Semivariograms of Digital Imagery for Analysis of Conifer Canopy Structure

Warren B. Cohen and Thomas A. Spies
USDA, Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, Corvallis, Oregon

Gay A. Bradshaw
Oregon State University, Department of Forest Science and the Environmental Remote Sensing Applications Laboratory, Corvallis, Oregon

Semivariograms were used to exploit the spatial information inherent in digital imagery of a variety of Douglas-fir [Pseudotsuga menziesii (Mirbel) Franco] forest stands in the Pacific Northwest region of the United States. Calculations involved digital numbers from single transects of pixels representative of each stand and from a full spatial matrix of pixels from each stand. Digitized aerial video images having pixel sizes of 1 m, 10 m, and 30 m were used. At 1 m spatial resolution the ranges of the matrix semivariograms related to the mean tree canopy sizes of the stands. The sills responded to the presence of vertical layering in the canopies and to percent canopy cover. The transect semivariograms were less representative of overall stand structure, but exhibited periodicity that was suggestive of patterns in stand structure. Semivariograms based on 10 m and 30 m pixels contained significantly less useful information. The ranges of the 10 m matrix semivariograms revealed only whether the tree canopy sizes were less than 10 m or were between 10 m and 20 m. The sills were greatly reduced, but still related well to canopy layering and percent cover. Periodicity in the transect semivariograms was greatly reduced, and in some cases, eliminated. At 30 m resolution, only the sills of the matrix semivariograms contained useful information. However, actual differences between the sills were small.

INTRODUCTION

The structure of coniferous forest canopies in the Pacific Northwest region of the United States is a subject of widespread interest. Debate over the fate of old-growth Douglas-fir [Pseudotsuga menziesii (Mirbel) Franco] forests has focused re-
search and management attention on structural differences between old-growth and young forest stages (Spies and Franklin, 1988). Information about canopy structure is needed to improve understanding of stand and landscape structure and dynamics, and to develop suitable methods for the inventory and mapping of old-growth forests. Until recently, most research attention has focused on characterizing old-growth forest structure from ground-sample plots. However, this method is not amenable to large area analysis and inventory. Characterization of coniferous forest canopy structure using remotely sensed data may be a way to efficiently evaluate forest conditions over large areas.

Much of the work in remote sensing of forested ecosystems has been in the spectral domain. This commonly has involved the analysis of multispectral images using statistically based decision rules for determining the identity, with respect to forest stand characteristics of interest, of each pixel in the images. Often, however, spectral characteristics of individual stands are highly variable, depending on location in the stand (Woodcock and Strahler, 1987). This makes distinguishing among stands using spectral properties alone a difficult task. Because forest structure is a spatial phenomenon, classification schemes that operate in the spatial domain may yield more reliable estimates of forest canopy structure. Such schemes rely on geometric shapes, sizes, and patterns in the image data (Lillesand and Kiefer, 1987).

We used semivariograms to exploit the spatial information inherent in image data of conifer forest stands. The primary objective was to evaluate the potential utility of this technique for distinguishing among stands having different canopy structures. Digitized aerial videography, at a nominal 1 m pixel size, was used. As we also wanted to examine the potential utility of semivariograms for canopy structure analysis with SPOT HRV panchromatic and Landsat TM data, analyses were repeated after the video data were spatially degraded to 10 m and 30 m.

Semivariograms

A semivariogram is a graphical representation of the spatial variability in a given set of data. The semivariogram, or $\gamma(h)$, is calculated as

$$\gamma(h) = \frac{1}{2(n-h)} \sum_{i=1}^{n-h} [Z(x_i) - Z(x_i + h)]^2,$$  \hspace{1cm} (1)

where $h$ is the lag (or distance) over which $\gamma$ (semivariance) is measured, $n$ is the number of observations used in the estimate of $\gamma(h)$, and $Z$ is the value of the variable of interest at spatial position $x_i$ (Journel and Huijbregts, 1978). The quantity $Z(x_i + h)$ is the variable value at distance $h$ from $x_i$. Thus, for spectral data, $\gamma(h)$ estimates the variability of radiance, $Z$, as a function of spatial separation. The reliability of this estimate decreases with increasing lag because the number of observations used to estimate $\gamma(h)$ decreases with increasing $h$. For this reason, the maximum lag used to calculate $\gamma(h)$ should be between one-fifth and one-third the total distance over which the data were collected (Webster, 1985).

