Spatial and Vertical Leaf Area Index of a Deciduous Forest Resolved Using the LAI-2000 Plant Canopy Analyzer

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ABSTRACT. The LAI-2000 Plant Canopy Analyzer (LI-COR Inc., Lincoln, Nebraska) was used to determine the spatial and vertical canopy structure of a heterogeneous deciduous forest near Chalk River, Ontario. Overstory vegetation area index (VAI) demonstrated the spatial heterogeneity that exists between points at 10 m spacing and also with direction along transects, emphasizing the need for an appropriate sampling strategy. Average (± standard deviation) VAI for the forest was determined to be $3.00 \pm 0.70$, which lies within 3% of an estimate made by litterfall analysis in 1989 for the same forest location. The average VAI differs from the plant area index (PAI) determined by hemispherical photography by 9%.

Owing to the large standard deviation in the estimate of VAI, it was calculated that 84 samples need to be taken to be within 5% of the mean at the 95% confidence level. This number drops to 21 if the accuracy requirement is relaxed to 10%. The large number of samples can be reconciled by the speed of sampling that is possible with the LAI-2000. One-hundred-thirty-two samples were obtained in this forest during a 7 day period.

Vertical measurements of VAI were made from five levels on a 25 m scaffold tower in all four cardinal directions. VAI in the top third of the canopy compared well with hemispherical photography values taken along the vertical profile. The estimates in the middle and bottom levels differ from PAI. Directional heterogeneity was shown to increase with height. VAI measured at the lowest canopy level from the tower ($3.11 \pm 0.34$) was not significantly different from the spatial overstory average of 3.00.

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Additional key words: Plant area index, hemispherical photography, aspen, birch.

The importance of leaf area index (LAI) as a surface state variable is seen in widespread applications ranging from biomass productivity models (McLeod and Running 1988) to radiative transfer studies (Lang 1987, Norman and Campbell 1989) and to studies involving remotely sensed data (Spanner et al. 1990). The determination of LAI is especially important in the context of the recent shift to large-scale intensive studies attempting to link remotely sensed data to ground-based measurements (Andre et al. 1989, Betts et al. 1990). For example, FIFE, HAPEX-MOBILHY, and the current BOREAS study all focus on such linkages. Leaves are the primary sites of energy and mass exchange within the forest environment, and therefore the interception of radiation and the process of evapotranspiration are proportional to LAI (Pierce and Running 1988). McNaughton and Jarvis (1983) have shown that LAI is important in determining canopy scale estimates of evapotranspiration. Canopy-based studies of water and carbon exchange require accurate estimates of the vertical distribution of foliage (Jarvis and Leverenz 1983).

With increasing emphasis on characterizing the underlying surface using remotely sensed data, LAI will take on increased importance in climatological research. Pierce and Running (1988) predict that there will be a need for effective techniques for providing ground truth at the large scale that is associated with the minimum resolution of satellite imag-
ery (up to 1 km), such that a large number of stand-level estimates of LAI must be collected in a relatively short period of time. The LAI-2000 Plant Canopy Analyzer (LI-COR Inc., Lincoln, Nebraska) is well suited for taking large numbers of samples in short time periods, even in tall canopies (Welles 1990). It has been used in a number of studies: Chason et al. (1991; oak-hickory forest), Fassnacht et al. (1994; coniferous canopies), Grantz et al. (1993; cotton), Runyon et al. (1994; coniferous and deciduous stands), Wang et al. (1992; oak forest), Yang et al. (1993; oak forest).

**LAI-2000 Plant Canopy Analyzer**

The LAI-2000 output is best interpreted as “an index based on one-half the surface area of hypothetical convex objects having the same projections as those plant elements that are distributed randomly in the canopy” (Fassnacht et al., 1994). In practice, this means that output must be corrected for the “shape” of the elements (conifer needles) when working in coniferous forests. Deciduous trees are assumed to have randomly distributed leaves that are flat. Thus, in a deciduous canopy, the LAI-2000 output is an approximation of single-sided LAI, but other light-blocking elements, for example branches and boles, are included to some degree.

