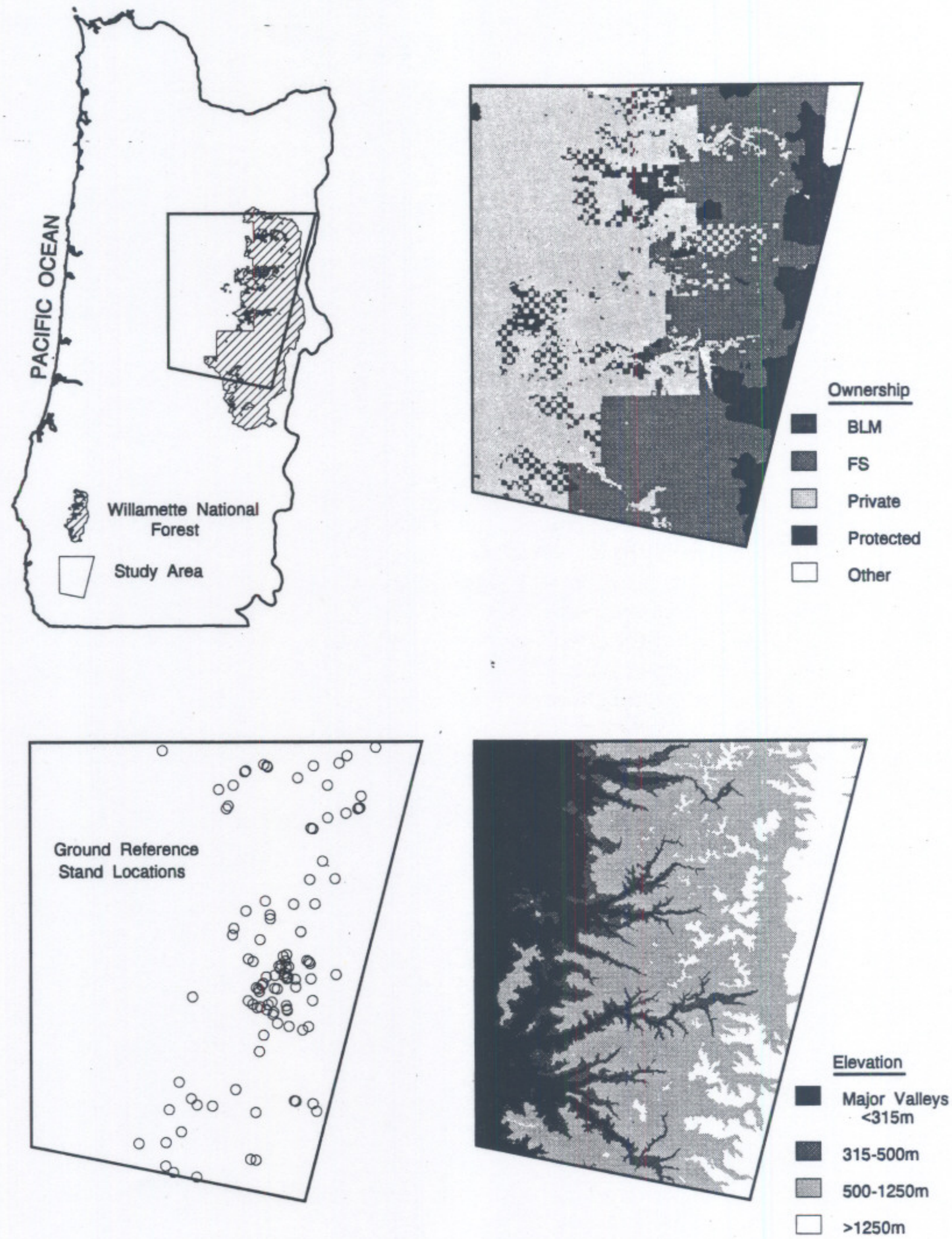


Figure 1. Location of study area in western Oregon, with enlargements showing the location of the 106 ground reference stands, land ownership classes (where BLM is the USDI Bureau of Land Management, FS is USDA Forest Service, Private is land not held in the public trust, Protected is all congressionally designated wilderness and administratively designated Research Natural Areas, and Other is all land administered by other public agencies), and elevation ranges (major agricultural valleys are restricted to areas below 315 m).

Assessment of brightness and greenness images revealed that they captured the majority of the remaining spectral variation associated with other forest conditions, albeit they are, like all of the original TM reflectance bands, highly sensitive to topography (Cohen and Spies 1992). To determine the actual proportion of the original six band TM spectral variation that was contained in the Tasseled Cap indices we calculated the variance in each TM band and the proportion of that total variance that was in each Tasseled Cap index, of which there are six (Crist *et al.* 1986). For comparison with principal component analysis (PCA) axes, original TM variation contained in the six PCA axes also was calculated.

We used the unsupervised classification algorithm called CLUSTR (ERDAS 1993) with the Tasseled Cap images to separate closed canopy conifer stands from several other cover classes. Cover classes associated with spectral clusters were identified using the airphotos and substantial ground knowledge. This process identified several spectral clusters that were confused among two or more cover classes. As a result, the image pixels representing these clusters were reclassified with CLUSTR. Reclassification was done iteratively to further refine informationally-confused clusters until satisfactory results were obtained. Using a 1:25 000 digital elevation model (DEM) we determined that agricultural activity was confined almost exclusively to elevations below 315 m. Using this elevation as a threshold, several spectral classes were stratified into agricultural and forest classes. One of these same classes consisted of rock outcrops (associated with major lava flows in a confined high elevation region of the study) and recently cleared forest. Using the airphotos as reference, we further stratified this class into forest and lava classes.

Cover classes representing forest conditions were quantitatively defined in terms of per cent cover of vegetation. For each of the non-closed canopy conifer classes 25 well-distributed stands from 5 ha to 25 ha were identified in the cover map and compared to the airphotos using a per cent cover template. From this exercise percentage cover bounds were defined for each class. For one of these classes (closed hardwood/conifer mix), using the photos we divided the per cent cover estimate into proportion of conifer and proportion of hardwood vegetation. The per cent cover of the closed canopy conifer class was quantified by evaluating one half of the ground reference stands on the airphotos. For this class also, the proportion of conifer versus hardwood was noted. Due to the scale of the photos and the size of trees and shrubs present, this separation proved impossible using the airphotos for the other forest classes.

For the closed conifer class we used regression analysis to develop models for estimating stand age and structural attribute values. In Cohen and Spies (1992) brightness and greenness were strongly influenced by topographic variation, or more precisely, cosine of the solar incidence angle. Correcting brightness and greenness values for incidence angle effects (Smith *et al.* 1980) did not improve their relationships with stand attributes, which is likely due in part to the non-Lambertian behaviour of forest canopies. For this study, an approach similar to that of Strahler (1981) was taken to improve the potential for reliable models using brightness and greenness. From the 1:250 000 DEM coregistered to the TM data, a cosine incidence angle image was created, and the 106 ground reference stands were stratified into three cosine incidence angle classes ($<0{\cdot}34$, 0·34 to 0·67, and $>0{\cdot}67$). Cohen and Spies (1992) showed that stand age is highly correlated to most of the stand attributes under study, and that of all these attributes age is the most highly correlated to TM spectral reflectance. Thus, in the present study stand age was used as a surrogate for all other attributes to determine the effectiveness of cosine incidence angle stratification on regression model predictions. To accomplish this, the 106 ground reference stands were ordered by stand age, all odd-numbered stands selected for model building, and all even-numbered stands selected for model accuracy assessment. Within the model building set separate models were constructed for each cosine incidence angle class and across classes for each combination of brightness, greenness, and wetness. In total 28 models were used, as defined by the four (incidence angle) by seven (vegetation index) matrix of possible combinations. Using the model strategy (i.e. stratification and vegetation index combination) that gave the highest accuracy for predicting stand age, regression models were developed and accuracy of predictions tested for all other attributes.