Typically, the shape of a semivariogram resembles one of three basic models. These include the exponential, linear, and spherical models, the latter being the most commonly used (Clark, 1979). In the spherical model $\gamma$ increases with $h$ until it reaches a maximum, or sill. The lag at which the sill is reached is called the range. The range and the sill are the two parameters of the semivariogram used to describe the data. The range can be used as a measure of spatial dependency, or homogeneity, whereas the sill reflects amount of variability. For a more in-depth discussion of semivariograms and related theory, see Matheron (1971), Journel (1989), Oliver et al. (1989a, b), and Webster and Oliver (1990).

The use of semivariograms in remote sensing is relatively new, but the technique is finding a wide variety of applications. Yoder et al. (1987) used the semivariogram to examine spatial scales of information in Coastal Zone Color Scanner imagery. Wald (1989) demonstrated the semivariogram's utility with thermal imagery for evaluating ocean turbulent energy transfer across spatial scales. Using radar data, de Miranda and MacDonald (1990) and Rubin (1990), respectively, demonstrated the potential utility of the semivariogram as the basis for a spatial classification technique and as textural classifier. Semivariograms have been applied to image resampling problems (Ramstein and Raffy, 1989), to designing sampling schemes for field radiometry (Webster et al., 1989),
for estimating the signal to noise ratio in hyperspectral imagery (Curran and Dungan, 1989), to determine the optimum spatial resolution for the remote sensing of conifer canopy structure in plantations (Atkinson and Danson, 1988), and to develop an optimal procedure for sampling remote sensing data prior to their storage and retrieval (Atkinson et al., 1990). Jupp et al. (1988a) demonstrated how the functional form of the relationship between the semivariogram of an image and the underlying scene covariance provides an analytical basis for scene inference. Jupp et al. (1988b) and Woodcock et al. (1988a, b) further explore this relationship using scene models and real images.

**METHODS**

**Description of Forest Stands**

To determine the potential utility of semivariograms for assessing conifer canopy structure from remote sensing data, five forest stands in the Willamette National Forest on the western slopes of the Cascade Range in Oregon were selected for study. Each stand had a different canopy structure and was similar to a type of stand sampled in a U.S. Forest Service study of forest structure (Spies and Franklin, 1990). The stands are dominated by Douglas-fir trees and are labeled here as young, mature, old-growth, young-mix, and mature-mix. The young and mature stands had relatively simple canopy structures and the old-growth and mixed stands had complex structures. The stands and their canopy structural attributes are summarized in Table 1 and are contrasted below.

<table>
<thead>
<tr>
<th>Stand</th>
<th>Spatial Pattern</th>
<th>Canopy Layers</th>
<th>Age (years)</th>
<th>Canopy Size (m)</th>
<th>Percent Cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young</td>
<td>uniform</td>
<td>single</td>
<td>80</td>
<td>10</td>
<td>high</td>
</tr>
<tr>
<td>Mature</td>
<td>uniform</td>
<td>single</td>
<td>140</td>
<td>10</td>
<td>high</td>
</tr>
<tr>
<td>Old-growth</td>
<td>clumpy</td>
<td>multiple upper, lower</td>
<td>450</td>
<td>15-20</td>
<td>moderate</td>
</tr>
<tr>
<td>Young-mix</td>
<td>clumpy</td>
<td>multiple upper, lower</td>
<td>400</td>
<td>15-20</td>
<td>low-moderate</td>
</tr>
<tr>
<td>Mature-mix</td>
<td>clumpy</td>
<td>multiple nondistinct</td>
<td>100-450</td>
<td>5-20</td>
<td>high</td>
</tr>
</tbody>
</table>