The LAI-2000 determines a vegetation area index (VAI). This is accomplished by integrating gap fractions obtained from above- and below-canopy readings of diffuse sky radiation at five zenith angles simultaneously. Detectors in the sensor head arranged in concentric rings measure sky brightness in five annuli in the ranges 0–12°, 15–28°, 31–43°, 45–58°, and 61–74° from zenith. A built-in optical filter rejects radiation above 490 (nm), thus ensuring that only the “blue” portion of the spectrum is seen. All zenith angles are collected in a single reading, and VAI is computed instantaneously. See Welles and Norman (1991) for further information on the theory of operation of the instrument.

**Methods**

The measurements of VAI were made on 7 days during a 10 day period from August 16 (day 228) to August 26 (day 238), 1991, in a deciduous forest at the Atomic Energy of Canada Laboratory (AECL), near Chalk River, Ontario (latitude 46°02’N, longitude 77°20’W). The overstory is dominated by aspen (Populus tremuloides Michx. and Populus grandidentata Michx.) and white birch (Betula papyrifera Marsh.) which comprise 81% of the total stems in the overstory (Iacobelli 1991). Other species include eastern white pine (Pinus strobus L.), red oak (Quercus rubra L.), red maple (Acer rubrum L.), balsam fir (Abies balsamea [L.] Mill.), and white spruce (Picea glauca [Moench] Voss.).

The understory is primarily beaked hazel (Corylus cornuta Marsh.) with red maple seedlings and bracken fern (Pteridium aquilinum [L.] Kuhn).

The maximum height of the overstory canopy is 25 m. The aspen and birch typically have foliage concentrated in the top third of the canopy, but the overstory is sparse, which allows thick understory to develop in some regions. The beaked hazel often grows to a height of 2 m. There are very few intermediate trees; the exceptions are the occasional maple and oak.

**LAI-2000 Measurement Procedures**

Overstory VAI was measured from a height of 2 m at 10 m intervals along four 100 m transects arranged in the cardinal directions from a central 25 m scaffold tower. A measurement of VAI utilizing a single LAI-2000 unit was accomplished by a three-step process. The unit was taken to the top of the canopy (the top level of the scaffold tower; 25 m) by a bucket and pulley, where a second operator took an “above-canopy reading” of sky brightness in the direction of the planned ground sampling, termed an “A” reading. The instrument was returned to the ground where the primary operator walked the predetermined transect, taking a series of sky brightness readings from beneath the canopy, termed “B” readings. The unit was then returned up the tower for another “A” reading. Care was taken to ensure that the unit was facing the same direction both above and below the canopy. The “A” readings were linearly interpolated between the initial and closing values for each below-canopy reading using the PC software. “B” readings were then compared to the closest “A” reading in time. This compensates for changes in sky brightness which often occur between the time of the initial and closing above-canopy readings.

As the LAI-2000 sensor head measures diffuse radiation, direct sunlight on the sensor or sunlit portions of the canopy causes the leaves to appear brighter, and thus, the “B” reading will be increased, resulting in an underestimate of VAI. A sunlit canopy was avoided by taking measurements just after sunrise and just before sunset when the solar elevation is low, as well as on days of uniform, dense cloud cover whenever possible. Table 1 summarizes the times and sky conditions when the data were collected. Data collection in the middle of