In Cohen and Spies (1992) we learned that there is little predictability in the spectral response of conifer forest stands beyond about 200 years of age, or once old-growth characteristics are attained. Forest stand conditions continue to evolve, but spectral changes appear uncorrelated with that development. When using all available data (including those of stands exhibiting old-growth characteristics) to construct regression models designed to distinguish among young, mature, and old-growth characteristics, the models generally overpredict successional stage of development. There is generally good distinction between old-growth characteristics and young and mature stand characteristics, but within the younger stands an overprediction bias is evident. To minimize this potential problem in our stand age estimates, the approach was modified as follows. The original, full model developed for the full spectrum of stand ages from near 20 to 700 years was first used to distinguish between old-growth and all younger forest stands. Then, a second, restricted model was constructed to more accurately distinguish between young and mature forests (up to 200 years of age). In practice, the full model was used to distinguish old stands from younger stands, then the restricted model was applied to those stands predicted from the first model as young or mature.

2.4. *Assessments of accuracy*

Accuracies of the percentage cover estimates for all forest classes resulting from the unsupervised classification were assessed using the airphotos and the percentage cover template used earlier. For each of the non-closed conifer classes an additional sample of 25 well-distributed stands was selected from the classified image, located on the airphotos, and percentage cover estimated. For the closed conifer class percentage cover of the remaining half of the ground reference set was assessed. For the closed conifer/hardwood mix and closed conifer classes percentages were segregated into conifer and hardwood proportions. Additionally, a few samples representing the non-forest classes above 315 m elevation were selected and checked on the photos.

For the closed canopy conifer class, accuracies were assessed for the regression models developed. Using the model accuracy assessment ground reference set, predicted versus observed values were compared. Each attribute evaluated consisted of continuous, rather than class values. Thus, to assess accuracy of the attributes, meaningful classes were designated—e.g., for stand age, which ranged from less than 20 to 700 years, classes were defined as young (<80 years), mature (80–200 years), and old-growth (>200 years). To determine the effect of the number of classes designated on percentage accuracy, accuracy assessment was done on two, three, and five classes for each attribute (table 2).

Table 2. Class boundaries for two, three, and five classes of each forest stand attribute evaluated. Age is stand age in years, DBH is tree bole diameter at breast height in centimetres, CD is tree crown diameter in metres, HGT is tree height in metres (sd represents standard deviation of tree size measure), Density is number of trees per hectare, BA is basal area in square metres per hectare, SCI is the Structural Complexity Index (see Cohen and Spies 1992).

Attribute	Two classes	Three classes	Five classes
Age	≤200, >200	<80, 80–200, >200	<40, 40–80, 80–120, 120–200, >200
DBHsd	≤25, >25	<15, 15–30, >30	<10, 10–20, 20–30, 30–40, >40
DBH	≤50, >50	<30, 30–70, >70	<25, 25–40, 40–60, 60–80, >80
CDsd	≤2·5, >2·5	<2, 2–3, >3	<1, 1–2, 2–3, 3–4, >4
CD	≤8, >8	<6, 6–10, >10	<5, 5–6, 6–8, 8–10, >10
HGTsd	≤15, >15	<10, 10–20, >20	<8, 8–12, 12–16, 16–20, >20
HGT	≤35, >35	<25, 25–45, >45	<20, 20–30, 30–40, 40–50, >50
Density	≤250, >250	<200, 200–400, >400	<100, 100–200, 200–300, 300–400, >400
BA	≤50, >50	<35, 35–60, >60	<25, 25–40, 40–55, 55–70, >70
SCI	≤(−)1, >(−)1	<(−)3, (−)3–1, >1	<2(−)4, (−)4−(−)2, (−)2–0, 0–2, >2

2.5. *Cover class distribution*

To characterize cover class distributions over the study area application of one of the regression models to distinguish among classes of closed canopy conifer was more desirable than relying on the single class representing this condition in the unsupervised classification map. We used the age models (full and restricted) to achieve this distinction among conifer stands. Using the initial land cover map as a mask, the Tasseled Cap wetness spectral values of all pixels classified as closed canopy conifer were isolated. The regression models were then applied to these pixels to predict age. The predictions of age were collapsed into young, mature, and old conifer classes.

Following refinement of the cover map, summaries of proportions of the study area in several classes were derived. Also, the ownership overlay of figure 1 was used to summarize forest cover class proportions by ownership category. The ownership categories evaluated include USDI Bureau of Land Management (BLM), USDA Forest Service, and other lands that are under the jurisdiction of miscellaneous government agencies (e.g., State of Oregon, Bureau of Indian Affairs, Armed Corps of Engineers) and unprotected from harvest activity, all public congressionally and administratively protected land (i.e., wilderness and Research Natural Areas), and private industrial and non-industrial lands.

3. **Results**

3.1. *Unsupervised classification*

Cover classes resulting from the unsupervised classification were water, snow/ice, open vegetation, semi-open vegetation, closed mix vegetation, and closed conifer forest. Snow and ice were restricted to a single location at the highest elevation range in the study area. The open, semi-open, and closed mix classes we found throughout the full elevation range. Closed conifer was mostly restricted to areas outside of the major valleys above 315 m. As described earlier, a 315 m elevation threshold was used to stratify agricultural fields from forestland, and airphotos were used to stratify lava flows from forestland. These operations caused the open vegetation class to be separated into open agriculture, open forest, and lava/rock classes. Similarly, the semi-open class was separated into semi-open agriculture, and semi-open forest, and the closed mix class was separated into closed agriculture and closed mix (hardwood/conifer) forest. Any closed conifer forest occurring in the valleys went unchanged.

The open and semi-open classes consisted of <30 per cent and 30–85 per cent vegetation cover, respectively. These are forest stands that had recently been severely disturbed, either from logging or wildfire, or that were growing on poor, rocky sites. The closed hardwood/conifer mix and closed conifer forest classes both had >85 per cent cover. The difference between these is that the latter consisted almost exclusively of conifer, whereas the former had at least 10 per cent of its total cover in hardwood species.

3.2. *Interpretations of Tasseled Cap Indices*

Most of the spectral variation in TM data of the study area is contained in band 4, the near-infrared band (table 3). Band 5, one of the mid-infrared bands, contains much of the remaining spectral variation. Between these two bands, almost 85 per cent of the total spectral variation was represented. Not unexpectedly, the first PCA axis contained almost as much as bands TM bands 4 and 5 together (80 per cent).

Table 3. Percentage of total image variance contained in each of the original TM bands (numbers 1–5 are the TM bands 1–5, number 6 is TM band 7) of imagery used in this study, the Principal Component Analysis axes derived from the original bands, and the Tasseled Cap axes derived from the original bands (number 1 is brightness, 2 is greenness, 3 is wetness, and 4–6 are the Tasseled Cap features 4–6).

No.	TM Band	PC Axis	TC Index
1	3·59	80·38	57·86
2	1·57	16·49	19·25
3	3·87	2·51	7·49
4	48·01	0·37	0·87
5	36·67	0·18	0·55
6	6·29	0·07	0·12
Total	100	100	86·15

The second PCA axis accounted for most of the remaining spectral variation. Brightness, the first Tasseled Cap index accounted for almost 58 per cent of the original spectral variation, whereas, greenness (the second axis) and wetness (the third axis) contained 19 and 7·5 per cent, respectively. The total variation accounted for by all six Tasseled Cap indices was only 86 per cent.