The young and mature stands had a single canopy layer with high percent cover of trees that were uniformly distributed. Tree size in these stands lacked significant variability. The primary difference between the stands was in the age and size of the trees. The old-growth stand had moderate percent cover in an upper canopy layer in which large trees occurred in clumps of various sizes and numerous gaps of various shapes and sizes were distributed throughout. The canopy gaps distinguished this stand from the other stands. In the gaps were trees similar in size and age to those of the mature stand. The mixed stands also had multiple canopy layers but their structures were considerably different from each other and from the old-growth stand. The young-mix stand had a canopy layer with high percent cover of trees. Towering above this canopy layer, in clumps of various shapes and sizes, were a significant number of remnant, old-growth trees. In this stand the lower canopy layer had trees with ages and crown diameters similar to those of the young stand and the upper layer had trees with ages and crown sizes similar to those of the larger trees in the old-growth stand. The mature-mix stand had high percent cover consisting of a mixture of tree sizes and ages. This stand was stocked with a large proportion of mature trees, but also had significant proportions of young and remnant old-growth trees. The canopy cover was distributed in clumps between several nondistinct canopy layers.

**Image Acquisition and Analysis**

We used low altitude vertical aerial videography in this study to examine forest structure. The data were obtained between 10:00 and 11:00 h local standard time using a Sony F40, 8 mm shuttered, true color video camera mounted on an MXL-Quicksilver ultralight aircraft. The camera had a 13 mm charge-coupled detector (CCD) and its focal length and shutter speed were set at 9 mm and 1/4000 s, respectively. During acquisition the aircraft flew at approximately 1000 m above the terrain, which varied in elevation from about 400 m to 1100 m.

After the flight, the video tape was viewed to select five images (frames), one for each forest
stand under study. Because the terrain at the
study site was variable, which could cause major
trends in the data, selection of images was guided
so that Matheron's (1971) intrinsic hypothesis of
stationarity was not severely violated. The selected
images were digitized into separate red, green,
and blue bands using a Matrox graphics board and
the Resource Analysis Software package from De-
cision Images. For each image, spatial resolution,
or pixel size \( P \) in meters, was calculated using the
equation
\[
P = \frac{(H \times w)}{f} / N,
\]
where \( H \) is the flying height (m) above terrain, \( w \) is the effective
width (mm) of the CCD in the focal plane of the
camera, and \( f \) is the lens focal length (mm). As
the quantity \( \frac{(H \times w)}{f} \) is the ground distance
across the image in a given dimension, dividing by
\( N \), the number of pixels in that dimension, gives
the width of the pixels. Because of variable terrain
and difficulties in maintaining a constant flying
height above terrain, actual pixel size was some-
what variable around a nominal 1 m. The range of
pixel sizes in the imagery was approximately
0.7–1.3 m. Visual examination of the images indi-
cated that pixel size variations were not significant
relative to stand structure characteristics. Each
image contained small proportions of neighboring
stands. Therefore, subsequent to pixel size calcula-
tions, and prior to calculating semivariograms, each
image was subset so that only the stand of interest
remained.

Semivariograms were calculated for each stand
using the digital numbers (DN) in the red band of
the images. The analysis was undertaken in two
separate ways: using single transects of pixel DN
(transect method) and using DN of the full two-
dimensional pixel matrices in the images (matrix
method). For the transect method a single, repre-
sentative row or column of pixels from each image
was chosen. The images did not have the same
number of pixels in the row direction as in the
column direction. Thus, for the matrix method a
single semivariogram was calculated for all row
transects and a single semivariogram was calcu-
lated for all column transects of each image. A
mean semivariogram for each image was then cal-
culated by averaging these two semivariograms,
weighted by the respective number of observa-
tions \((n-h)\) at each lag in the row and column
directions. Calculation of the matrix semivari-
ograms assumes a lack of anisotropy in the data.
Comparison of row semivariograms with column
semivariograms from each image prior to combing
them to obtain the mean semivariograms indi-
cated that anisotropy, primarily from differential
illumination due to topography, had an insignifi-
cant effect on the semivariograms.

To evaluate the potential utility of semivari-
ograms using SPOT HRV 10 m panchromatic and
Landsat TM 30 m data for analysis of canopy
structure, the calculations of transect and matrix
semivariograms were repeated after the video im-
ages were spatially degraded to 10 m and 30 m
pixel sizes. Degradation to 10 m was accomplished
—using methodology similar to that of Woodcock
and Strahler (1987)—by stepping a 10 by 10 pixel
window across each image and replacing the 100
DN in each window with their mean DN. The
resulting images had one-tenth the number of
rows and columns. Degradation to 30 m was ac-
complished by stepping a 3 by 3 pixel window, in
a similar fashion, across the 10 m images.