<table>
<thead>
<tr>
<th>Date</th>
<th>Measurement period (EDT)</th>
<th>Transect</th>
<th>Sky conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 16</td>
<td>1033–1113</td>
<td>South 0–50 m</td>
<td>Overcast</td>
</tr>
<tr>
<td></td>
<td>1114–1152</td>
<td>East 0–50 m</td>
<td></td>
</tr>
<tr>
<td>August 17</td>
<td>0626–0721</td>
<td>North 0–50 m</td>
<td>Thin cloud</td>
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<td></td>
<td>1313–1404</td>
<td>West 0–50 m</td>
<td>Overcast</td>
</tr>
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<td></td>
<td>1406–1452</td>
<td>East 50–100 m</td>
<td></td>
</tr>
<tr>
<td>August 19</td>
<td>0833–0725</td>
<td>West &amp; south vertical</td>
<td>Broken cloud</td>
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<td></td>
<td>2005–2027</td>
<td>South 50–100 m</td>
<td>Clear</td>
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<tr>
<td>August 20</td>
<td>1905–2001</td>
<td>North 50–100 m</td>
<td>Overcast</td>
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<tr>
<td>August 21</td>
<td>1752–1832</td>
<td>West 50–100 m</td>
<td>Broken cloud</td>
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<tr>
<td>August 23</td>
<td>0922–0938</td>
<td>North vertical</td>
<td></td>
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<tr>
<td>August 26</td>
<td>1700–1707</td>
<td>East vertical</td>
<td>Overcast</td>
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the day on August 17 was possible because of the nearly totally diffuse solar radiation input as a result of dense cloud cover. Sampling in broken cloud conditions only occurred near sunrise and sunset.

A 90° view lens cap was used to restrict the view of the sensor such that a 270° arc was not seen by the instrument. Lang and Xiang (1986) showed that averaging the logarithms of transmittances (rather than a linear average) obtained along a transect in heterogeneous canopies overcomes the errors due to gaps. At any point where there are significant gaps in the canopy, the sensor might “see” these in one direction while simultaneously “seeing” full canopy in another direction for the same sensing ring. While logarithmic averaging is done by the instrument on groups of “B” readings, each individual “B” reading is a linear average of the azimuthal variations seen by the sensor (Welles and Norman 1991). In essence, the instrument is forced to take a linear average transmittance for two very different cover types, which leads to underestimation of the VAI for that location. By restricting the view of the sensor using a 90° lens cap, this problem is alleviated.

Each transect was sampled three times. The first sampling run was made with the instrument facing the direction of the transect (facing north if on the north transect), while the second and third runs were sampled with the instrument facing orthogonal to the cardinal direction (east and west along the north transect). Thus, in total, 270° of view were sampled at each measurement location. It was not necessary to sample in the fourth cardinal direction (facing south on the north transect) as this would effectively have been a resampling of this orientation.

Vertical estimates of VAI were made from five levels on the scaffold tower. Two measurements were taken facing each of the four cardinal directions, for a total of eight at each level. The multiple reading strategy ensures that any local differences in vegetation cover do not influence the reading unduly. Each pair of similar orientation measurements was averaged to produce a single VAI value for each orientation, totaling four measurements at each level.

The outermost ring (zenith angle > 61°) was removed from the calculations of VAI to prevent any direct beam influence as the sun set and rose. This was easily accomplished through the software supplied with the device. Both Chason et al. (1991) and Grantz et al. (1993) found that the outermost ring gave greater transmittances which resulted in lower VAI values than produced by destructive sampling.

In a previous study, Iacobelli (1991) determined single-sided LAI at the AECL forest using litterfall and hemispherical photography. Two plots measuring 40 × 100 m were set out to the northeast and southwest of the tower. Four 0.4 m² traps were placed within 5 quadrats randomly located within each plot for a total of 20 traps per plot. Leaves were collected on 5 occasions between October 1 and November 8, 1989. Forty pairs (fully leafed and leafless) of photographs were taken in the same locations as the litterfall traps from a height of 2 m. From these 40 pairs, 20 pairs were randomly chosen, and a spatial plant area index (PAI) was determined following Neumann et al. (1989) using a negative binomial model. Photographs were also taken from opposing sides of the tower at six heights to yield a vertical profile of PAI.