In figure 2 the effect of changing land cover on the Tasseled Cap axes can be readily seen. In figures 2(*a*), (*b*) and (*c*), brightness, greenness, and wetness, respectively, are illustrated. In figure 2 (*d*) brightness is displayed through the colour red, greenness through green, and wetness through blue. Bare soil, as in the sand beach around the reservoir (the linear, almost black feature on the upper-left side of the images), and the new clearcuts and rock outcrops, are devoid of vegetation, and in figure 2 (*d*) appear bright red. As vegetation begins to grow, greenness increases and the colour changes to orange (brightness plus greenness). A completely closed deciduous stand appears bright yellow, as greenness and brightness are about equal, and wetness is relatively low. Young conifer stands are only moderately bright and green, but are extremely wet. This causes them to appear a whitish-blue in figure 2 (*d*). Once a conifer stand begins to mature it becomes less wet, and thus a darker blue in the colour composite. Topographic effects on brightness and greenness can be readily seen as variations in colour intensity, especially within the conifer forests on the right-hand side of the images. In the colour composite (figure 2 (*d*)), intensity variations are due to this effect on brightness and greenness, not on wetness, as it might appear. Figure 2 (*c*) clearly supports this claim, as no substantial topographic effects are evident. Wetness, as the term would imply, is sensitive to water in the scene (Crist *et al.* 1986). This would cause one to believe, however, that water should be the 'wettest' component of the scene. Obviously, this is not so, as the lake in figure 2 has only moderate wetness values, whereas young forest plantations clearly have the highest wetness values. Furthermore, snow and ice, and clouds (not shown), have even higher wetness values than plantations.

Locations of the four forest classes defined during unsupervised classification, as well as typical successional trajectories for conifer dominated and hardwood dominated stands, are shown in figure 3. Each of the four classes tends to occupy its own area of Tasseled Cap space. Open forest stands, revealing little more than soil, have low greenness, varying mostly along the brightness and wetness axes, the actual location depending on soil brightness and moisture (Musick and Pelletier 1988). Increasing green vegetation (as represented by semi-open forest) causes an image pixel to go off of the soil line (brightness axis, in the Plane of Vegetation), and traverse along the greenness axis toward higher values. Similarly, higher wetness values are achieved. The semi-open forest class occupies the more centrally located portion of Tasseled Cap space, the precise location of a particular semi-open condition being dependent on soil background, proportion of vegetation cover, and foliage type and physical or phenological condition. Closed hardwood/conifer mix stands tend to have the highest greenness, moderate brightness, and relatively high wetness. Increasing proportion of hardwood causes higher greenness and brightness and lower wetness. Closed canopy conifer forests occupy only a small fraction of the full volume of Tasseled Cap space. The wettest, brightest, and greenest of these stands are young, vigorous, dense conifer forest plantations. As conifer stands age, their canopies become covered with lichens, branches and tops begin to die, and proportion of shadow increases, causing them to become less bright, green, and wet. With increasing shade the three axes converge, inhibiting the separation of soil and vegetation. If a forest stand is clearcut or otherwise severely disturbed, it would instantaneously return to near its origin on the soil line. In the absence of severe disturbance, several alternate trajectories through Tasseled Cap space are possible, and the time spent in different sections of a given trajectory are variable (table 3).

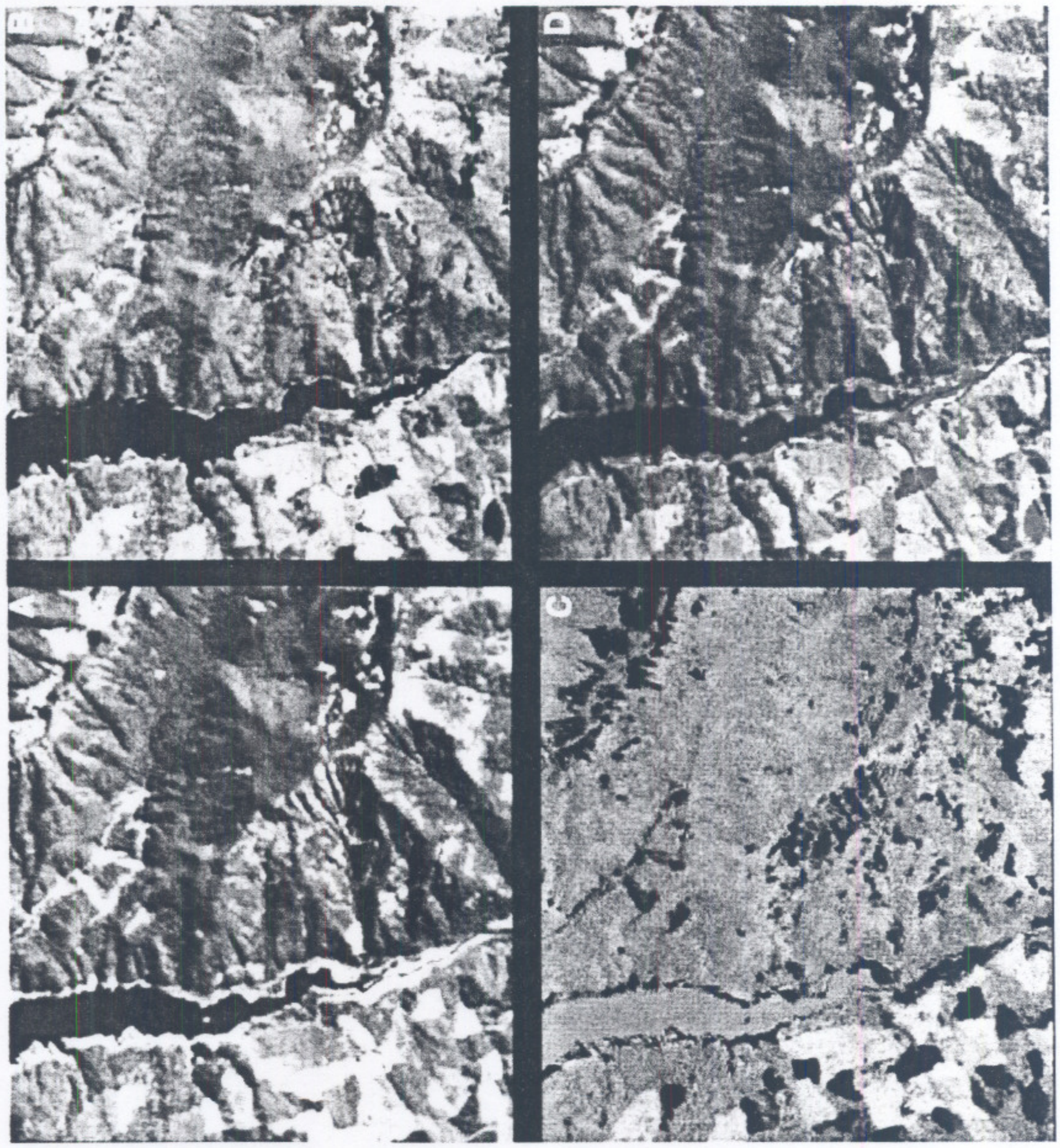
3.3. *Tasseled Cap responses in closed conifer forests*

Within closed canopy conifer forest stands of the PNW region wetness was more strongly related to all attributes than brightness and greenness (table 4). Brightness was least strongly correlated to all attributes. For all three vegetation indices, stand age exhibited the strongest relationship. Most other attributes were about equally related to each index, except basal area for greenness and wetness, which was less correlated than other attributes. The influence of cosine of the solar incidence angle on wetness was minimal (table 4). Brightness is the most responsive index to incidence angle.