In geostatistical terminology, averaging over
areas is called **regularization**, which has the effect
of decreasing the overall variance in the variable
of interest. For remotely sensed images, the initial
unit of regularization is the instantaneous field of
view (IFOV) of the sensor, with the point spread
function (PSF) describing the form of the regular-
ization (Woodcock et al., 1988a). Because we are
not using a PSF, we are only simulating, not
replicating, the IFOV of the HRV and TM sensors.

**RESULTS AND DISCUSSION**

**Image Appearance**

Visual characteristics of the video images clearly
distinguish the five stands. These characteristics
can be described using standard air photo inter-
pretation parlance (Lillesand and Kiefer, 1987;
Paine, 1981). For the purpose of discussion we
define contrast as the abruptness of tonal change,
which can vary from low to high. A high contrast
image would have a large proportion of both bright
and dark tones with only a small proportion of
medium tones. A low contrast image would have a
high proportion of medium tones. Texture refers to
the frequency of tonal change, or "grain size" of
the distinguishable components in the image. Tex-
ture ranges from fine to coarse. Pattern refers to
the spatial arrangement of textural components in
Figure 1. Reproductions of the red band from digitized video images of the five conifer forest stands. The stands A) young, B) mature, C) old growth, D) young-mix, and E) mature-mix. Nominal pixel size is 1 m.
the image. Pattern is often difficult to objectively evaluate. We describe patterns in the images of this study as being either uniform or clumpy. A clumpy pattern suggests that textural components are aggregated. Clumps can occur in various sizes and shapes, in which case pattern becomes a function of scale. A uniform pattern suggests a lack of aggregation, and thus that pattern is not a function of scale.

The young and mature stands had a single canopy layer with high percent cover of relatively uniform size trees. The video images of these stands (Figs. 1A and 1B) have a corresponding low contrast and uniform pattern. The smaller tree crowns of the young stand gave the image of this stand a fine texture, relative to the medium texture of the image of the mature stand having larger trees.

The image of the old-growth stand (Fig. 1C) differs greatly from those of the young and mature stands. In this image only the upper canopy layer, consisting of groups of large tree crowns having moderate percent cover, can be clearly seen. Visible trees are brightly sunlit, whereas gaps between trees appear dark, giving the image a high contrast. The large tree crowns give the image a coarse texture, whereas the spatial distribution of trees and gaps give the image a clumpy pattern.

There are no distinctive gaps in the canopies of the mixed stands, but, under the conditions of illumination, tree crowns in the upper layers of these stands cast shadows on the shorter trees. Although tree shadows appear as dark in the images of these stands (Figs. 1D and 1E), as do gaps in the image of the old-growth stand, proportionally, the shadows cover significantly less of the images. As a result, the images of these stands have moderate contrast. Because these stands had mixed tree sizes and a clumpy arrangement of trees, their textures on the imagery are mixed and their patterns clumpy. The young-mix and mature-mix stands can be distinguished from each other on the imagery. The former has a distinctly bimodal texture and more clearly definable clumps, whereas the latter has multiple textures and the identification of tree clump boundaries, and therefore patterns in the stand, are largely subjective.

All forest stands except the mature-mix were on sloping terrain that was variable in both steepness and aspect among stands. To a lesser degree, similar within-stand variation in topography was present. Among-stand terrain variation means all stands were illuminated at different angles. Similarly, within-stand illumination angle was somewhat variable. Illumination angle interacts with stand structure influencing the radiance received by a nadir-looking sensor, and thus influencing the appearance of a forest stand on remote sensing imagery. Eby (1987) capitalized on this phenomenon to classify coniferous forest stands in the Washington Cascades. Variations in the signal received by a nadir-looking sensor resulting from the interplay of stand structure and illumination can be modeled, and therefore the effect better understood (Li and Strahler, 1985). In this study, we simply recognize the presence of this interaction and modify our interpretation of results accordingly.