**Results and Discussion**

**Spatial Variation of LAI**

The three view orientations at any given point were combined to produce average VAI point estimates for each of the transects (Figure 1). Although some of the directional variability is dampened, spatial variability is still evident at the scale of 10 m. The canopy is most uniform to the north of the tower, most open to the west, and increasingly heterogeneous to the south and east. Neumann et al. (1989) also noted considerable spatial variability in overstory LAI as determined by hemispherical photography in a square grid with 5 m spacing in the maple-aspen forest at Borden, Ontario. The overall average VAI for the AECL forest based on 132 measurements was 3.00 ± 0.70 (mean ± standard deviation).

Iacobelli (1991) calculated a LAI value of 3.07 (no standard deviation available) for the overstory based on litterfall analyses and a PAI value of 3.27 ± 0.66 using hemispherical photography. The LAI-2000 estimate is not significantly different from either of these methods. In a similar study conducted in an oak forest, Wang et al. (1992) found that the LAI-2000 VAI underestimated PAI derived from hemispherical photographs by 1% to 15%. Repeatability was studied and the average precision of the LAI-2000 was determined to be superior to the photographs as the instrument computed the gap fraction more consistently than the human photo interpreter.

![Graph of Average VAI for overstory for 10 m intervals along the transects.](Image)

*Figure 1. Average VAI for the overstory for 10 m intervals along the transects. Average values are determined by combining the three VAI values (view orientations) at each point within each transect. Error bars represent one standard error from the mean.*
**Vertical Variation of LAI**

The downwards cumulative vertical VAI distributions (Figure 2A) and the frequency plots (Figure 2B) show the changing canopy structure in terms of direction. The canopy to the east is dominated by aspen in close proximity to the tower. The VAI frequency plot for the east indicates that the majority of the foliage occurs at the highest measurement level (greater than 22 m). The bimodal nature of this plot is reflective of a high primary canopy with an intermediate layer of foliage present at a lower height—there is a slight maximum at 10 m. The west frequency plot reinforces the notion of a primary canopy layer at the top of the canopy, as again foliage is clustered near the top measurement levels (greater than 18 m). In the west view, birch is the dominant species seen. The south and north plots are reflective of the other canopy conditions present in this forest. The north plot shows a peak lower into the canopy, while the south plot shows large clustering at the intermediate to high portions of the canopy.

These plots are similar to those of Jurik et al. (1985), who found both unimodal and bimodal distributions of VAI present in an aspen-hardwood forest. In samples containing both aspen and maple, Jurik et al. (1985) showed the aspen foliage to be clustered at the top of the canopy while the maple foliage reached lower heights, often forming a bimodal distribution. This is likely attributable to the shade-intolerant nature of the aspen.

The ideal sampling strategy for determining the vertical distribution of foliage would be multiple point estimates (e.g., Wang et al. 1992) taken at regular intervals to find an average vertical canopy structure and the accompanying spatial variation within that structure. However, this was logistically impossible as only one tower was available. The measured vertical VAI at AECL then represents a "best guess" of the vertical canopy structure. That the average VAI at the lowest measurement level (3.11 ± 0.34) is not significantly different from the average overstory VAI (3.00 ± 0.70) at the 95% confidence level is encouraging.

Vertical PAI estimates had been made previously from hemispherical photography at six heights within this canopy from the tower (Iacobelli, 1991). These values, compared to those from the LAI-2000, show close agreement at the top three photographic levels, but the LAI-2000 values are less at the lower three levels (Figure 3). The rather large difference at the lower canopy levels is thought to be a function of the interpretation of the hemispherical photographs. Iacobelli's average overstory spatial PAI by the photographic technique was 3.27 ± 0.66; however, his vertical PAI at the lowest...
measurement level (6 m) was 3.87. It would appear that the vertical photographic values overestimate their spatial counterparts. The vertical hemispherical photographs become increasingly complex as more light blocking elements are present and therefore the potential for interpretation error increases towards the ground level.