Using stand age as a surrogate for all other attributes we can see the effect of cosine of the solar incidence angle on vegetation indices (figure 4). For both brightness and greenness the correlation with stand age is essentially the same for the lowest illumination class (#1) as it is across illumination classes. For the two higher illumination classes (#'s 2 and 3) the relationship between stand age and brightness and greenness is significantly improved by incidence angle stratification. For all indices the moderate illumination class (#2) shows the best improvement in correlation with stand age. For wetness the improvement for class #2 is less significant than for brightness and greenness. Furthermore, for wetness, the correlation in relation to stand age actually increases for class #1 and decreases for class #3.

3.4. *Conifer attribute regression models*

Whether stratification by cosine of the solar incidence angle class improved the overall stand age regression model prediction accuracy in closed conifer forests was dependent on the vegetation index combination used and number of age classes defined (table 5). The highest accuracy for two age classes (⩽200 years, and >200 years) was 81·1 per cent, which occurred for wetness alone, with and without incidence angle stratification, and for some other index combinations when wetness


B
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C

was included. For three age classes (<80 years, 80–200 years, and >200 years), the highest accuracies were obtained for wetness alone, with a slightly higher accuracy across incidence angle classes (73·6 per cent versus 71·7 per cent). Overall, there was small, or no, improvement in a model's performance with stratification.

The above results led to the construction of regression models to predict all attributes of interest based solely on wetness across solar incidence angle classes (table 6). None of the models provided particularly strong predictions, as revealed by their coefficients of determination. In Cohen and Spies (1992) similar models had higher coefficients of determination, but this was due largely to the more limited range of stand conditions sampled with the original ground reference data set.

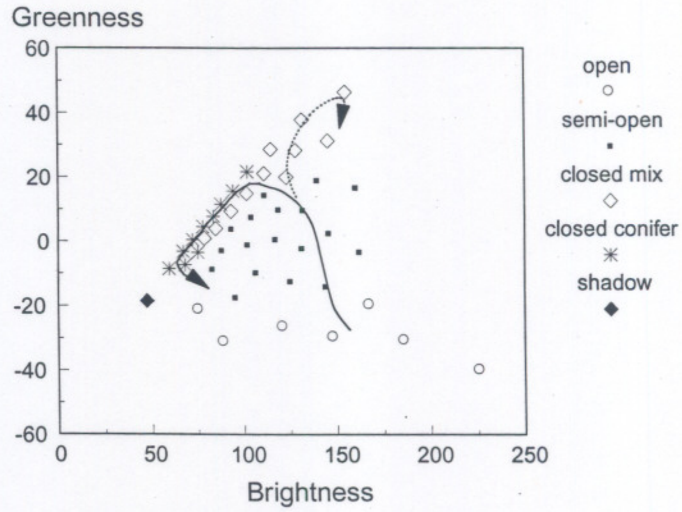
The accuracy of the classification declined rapidly for all closed conifer attributes as the number of classes increased. Two classes could be estimated with at least 77 per cent accuracy for all attributes except basal area (figure 5). Two classes of diameter at breast height and the structural complexity index were estimated with nearly 90 per cent accuracy. Definition of three attribute classes reduced accuracies to as low as 45 per cent. For stand age, density, and the structural complexity index, three classes were estimated with nearly 70 per cent accuracy. Definition of five attribute classes dropped accuracies to below 50 per cent for all attributes, and to less than 40 per cent for most.

3.5. *Land Cover*

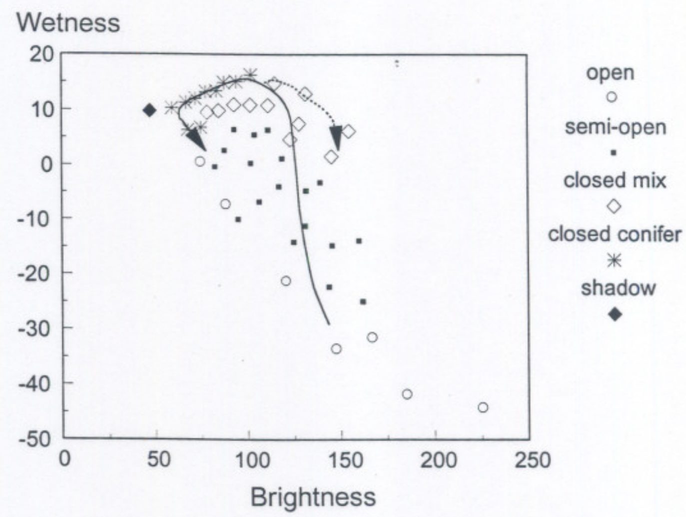
Land cover of the study area is shown in figure 6. The area consisted of 21·5 per cent agricultural land and 76·1 per cent forestland (table 7). Less than 3 per cent of the image was water, snow/ice, and lava/rock. Of the forestland, 70 per cent was in closed canopy conifer forest. The most abundant forest vegetation classes were semi-open and old-growth conifer. Of all forestland, 42 per cent was mature and old-growth. Overall accuracy for the non-agricultural classes of the cover map was 82 per cent (table 8).

The distribution of cover classes across the study area was spatially heterogeneous (figure 6). This unsmoothed map reveals considerable fine-grained, pixel-level variation, associated with within-stand compositional and structural variation. At larger scales aggregations of vegetation classes are evident, with strong zonation from west to east across the study area. These coarser-scale patterns reflect land use/ownership and environmental patterns. The agricultural areas of the Willamette Valley and its lower elevation tributaries on the west side of the map are largely devoid of green vegetation at this time of year (late August) because of plant senescence or crop harvesting. Most of the lower elevation forestland in the study area, which is privately owned (see figure 1) and managed for timber production, is characterized by relatively high amounts of young conifer and pre-canopy closure forest. In the eastern portion of the study area, which is primarily public ownership and managed on longer rotations than private lands or is protected from timber harvest, mature and old-growth forests are most common. The extreme eastern portions of the study area, which largely are high elevation wilderness areas, are

Figure 2. Tasseled Cap vegetation indices from a representative forest landscape in the study area: (A) Brightness, (B) Greenness, (C) Wetness, and (D) Colour composite, with brightness in red, greenness in green, and wetness in blue.



(*a*)



(*b*)

Figure 3. Actual locations of forest cover class clusters resulting from unsupervised classification in Tasseled Cap space, and hypothetical forest successional trajectories through Tasseled Cap space. Note that in (*a*) the brightness-greenness plane (Plane of Vegetation), and in (*b*) the wetness-brightness plane (Plane of Soils) all defined classes occupy relatively unique portions of spectral space. The solid line in both (*a*) and (*b*) represents a hypothetical successional trajectory for conifer-dominated stands, whereas the dotted line represents an alternative trajectory leading to hardwood domination. In reality, there are several possible trajectories, depending on disturbance, site, and climate conditions. Downward pointing arrows indicate hypothetical directions of pathways back to the origin. Pathways are not linear with respect to time. See text for percentage cover bounds on the forest classes.

Table 4. Correlation coefficients for the relations of conifer stand attributes and cosine of the solar incidence angle (cosine SIA) with brightness, greenness, and wetness. Age is stand age in years, DBH is tree bole diameter at breast height in centimetres, CD is tree crown diameter in metres, HGT is tree height in metres (sd represents standard deviation of tree size measure), Density is number of trees per hectare, BA is basal area in square metres per hectare, SCI is the Structural Complexity Index (see Cohen and Spies 1992).

Attribute/site	Brightness	Greenness	Wetness
Age	0·625	0·735	0·801
DBHsd	0·452	0·580	0·686
DBH	0·465	0·585	0·740
CDsd	0·406	0·534	0·678
CD	0·523	0·621	0·723
HGTsd	0·436	0·565	0·691
HGT	0·459	0·581	0·682
Density	0·411	0·564	0·690
BA	0·430	0·474	0·486
SCI	0·456	0·581	0·697
cosine SIA	0·572	0·456	0·032

comprised of closed canopy subalpine conifer stands, sparsely vegetated subalpine parklands, lava fields, and glaciers.