**Transect Semivariograms (1 m Spatial Resolution Imagery)**

In graphical plots of the DN from the 1 m pixel transects (Fig. 2), peaks are associated with sunlit portions of tree crowns, and troughs, with shaded portions of the crowns and/or gaps between trees in the stands. As such, these plots illustrate the relationship between stand structure and image appearance.

The distances between successive troughs in the transect plots are associated with tree crown

![Figure 2](image-url)
sizes in the stands. Where troughs are not well pronounced, tree canopies may be overlapping in space. Focusing on the widths of the peaks in each transect, we see the relative sizes of tree crowns among stands and can appreciate the relative textures of the images. Variation in the width of peaks within a single transect illustrates tree crown size variation within a stand and thus textural variation in the associated image.

The ranges of DN in the transects illustrate the presence or absence of canopy layering in the stands. The young and mature stands, both of which have single canopy layers, have the smallest transect DN ranges. The transects DN ranges from the three multiple-layer stands are significantly greater than those of the single-layer stands. In the old-growth transect the pronounced troughs centered at 65 m, 145 m, and 370 m are associated with extended gaps in the canopy cover. As this is the only stand characterized by canopy gaps and moderate percent cover, one can see that the percentage of low DN in the transects relates to percent canopy cover in the stands. Because contrast in the transects, and thus the imagery, is partly a function of both the range of DN and the percentages of DN at both extremes of the range, we can see how contrast relates to canopy layering and percent cover. Low contrast is indicative of a lack of layering, whereas moderate or high contrast indicates the presence of layering. High contrast suggests the presence of gaps in the upper canopy layer, whereas moderate contrast suggests the lack of canopy gaps. Illumination angle may have a major effect on contrast. As such, these relationships may not hold across an array of conditions without incorporating into the analysis scheme a means of accounting for illumination differences.

Patterns in the transect DN are a function of clumpiness of tree canopies in the stands. Patterns are somewhat difficult to objectively evaluate on the imagery, and are even more difficult to evaluate when viewing only a small sample of the imagery, i.e., the transects. One can see rather clearly, however, the clumpy nature of the old-growth stand exhibited in the transect DN. Similarly, the general uniformity, or lack of clumpiness, of DN from the young stand is fairly evident. We make no attempt to relate pattern in the transect DN of the other stands to pattern of the trees in those stands.

Semivariograms calculated from the transect DN are shown in Figure 3. All the semivariograms appear to pass through the origin and thus do not exhibit the nugget effect associated with random variance (Journel, 1989). The range of the semivariogram for the young stand is about 5 m, which is approximately equal to the average tree crown diameter in the stand. Similarly, the ranges of the mature and old-growth transect semivariograms (approximately 8 m and 18 m, respectively) reflect the mean crown diameters of trees in these stands. The young-mix and mature-mix transect semivariograms have ranges equal to about 6 m and 9 m, respectively. These values are similar to the sizes of the dominant trees in the stands, but because there are a significant number of large trees in these stands, are somewhat less than the average tree sizes. A possible explanation for this is that tree sizes are variable in these two stands and the selected transects may not adequately represent the stand. Alternatively, the basic spatial units in the transect DN from these stands may be just the sunlit portions of the tree canopies, as opposed to the full crown diameters.

The sills of the transect semivariograms relate to contrast in the imagery, which in turn relates to percent canopy cover and layering in the stands. The image of the young stand has the lowest contrast and its semivariogram has the lowest sill. The image of the mature stand has slightly higher contrast and its semivariogram has a slightly higher sill. Both of these stands have a single canopy
layer of high percent cover. The image of the old-growth stand has the highest contrast, and its semivariogram, the highest sill. This stand had multiple canopy layers and only the upper layer, with moderate percent cover, was illuminated by sunlight. Images of the two mixed stands have intermediate contrasts and their semivariograms have intermediate sills. Because of the lack of gap structure, the multiple layer in these stands were all fairly well illuminated.