Whereas in this study, the comparison shows that similar results are obtained high in the canopy with a poorer comparison near the ground, both Wang et al. (1992) and Chason et al. (1991) report the opposite trend. Wang et al. (1992) and Chason et al. (1991) agree that the overstory heterogeneity should increase with height as more gaps become prevalent. The coefficient of variation (mean/standard deviation) increases consistently with height from 0.11 at the lowest measurement level (4.57 m) through 1.06 at the top measurement level (22.85 m), indicating that increased heterogeneity is indeed present with height (Figures 3 and 4).

Spatial Heterogeneity

Noting the rather large standard deviation in the spatial estimates, it would require 84 sample points in this forest to ensure that the VAI lies within ±5% of the mean estimated in this experiment (at a 95% confidence level). If the accuracy is relaxed to ±10%, then 21 samples would be required. This is in contrast to Wang et al. (1992), who reported that only 16 and 4 samples would be required to produce 5% and 10% accuracy, respectively, in an oak–hickory forest with a mean LAI on the order of 3.40. It is evident that the spatial variability in our forest is far greater than that measured by Wang. Nilson (1977) cautions that to obtain a reliable statistical set of data on light penetration through a forest canopy using hemispherical photographs, approximately 100 photographs must be taken.

Spatial heterogeneity was also shown to be present with direction and within transects (Figure 1). If the preceding analysis is repeated using data from individual transects (33 sample points each), then the directional bias of the heterogeneity is shown. The north transect (VAI = 3.05 ± 0.31), which was shown to be the most spatially homogeneous, would require 17 samples to be within ±5% of the transect mean, and only 4 samples to be within ±10% of the transect mean—identical results to Wang et al. (1992). However, the more heterogeneous east transect (VAI = 3.07 ± 0.49) would require 41 samples to be within ±5% of the transect mean and 10 samples to be within ±10% of the transect mean. Both of these transects have similar mean VAI values, and yet the different heterogeneity requires that different sampling frequencies be used to obtain the same results. Pierce and Running (1988) report identical results between stands with similar LAI but different standard deviation of the estimates. The standard deviation of the LAI estimates is controlled by the spatial heterogeneity present within the overstory of a stand.

These less promising findings can be tempered when it is realized that in this study 132 samples were taken over a 7 day period. This large coverage in a relatively short time period gives credence to the ability of the instrument to provide "large accurate spatial coverage" in a natural (nonplantation) forest.

Summary and Conclusions

The LAI-2000 has been shown to estimate accurately the vegetation area index of a deciduous forest when compared with estimates made by the traditional techniques of litterfall analysis and hemispherical photography. The instrument is simple to use, and, provided that careful observance of the underlying assumptions is made, has the potential to yield large, rapid areal coverage of natural surface cover types.

While it has been noted by both Wang et al. (1992) and Chason et al. (1991) that the fisheye technique "spatially integrates" the overstory such that few samples need to be taken, the current study suggests strongly a closer examination of the heterogeneity present in natural forest stands is important. We agree that directional heterogeneity increases with height due to the presence of gaps as was shown by the coefficient of variation in vertical estimates by the LAI-2000. However, the overstory sampling issue is forest-specific. Two 100 m transects with the same mean estimate of VAI yielded different required sampling frequencies as a result of the different degrees of heterogeneity present. This study corroborates the findings of Pierce and Running (1988), who concluded that stands with different foliage distributions require different sampling densities to obtain a given level of accuracy. We would therefore err on the side of caution and utilize the rapid estimation capabilities of the LAI-2000.

Sampling must be dense enough to account for the degree of heterogeneity present in the forest.

Finally, no attempt has been made to address the issue of higher orders of foliage organization. Much work has been done with the clumping at the needle and branch levels associated with coniferous species (Chen and Black 1991, Fassnacht et al. 1994, Gower and Norman 1991, Smith et al.
1993). Although an assumption of random orientation of leaves has been made in application to this deciduous forest, Gower and Norman (1991) caution that the LAI-2000 could overestimate LAI in deciduous canopies with numerous low dead branches and suggest that measurements be made at the base of the live crown if this situation exists. This possibility should be explored further in light of the vertical foliage distribution of this and other forests.

**Literature Cited**