Of the total forestland of study area, over 35 per cent was privately owned. Unprotected forestlands administered by the BLM and the Forest Service, respectively, were 8 and 45 per cent. Ten per cent of total forestland in the study area was in protected status, but forestland was only 88 per cent of the total protected area. Most of the remaining 12 per cent was lava and rock, with small amounts of water,

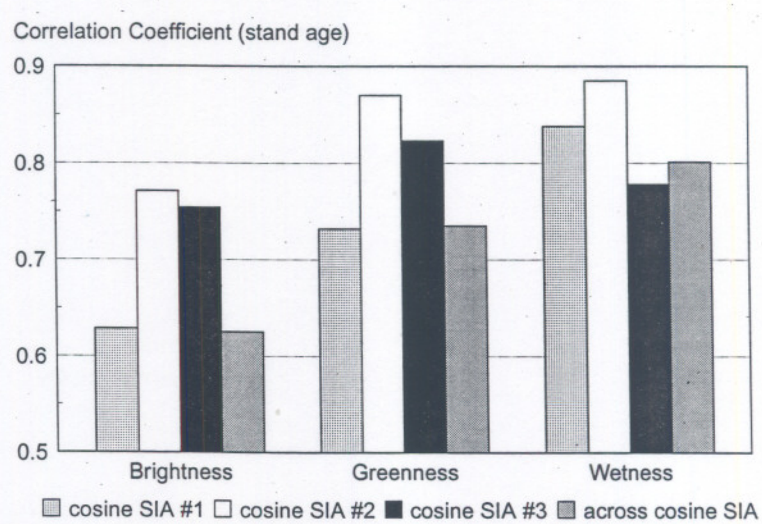


Figure 4. Relationship between Tasseled Cap spectral indices and conifer forest stand age as a function of cosine of the solar incidence angle (cosine SIA). Class #1 is <0·34, #2 is 0·34 to 0·67, and #3 is >0·67).

Table 5. Percentage correctly classified for two and three classes of conifer stand age, by cosine of the solar incidence angle (SIA) class and across cosine SIA classes, for models based on different combinations of brightness, greenness, and wetness.

	Stratified by cosine SIA class		Not stratified by cosine SIA class	
Indices	Two age classes	Three age classes	Two age classes	Three age classes
Brightness (B)	71·7	50·9	62·3	50·9
Greenness (G)	71·7	56·6	73·6	56·6
Wetness (W)	81·1	71·7	81·1	73·6
B,G	73·6	52·8	73·6	60·4
B,W	81·1	64·2	77·4	64·2
G,W	79·3	64·2	81·1	67·9
B,G,W	81·1	66·0	79·3	67·9

and snow and ice. The land ownership category other represented only 2 per cent of the total forestland.

Land ownership categories differed substantially in relative abundance of forest cover types (figure 7). Private lands consisted primarily of pre-closed canopy and young conifer forest (73·4 per cent), reflecting the short rotation (less than 80 years) timber management activities on this ownership category. The BLM and Forest Service had 63·1 and 49·15 per cent, respectively, of their unprotected land in pre-canopy closure and young conifer forest condition, reflecting moderately longer timber rotations (80 to 120 years), and the presence of riparian buffers, scenic corridors, and small wildlife habitat protection areas. Forest Service lands had higher proportions of old-growth and mature forest and lower proportions of earlier

Table 6. Regression models for conifer stand attributes predicted as a function of wetness. Age is stand age in years, DBH is tree bole diameter at breast height in centimetres, CD is tree crown diameter in metres, HGT is tree height in metres (sd represents standard deviation of tree size measure), Density is number of trees per hectare, BA is basal area in square metres per hectare, SCI is the Structural Complexity Index (see Cohen and Spies 1992). See text for discussion of full and restricted age models. All models are for the natural log of attributes, except for the SCI.

Attribute	Intercept	Slope	Coef. Det.	RMSE
In(Age)–full model	8·062	−0·250	0.659	0·570
In(Age)–restricted	6·572	−0·162	0·515	0·450
In(DBHsd)	4·709	−0·116	0·518	0·356
In(DBH)	5·377	−0·115	0·498	0·366
In(CDsd)	1·926	−0·079	0·494	0·254
In(CD)	2·875	−0·068	0·531	0·204
In(HGTsd)	3·700	−0·081	0·546	0·233
In(HGT)	4·514	−0·079	0·523	0·240
In(Density)	3·436	0·148	0·515	0·456
In(BA)	4·905	−0·087	0·300	0·421
SCI	6·286	−0·589	0·534	1·742

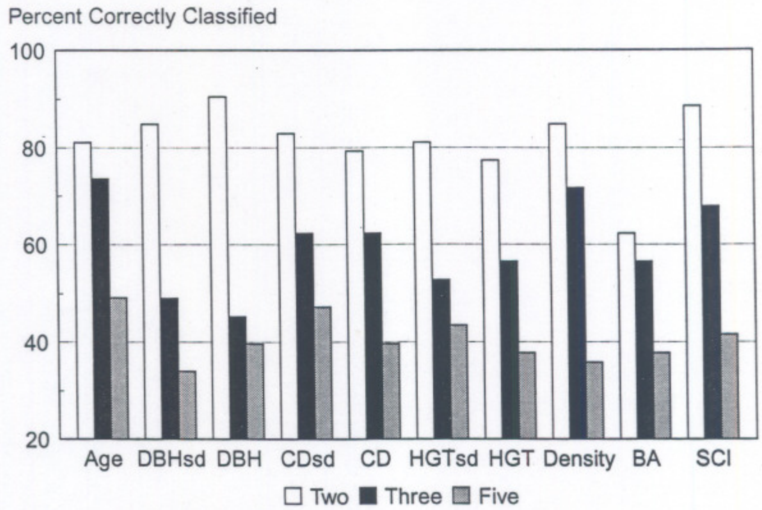


Figure 5. Effect of number of classes (two, three, and five) of conifer stand attributes on overall percentage correctly classified. Age is stand age in years, DBH is tree bole diameter at breast height in centimetres, CD is tree crown diameter in metres, HGT is tree height in metres (sd represents standard deviation of tree size measures), Density is number of trees per hectare, BA is basal area in square metres per hectare, SCI is the Structural Complexity Index (see Cohen and Spies 1992).

successional forest than BLM lands as a result of differences in either cutting or wildfire history, or both, in unprotected lands. Protected lands were dominated by mature and old-growth conifer (60·2 per cent). This is due largely to the existence of administratively and congressionally protected lands where no timber cutting occurs. Of all mature and old-growth forest, 22·1 per cent was found on private land, 7·1 per cent on unprotected BLM land, 55·4 per cent on unprotected Forest Service land, and 15·4 per cent in protected land.

4. Discussion

4.1. *Accuracy and class definition*

In this study an overall accuracy of 82 per cent was achieved in estimating forest cover classes. Although this may not be as high as ultimately desired, a perusal of related literature indicates that this level of accuracy is moderately high compared to results of many other forest classification studies. Several factors contributed to this. Most importantly, the forest cover classes, open, semi-open, closed mix, and closed conifer occupied nearly unique portions of Landsat-TM spectral space (figure 3). The minor cover classes water and snow and ice were well defined spectrally, and the lava/rock class, although spectrally confused with open forest, could be separated by its location in geographical space. The number of classes of closed canopy conifer that could be reliably estimated and mapped was low; between two and three, depending on error tolerance and attribute of interest. Identifying any more than three age classes would have seriously lowered the accuracy of the cover class map.