All five transect semivariograms exhibit periodicity, indicative of a repetitive spatial pattern along the transects (Curran, 1988; Woodcock et al., 1988b). If we assume clumpiness translates to variations in pattern at different scales, this permits the opportunity to evaluate complexity of pattern in stand structure at different scales. The lengths of the periods in the young and mature transect semivariograms are nearly the same as the range of the semivariograms. Thus, in these single-layer stands with high percent cover and lack of clumpiness, the second peak is associated with pairs of trees, the third with groups of three trees, and so on. This indicates spatial pattern is not scale-dependent in these stands. Because the contrast in these two stands is low, the troughs in these periodic semivariograms are not well pronounced. The second and third peaks in the semivariogram for the old-growth transect are not the same distance as the range, and may be responding to different-sized clumps of trees, as well as single gaps or clumps of trees and gaps. As a result, we can say that pattern in this old-growth stand varies with scale. Because of high contrast in the DN of this transect, the troughs in this semivariogram are well pronounced. The second peak of the mature-mix transect semivariogram, although the same distance from the first peak as the range, is not well pronounced. Furthermore, successive peaks beyond the second are a larger distance apart than the range. These apparent anomalies are likely due to the mixed clumpy pattern of trees in the stand.

Matrix Semivariograms (1 m Spatial Resolution Imagery)

The above analysis suggests that transect semivariograms of the 1 m spatial resolution images were useful for obtaining a rough estimate of tree canopy size and for detecting the presence of canopy layering, gaps, and patterns in stand structure. However, matrix semivariograms permit a more complete evaluation of the imagery and thus a more accurate assessment of stand structure.

If average tree size and spacing do not greatly vary in the stands, the ranges for the matrix semivariograms should be essentially the same as the ranges for the transects semivariograms. For the young, mature, and old-growth stands this is indeed the case (Fig. 4). The two mixed stand matrix semivariograms, however, have ranges that differ from those of transect semivariograms. The matrix semivariogram for the young-mix stand has 10 m range, where the transect semivariogram has a 6 m range. The preponderance of clumps of large, old trees in this stand is most likely responsible for this, suggesting that the transect did not adequately represent the stand. The mature-mix stand has a variety of tree sizes. As a result, the shoulder of the semivariogram extends from about 12 m to 30 m, with no well-defined range.

The sills of the matrix semivariograms are essentially flat, lacking the periodicity of the transect semivariograms. This is a result of averaging (Fig. 5). Although the absolute values of the matrix semivariogram sills differ from those of the
Transect Semivariograms (10 and 30 m Spatial Resolution Imagery)

Transects of DN were extracted from the images with 10 m and 30 m spatial resolution (Fig. 6). The transects traversed the same portions of the stands as those of the 1 m spatial resolution images. As expected, and as represented in the transects, because of regularization the 10 m resolution images exhibit significantly less variability than do the 1 m resolution images. Similarly, the 30 m spatial resolution images exhibit less variability than the 10 m resolution images. Although slight trends are evident in the 1 m transect data, they are not obvious and therefore were not discussed. Trends are clearly more visible in the 10 m and 30 m transect data. The young and old-growth transects have a slightly positive slope, whereas those of the two mixed stands have a slight negative slope. The trends are probably caused by topographic relief and thus differential illumination. Because the trends are slight and the lag over which the semivariograms were calculated is less than one-fourth the full width of the stands, this is not serious grounds for disqualification of the semivariogram technique for image classification within the scope of this study.

As a result of regularization, semivariograms calculated from the transects of the 10 m and 30 m spatial resolution images (Fig. 7) exhibit several differences from the 1 m transect semivariograms. Except for the old-growth stand, the dominant tree crown size along the transect was less than 10 m. Since 10 m is the pixel size, and thus the location of the first data point in the 10 m semivariograms, only the old-growth transect semivariogram has a range greater than 10 m. Also, the heights of the sills are greatly reduced in the 10 m transect semivariograms and periodicity is greatly reduced, and, in some cases, eliminated. As none of the stands had tree crowns larger than 30 m, the ranges of all the 30 m transect semivariograms are at 30 m. The sills of these semivariograms are not

Figure 5. Semivariograms for five individual pixel transects from the young stand. Each transect is from the row direction of the 1 m spatial resolution images.