Congalton *et al.* (1993) and Morrison *et al.* (1991) mapped forest cover on nine National Forests in the PNW region. Both studies limited the number of classes to a minimum needed to estimate amounts, and map locations, of early and late

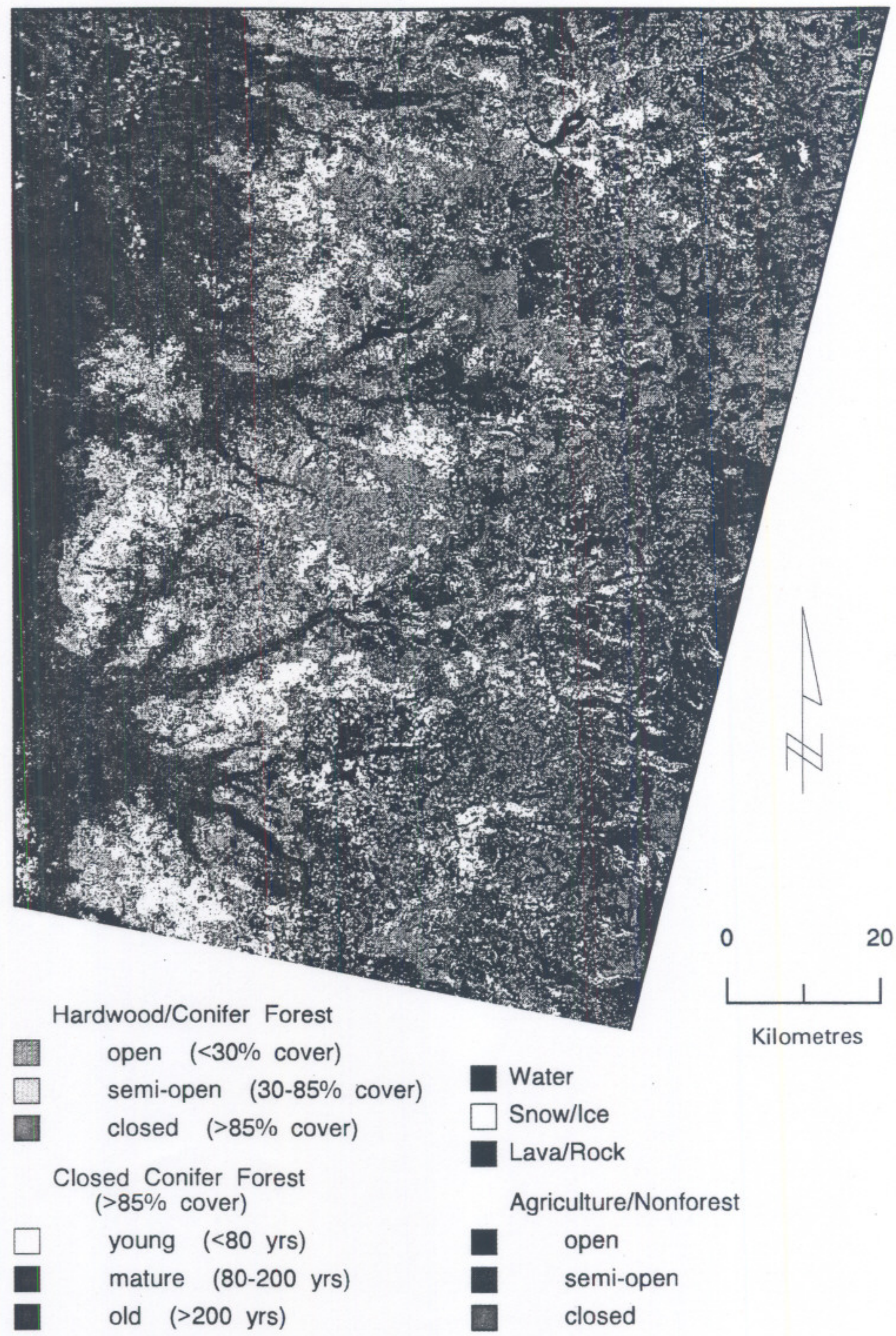


Figure 6. An August 1988 land cover map derived from the combination of unsupervised classification and regression model analysis (for conifer stand age).

Table 7. Number of hectares for each land cover class in the study area, and the percentage of total forest area represented by each forest class.

Class	Number of hectares	Percentage of total	Percentage of forest
Water	8045	0·65	
Snow/ice	444	0·04	
Lava/rock	21 434	1·73	
Open agriculture	122 022	9·86	
Semi-open agriculture	129 584	10·47	
Closed agriculture	14 178	1·15	
Open forest	51 005	4·12	5·41
Semi-open forest	252 320	20·39	26·79
Closed mix forest	64 206	5·19	6·82
Young conifer forest	178 459	14·42	18·95
Mature conifer forest	123 966	10·02	13·17
Old conifer forest	271 819	21·97	28·87
Total	1,237 482	100·00	100·00

Table 8. Error matrix for the land cover map. See text for descriptions of classes. Weighted by area of each class the accuracy for all classes was 80 per cent; the Kappa statistic was 79 per cent.

		PREDICTED									
		Water	Snow/ ice	Lava	Open	Semi- open	Closed mix	Young conifer	Mature conifer	Old conifer	Percentage correct
	Water	3									100
O	Snow/ice		2								100
B	Lava			2							100
S	Open				22	3					88
E	Semi-open				2	21	2				84
R	Closed mix					3	22				88
V	Young conifer							15	2		88
E	Mature conifer							2	9	5	56
D	Old conifer								5	15	75
	Percentage correct	100	100	100	92	78	92	88	56	75	82

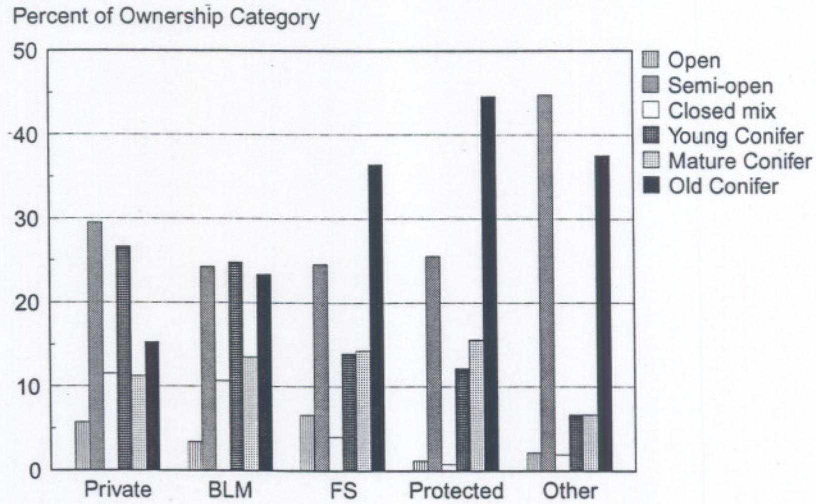


Figure 7. Distribution of land cover classes by ownership category (in percentage of ownership category).

successional forests. With such few classes, estimates of amounts, if not locations, of late successional forest by the two studies should have reasonably matched. In fact, their estimates for some national forests differed by as much as 100 per cent, and overall, Congalton *et al.* (1993) estimated that there was 25 per cent more late successional forest than Morrison *et al.* (1991) (table 1). This disparity occurred even though Morrison *et al.* (1991) used a more broad, and thus inclusive, definition of late successional forest. Although some of the difference is attributable to differing definitions, the effect of differences in methodologies and data sources is obvious. The most important lessons from a comparison of these two studies, however, are that the probability of classification error is substantial, and that what is needed is a standardized set of definitions and methodologies (realizing that both will need to evolve over time), as well as fully disclosed accuracies. Furthermore, it appears unlikely that acceptable classification accuracies will be achieved with large numbers of classes, such as the 120 crown closure-size-structure classes proposed by Congalton *et al.* (1993).

4.2. *Management implications*

We demonstrated that two or three structural classes of closed canopy conifer forest (e.g., young, mature, and old-growth) can be estimated and mapped with moderately high accuracies; however, no discrimination is likely for structural and composition canopy changes that occur after stands achieve old-growth conditions, which are characterized by high shadow and low reflectance. Maps with this limited number of classes will be useful for some purposes; for example, the habitat optimization model for northern California of Hof and Raphael (1993) relies on five classes of forest development: early regeneration, late regeneration, young closed canopy, mature closed canopy, and old-growth.

From a management perspective it is significant that although there was confusion between mature and old-growth and mature and young, there was none between old-growth and young. This is important because ecologically the two are more distinct than mature and old-growth. Also, the cost of confusion between old-growth and young is much higher than between mature and old-growth. This is true because if we map something as old-growth that is really mature, it can still support most old-growth species and will probably develop old-growth characteristics within 50 to 100 years, while mapping young as old-growth would mean that some old-growth species would not find suitable habitat in that area and it might be at least 75 to 150 years before it becomes suitable.

The fact that mature stands are less distinct than old-growth and young stands reflects the intermediate nature of the structure of this condition, which often has elements of both young and old-growth (Spies and Franklin 1991). Old-growth elements may represent surviving structures from partial burns, small scale disturbances that create gaps in younger aged stands, rapid canopy differentiation resulting from high productivity, mixed species conditions or patchy establishment that created heterogeneous stands early on.

Although we may be able to achieve a relatively high accuracy for mapping some characteristics of closed canopy forests, the map and accuracy is still probably not of sufficient quality for many management planning purposes. For example, we can not characterize understories, standing dead trees, species differentiation by spectral characteristics alone is improbable, and there will be problems detecting small features such as narrow riparian zones, which are ecologically important. Consequently, we may need to use such technologies as airborne video or data from new satellite sensors as they become available.

4.3. *Forest conditions in the study area*

Results of this study extend to a larger area the results of Spies *et al.* (1994), who focused on a 258 390 ha subset of this study area. Spies *et al.* (1994) considered only two cover classes (closed conifer forest and all else) and three ownership/land use classes (private, non-wilderness public, and wilderness). They found that, in 1988, 57·8 per cent of the total area was in the closed conifer state. This compares with 59·1 per cent found here, when agricultural lands are excluded. On public, non-wilderness lands, Spies *et al.* (1994) found that 68·4 per cent was closed conifer, compared to 64·3 per cent in this study, excluding the other land ownership category. The proportion of wilderness reported in the Spies *et al.* (1994) study that was in closed conifer forest is considerably higher (92·4 per cent) than that reported here (63·6 per cent). This can be explained by the fact that in their study the high Cascade Range was not evaluated. The high Cascades consist of a large proportion of land in lava flows and above timberline, whereas in other wilderness areas these proportions are less. Spies *et al.* (1994) found that on private land only 27·6 per cent was closed canopy conifer. We found that 46·2 per cent existed in this state. The discrepancy is most likely due to differences in the area sampled by the two study areas.

The land cover map reveals a complex pattern of forest development and condition classes associated with land use and environmental patterns. Landscape diversity is relatively high, in the sense that there are comparable proportions of closed canopy conifer forest and pre-closed canopy conifer forest. However, the forest conditions are not equally distributed across the environment—low elevations lack old-growth forests and mid to high elevations lack closed mix forest. The ecological diversity of a landscape and its capacity to support viable populations of sensitive species and maintain important ecological processes, is not simply a matter of obtaining equal proportions of habitat conditions across the landscape. Some early successional weed species are widely distributed and have good dispersal abilities, while some late successional species have restricted ranges and low dispersal abilities (Hof and Raphael 1993). Differences in species life history characteristics indicate that some habitat conditions should be weighted more heavily than others to maintain viability of a diversity of organisms. In addition, the abundance of habitat is not the only factor associated with population viability, for example the spatial pattern of the habitat, especially fragmentation can affect population dynamics. Consequently, the implications of the abundance and pattern of habitats that we have mapped to biological diversity and forest planning will require much more analysis than we have undertaken in this paper. However, our overall results indicate that late successional habitats are much more abundant on public lands than on private and that there are still relatively large areas of mature and old-growth forest left on public lands from which to build a strategy for maintaining these ecosystems and their species into the future. The results also indicate that old-growth forest ecosystems in low elevation environments are uncommon in the study area.

4.4. *Age as a forest attribute*

Although forest stand age is highly correlated to structural and compositional attributes (Spies and Franklin 1991, Cohen and Spies 1992), it is not itself one of these attributes. Physical stand attributes such as canopy closure and change from soil to vegetation, variations in density of conifer over deciduous species, changes in tree size and crown condition, and increases in shadow depth and extent, are all properties that affect reflectance. Age is a surrogate for these structural and compositional changes that occur with forest succession, but it does not in itself alter reflectance. This implies that models to estimate stand age in a given forest type will readily break down when applied to other forest types, or when applied in the same type where stands have been silviculturally treated or otherwise disturbed in ways that weaken the relationship between stand age and other attributes. Models for estimating attributes that more mechanistically alter reflectance are likely to be more robust.

4.5. *Choice of spectral variables*

In any TM data analysis, one is faced with the question of which bands to use, or what spectral indices to create. There are large numbers of users that employ the original TM bands, and those that use vegetation indices. For users of TM data that prefer the index approach, the NDVI (Rouse *et al.* 1974) is commonly chosen. However, as only two of the original TM bands are used in the NDVI, much of the original spectral information is discarded (nearly 50 per cent in this study). The Tasseled Cap is an important group of indices that was widely used in the 1970's and 1980's, but almost exclusively for agricultural applications. In forestry, brightness and greenness have been used by Li and Strahler (1985) and Hall *et al.* (1991). The Tasseled Cap indices preserve much of the original spectral information in TM data, and with the exception of wetness are clearly interpretable in physical terms. Tasseled Cap wetness is an important indicator of maturity and structure in closed canopy forest stands. As wetness is relatively insensitive to cosine of the incidence angle, it has definite advantages over other indices or original TM bands for some applications.

Wetness is probably not the best term for this third axis of the TM Tasseled Cap. The axis is clearly sensitive to moisture (Crist *et al.* 1986, Musick and Pelletier 1988, Cohen 1991), but water itself is only moderately wet. Rather, it appears to be the interaction of electromagnetic energy with the structure of the scene component and its water content that are responsible for the response of the wetness axis. For example snow, clouds, and conifer foliage are all wetter than lakes. In Cohen and Spies (1992) the term maturity index was proposed as a replacement term for wetness, but this is perhaps too exclusive of other scene features. A more appropriate term may be structure-wetness index, implying that both the structure of a scene component and its water content are important. Additional research on this important spectral index can help us understand more precisely the mechanisms driving its response.

5. Conclusions

Results of this study indicate that with an empirical classification strategy using Landsat-TM imagery, airphotos, digital elevation model data, and ground reference data, several land cover types and forest structural attributes can be estimated and mapped in western Oregon with a moderately high degree of accuracy. Only six forest cover classes were accurately estimated and mapped however, and although this limited number of classes may be useful for many purposes, other applications require significantly more classes. One way to improve this situation is to develop a fairly detailed mechanistic model that would require parameterization of proportions, spatial distributions, and reflectance properties of a number of scene components (e.g., a future generation Li and Strahler (1985) type model). More advanced analytical techniques such as mixture modelling (e.g., Smith *et al.* 1990) may also help, as will more powerful computing, and incorporation of more detailed ground reference data. However, even these embellishments would likely provide only small increments of success in accuracy and number of classes. A major limiting factor is probably in the nature of the TM data itself, having only six broad reflectance bands and a roughly 30 m spatial resolution. Higher spectral and spatial resolution imagery would likely provide more substantial gains in accuracy and number of classes, but processing that kind of data over large geographic regions will require innovative techniques and computational advances that take time to mature.