Figure 6. Digital numbers for the transects of pixels selected from the 10 m and 30 m spatial resolution images of the five forest stands.
Matrix Semivariograms (10 and 30 m Spatial Resolution Imagery)

Like the 10 m transect semivariograms, only the 10 m matrix semivariogram for the old-growth stand has a definite 20 m range (Fig. 8). One could argue, however, that the range for the mature-mix stand also is 20 m, responding to the significant number of large, old-growth trees in the stand. The ranges for all the 30 m matrix semivariograms are 30 m. Regularization reduced the sills of the matrix semivariograms in a similar manner as it reduced those of the transect semivariograms.

CONCLUSIONS

Semivariograms of image data are a useful means of evaluating canopy structure in the Douglas-fir forests of the Pacific Northwest. Indicated herein is that matrix semivariograms may provide fairly accurate estimates of stand structure parameters, but will not readily permit the evaluation of patterns in stand structure. Because transect semivariograms exhibit periodicity, they may permit the detection of the presence of patterns. However, as
Transects represent only a sample of data values, transect semivariograms will not depict stand structure parameters as accurately as matrix semivariograms. It is clear from this study that the utility of both transect and matrix semivariograms for evaluating within stand conifer canopy structure from remotely sensed images is greatly influenced by image spatial resolution. However, caution must accompany the use of transect semivariograms where anisotropy is great. Additionally, caution should be used when interpreting the semivariograms associated with the 30 m data in this study, as the number of comparisons used in the calculations was relatively small.

At a spatial resolution of 1 m, radiant energy sensed from all tree crowns, excluding those of seedlings, will be expressed in the DN of several pixels. Because of this, the range of the 1 m matrix semivariogram is a valuable measure of tree crown size in a conifer forest stand. At a 10 m pixel size (e.g., SPOT HRV panchromatic data) the range of the matrix semivariogram is less useful, yielding only a coarse estimate of crown size. If the range is 10 m, the tree canopy sizes are likely to be near or less than 10 m in diameter; if the range is larger, tree canopy size can be estimated to the nearest 10 m. As few trees have crowns that are 30 m in diameter or greater, the range of the semivariograms using Landsat TM data should not be useful for estimating tree crown sizes.

Sills of the 1 m matrix semivariograms are useful for detecting the presence of canopy layering and gaps in the stands. Because the sill responds to both percent canopy cover and canopy layering however, their use may not always facilitate distinguishing mixed stand structures from old-growth structures. This is largely because the distinction between these categories of forest structure are not always clearly distinguishable on the ground. Additionally, unless illumination angle differences are accounted for, the value of the sills may be further limited for analysis of stand structure.

Because the sills are reduced with increasing units of regularization, like the range, the sills seem less informative as image pixel size increases. For the 30 m data the sills were very similar in magnitude, again, indicating a limitation for the potential usefulness of semivariograms of Landsat TM data for stand structure analysis. Using semivariograms of SPOT HRV data to distinguish old growth from stands that are young or mature but have significant number of remnant old-growth trees may only be practical if the HRV data are supplemented with digitized aerial photographs or videography, or with high spatial resolution spectroradiometer and image data.

To apply the semivariogram technique to image data for within stand structure analysis, separate semivariograms must be calculated for each stand. This may be impractical on a full HRV scene that may contain hundreds, or perhaps thousands, of individual stands. If this procedure were to be executed, however, the sills could be used as single numbers—and in some cases the ranges and thus a pairs of numbers—as indices of stand structural complexity. An alternative, and maybe more practical approach, would be to create an image data layer from the existing image data (e.g., HRV or merged HRV and TM) that largely distinguishes each stand’s structural complexity from that of the other stands. This data layer could be used in the multispectral image processing context. Some measure of local variance for an image containing numerous stands would be helpful. Several measures of local variance, or texture, are possible (e.g., Woodcock and Strahler, 1987; Rubin, 1990; Wang and He, 1990) and adapting or developing one that performs well will be a focus of our continued research.

An alternative approach for obtaining canopy structure information from satellite data is to use an invertible canopy reflectance model. The Li–Strahler (1985) geometric-optical model has been used to estimate tree size and density in a variety of forest stand conditions from 80 m spatial resolution Landsat MSS data and TM data (Franklin and Strahler, 1988; Strahler et al., 1988). This model is driven by within stand spectral variance, but has not been severely tested when stand conditions and associated image DN variance are similar to those in the stands used here. We are currently evaluating the Li–Strahler model under these conditions.

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