The TM Tasseled Cap contains most of the spectral variability in TM imagery and is a fixed transformation interpretable in biophysical terms. Although brightness and greenness are highly sensitive to topographic variation, they capture much of the spectral variability associated with major changes in cover type. Wetness is an important spectral variable for distinguishing among classes of closed canopy conifer forests, and the inclusion of brightness and greenness in predictive models, even when these are stratified by classes of illumination intensity, reduces the accuracy of classification. Although the wetness index is responsive to moisture in scene components, it appears more responsive to the interaction between the water content of the component and the structure of the component. Thus, the term structure-wetness, rather than wetness, more aptly describes this index.

For satellite remote sensing data to be more efficiently utilized in helping to solve natural resource issues in the Pacific Northwest, a standardized set of definitions of forest classes, across ownerships, is needed. Likewise, a standardized, unbiased set of remote sensing procedures (realizing that these will need to evolve over time) is needed for classification and accuracy assessment. From this multi-ownership study in the central Oregon Cascade Range, it appears that public lands, in 1988, contained significantly more late-successional forest than private lands, and that if this has not changed drastically since 1988, there are still relatively large areas of mature and old-growth forest remaining on public lands from which to build a strategy for maintaining these ecosystems and their species into the future.

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References

Cohen, W. B., 1991, Response of vegetation indices to changes in three measures of leaf water stress. *Photogrammetric Engineering and Remote Sensing*, **57,** 195–202.

Cohen, W. B., (in press), GIS applications perspective: current research on remote sensing of forest structure. In *Forest Ecosystem Management at the Landscape Level: the Role of Remote-Sensing and Integrated GIS in Resource Management Planning, Analysis, and Decision Making*. Sample ed. (Washington, D.C.: Island Press).

Cohen, W. B., and Spies, T. A., 1992, Estimating structural attributes of Douglas-fir/western hemlock forests stands from Landsat and SPOT imagery. *Remote Sensing of Environment*, **41,** 1–17.

Cohen, W. B., Spies, T. A., and Bradshaw, G. A., 1990, Semivariograms of digital imagery for analysis of conifer canopy structure. *Remote Sensing of Environment*, **34,** 167–178.

Congalton, R. G., Green, K., and Teply, J., 1993, Mapping old growth forests on National Forest and Park Lands in the Pacific Northwest from remotely sensed data. *Photogrammetric Engineering and Remote Sensing*, **59,** 529–535.

Crist, E. P., Laurin, R., and Cicone, R. A., 1986, Vegetation and soils information contained in transformed Thematic Mapper data. In *Proceedings, IGARSS '86 Symposium, Zürich, Switzerland, 8–11 September 1986* (Paris: ESA).

ERDAS 1993, *Earth Resource Data Analysis System*, Version 8.01, ERDAS Inc., Atlanta, GA.

FEMAT 1993, Forest Ecosystem Management: An Ecological, Economic, and Social Assessment, Report of Forest Ecosystem Management Assessment Team, USDA Forest Service, Ogden, UT.

Fiorella, M., and Ripple, W. J., 1993, Determining successional stage of temperate coniferous forests with Landsat satellite data. *Photogrammetric Engineering and Remote Sensing*, **59,** 239–246.

Franklin, J. F., and Dyrness, C. T., 1988, *Natural Vegetation of Oregon and Washington* 2nd edition (Corvallis, OR: Oregon State University Press).

Freiberger, W. F., 1960, *The International Dictionary of Applied Mathematics* (New York: Van Nostrand Co.).

Hall, F. G., Botkin, D. B., Strebel, D. E., Woods, K. D., and Goetz, S. J., 1991, Large-scale patterns of forest succession as determined by remote sensing, *Ecology*, **72,** 628–640.

Hof, J. G., and Raphael, M. G., 1993, Some mathematical programming techniques for optimizing timber age class distributions to meet multispecies wildlife population objectives. *Canadian Journal of Forest Research*, **23,** 828–834.

KAUTH, R. J., and THOMAS, G. S., 1976, The tasseled cap—a graphic description of the spectral-temporal development of agricultural crops as seen by Landsat. In *Proceedings on the Symposium on Machine Processing of Remotely Sensed Data*, 4b:41–51, 6 June–2 July 1976 (West Lafayette, Indiana: LARS, Purdue University).

LI, X., and STRAHLER, A. H., 1985, Geometric-optical modeling of a conifer forest canopy. *I.E.E.E. Transactions on Geoscience and Remote Sensing*, **23,** 705–721.

MARSHALL, J. D., and WARING, R. H., 1986, Comparison of methods of estimating leaf-area index in old-growth Douglas-fir. *Ecology*, **67,** 976–979.

MORRISON, P. H., KLOEPFER, D., LEVERSEE, D. A., SOCHA, C. M., and FERBER, D., 1991, *Ancient Forests in the Pacific Northwest* (Washington, D.C.: The Wilderness Society).

MUSICK, H. B., and PELLETIER, R. E., 1988, Response to soil moisture of spectral indices derived from bidirectional reflectance in Thematic Mapper wavebands. *Remote Sensing of Environment*, **25,** 167–184.

ROUSE, J. W., HAAS, R. H., SCHELL, J. A., and DEERING, D. W., 1974, Monitoring vegetation systems in the Great Plains with ERTS. In *Proceedings of the Third Earth Resources Technology Satellite-1 Symposium*, Goddard Space Flight Center, NASA SP-351, Science and Technical Information Office, NASA, Washington, D.C., pp. 309–317.

RUGGIERO, L. F., JONES, L. L. C., and AUBRY, K., 1991, Plant and animal habitat associations in Douglas-fir forests of the Pacific Northwest: an overview. In *Wildlife and Vegetation of unmanaged Douglas-Fir Forests*, edited by L. F. Ruggiero *et al.*, USDA Forest Service General Technical Report PNW-GTR-285, Portland, OR, pp. 447–462.

SCHOWALTER, T. D., 1989, Canopy arthropod community structure and herbivory in old-growth and regenerating forests in western Oregon. *Canadian Journal of Forest Research*, **19,** 318–322.

SMITH, J. A., LIN, T. L., and RANSON, K. J., 1980, The Lambertian assumption and Landsat data. *Photogrammetric Engineering & Remote Sensing*, **46,** 1183–1189.

SMITH, M. O., USTIN, S. L., ADAMS, J. B., and GILLESPIE, A. R., 1990, Vegetation in deserts: I. A regional measure of abundance from multispectral images. *Remote Sensing of Environment*, **31,** 1–26.

SPIES, T. A., and FRANKLIN, J. F., 1991, The structure of natural young, mature, and old-growth forests in Washington and Oregon. In *Wildlife and Vegetation of unmanaged Douglas-Fir Forests*, edited by L. F. Ruggiero *et al.*, USDA Forest Service General Technical Report PNW-GTR-285, Portland, OR, pp. 90–109.

SPIES, T. A., RIPPLE, W. J., and BRADSHAW, G. A., 1994, Dynamics and pattern of a managed coniferous forest landscape, *Ecological Applications*, **4,** 555–568.

STRAHLER, A. H., 1981, Stratification of natural vegetation for forest and rangeland inventory using Landsat digital imagery and collateral data. *International Journal of Remote Sensing*, **2,** 15–41.

WALSH, S. J., 1987, Variability of Landsat-MSS spectral responses of forests in relation to stand and site characteristics. *International Journal of Remote Sensing*, **8,** 1289–1299.