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MEASURING LEAF AREA INDEX WITH THE LI-COR LAI-2000 IN PINE STANDS

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Because leaf area index (projected one-sided leaf surface area per unit ground surface area, hereafter referred to as LAI) is a critical variable in models that attempt to simulate carbon, nutrient, water, and energy fluxes for forest ecosystems (e.g., Running and Coughlan 1988), techniques to rapidly estimate LAI over large areas are in great demand. LAI can be measured either directly or indirectly (e.g., Norman and Campbell 1989). Direct techniques involve dimensional analysis of the canopy and imply felling trees that are representative of the stands being studied. As a consequence, these techniques are labor-intensive and expensive. Moreover, the allometric relations are influenced by environmental factors and therefore may not be transferable to other forests. Indirect measurement techniques involve estimating LAI from the light penetration through canopies and were developed primarily for agroecosystems. Welles (1990) summarized and compared several techniques that use optical devices to measure LAI. The potential use of these instruments in forested environments is still under study (Chason et al. 1991, Chen and Black 1991, Chen et al. 1991, Gower and Norman 1991, Wang et al. 1992). The main difficulties in forested environments are that (1) plant elements may be grouped or clumped and thus are not randomly distributed, as is assumed by the theory that led to the development of these instruments; and (2) stem and branch components cannot necessarily be neglected with respect to total plant area.

The LAI-2000 Plant Canopy Analyzer (LI-COR 1990) was selected for our study because measurements along transects can be performed quickly even in the presence of understory vegetation. Other optical devices were also considered (Welles 1990). The DEMON (Assembled Electrics, Yagoona, New South Wales, Australia), for example, requires that the sensor always be pointed towards the sun. This is very difficult to do in the presence of understory vegetation. Furthermore, cloudless skies in eastern Canada are not frequent. This would also be a problem for the sunfleck ceptometer (Decagon Devices 1989*a*), which also requires one to assign a value to the light extinction coefficient (Pierce and Running 1988, Smith et al. 1991).

In a study that involved measuring the seasonal variation of LAI in an oak–hickory stand, Chason et al. (1991) found that the LAI-2000 underestimated (by ≈45%) LAI obtained with a litter trap method. Using a negative binomial model for the probability of light transmittance instead of the Poisson model, which is used in the LAI-2000 software, they obtained a LAI that was closer to the direct LAI. Using the LAI-2000 in a Douglas-fir forest stand, Chen et al. (1991) obtained a plant area index that was half as large as the one obtained using allometric relations based on diameter at breast height (dbh). They also concluded that a clumping index should be taken into account.

The objective of our study was to assess whether LAI of coniferous species that are also found in the vast Canadian boreal forest could be estimated with the LAI-2000 using the technique developed by Gower and Norman (1991). The LAI-2000 measures the total plant area index, which includes branches, stem, and fruit, as well as leaves or needles. The probability of light transmission is described by a Poisson distribution and does not take into account the fact that plant elements may be grouped or clumped. The grouping of these plant elements is characterized by a clumping index. Gower and Norman (1991) showed that for coniferous plantations with LAIs ranging from 5 to 10, the LAI-2000 estimated LAI correctly when LAI-2000 results were multiplied by a clumping index. For the broadleaf deciduous plantation included in their study (red oak, LAI of 3.1), no correction factor was necessary. We show that their proposed technique is not applicable in the stands that we studied and suggest factors that may limit the general applicability of their technique.

Methods

LAI was measured for pine stands at the Petawawa National Forestry Institute, which is situated at 46°00′ N, 77°27′ W (Eastern Ontario, Canada). Both plantations and natural stands were chosen for this study. Stand characteristics are given in Table 1. The first three stands (≈60 yr old) were red pine (*Pinus resinosa* Ait.) plantations which had different basal areas due to selective thinning. We also studied three jack pine (*Pinus banksiana* Lamb.) plantations that were ≈30 yr old (J1, J2, and J3); one natural jack pine stand (J4, ≈30 yr old), the result of natural regeneration after a

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fire; and a mature jack pine stand (J5, ≈60 yr old) that included 14% (by basal area) of overmature white pine. Stand J5 suffered from a jack pine budworm infestation, which resulted in the partial defoliation of current-year needles. The summer of 1992 was colder than normal, and by mid-July (the time when the direct measurements were taken) full elongation of the current-year shoots had not yet occurred.

Temporary sample plots were established along the transects (linear contiguous segments) where LAI-2000 measurements were taken. Trees were selected for measurement by a standard variable-plot sampling technique similar to Marshall and Waring (1986) using a basal area factor of 2 $m^2 \cdot ha^{-1} \cdot tree^{-1}$. Each tree selected was tallied by species and dbh (measured at 1.3 m above ground surface), and represents 2 m^2 of basal area per hectare.The first five trees were also sampled for total height and height to base of live crown and cored at breast height to determine age, sapwood width, and sapwood age. A description of the computation of direct LAI follows.

Based on the results of all the trees tallied by the technique described above, trees representative of the range of dbh's for each stand (taken away from the transects) were selected for destructive sampling. Thirteen jack pine trees (two taken from J1, six from J4, and five from J5), four red pine trees (taken from R2), and one overmature white pine tree (taken from J5) were felled. In the summer of 1991, biometric data was also obtained for 16 red pine trees from nearby plantations. These data were combined with the red pine data obtained in the summer of 1992.

The procedure used to calculate direct LAI at the tree level was as follows. For each tree, the live crown was subdivided into three strata of equal bole length. All branches (with needles still on) within each stratum were weighed in the field. In each stratum, two branches were selected randomly and processed in the laboratory to determine fresh and dry masses of branch, fruit, old (2 yr and older) needles, and current-year needles. All tissue was dried at 70°C for ≥48 h. The ratios of dry to fresh masses were then used to compute the total dry needle mass per stratum. To obtain the needle area for each stratum, the dry needle mass was multiplied by the specific leaf area (SLA), which is defined as the projected leaf area per unit of dry leaf mass. The AgVision system (Decagon Devices 1989*b*) was used to determine the projected one-sided leaf area. Fifty needles per stratum for both old and current-year foliage were selected randomly and were positioned to lie flat and unconstrained on a backlit glass plate. Total projected one-sided needle area for the tree was obtained by adding the needle areas for each stratum.

The next step involved translating the leaf area obtained from the felled trees to the stand level. Several authors have found good relationships between sapwood area and leaf area and/or leaf mass (e.g., Waring et al. 1982, Marshall and Waring 1986). With the wide range of densities encountered in the study, it was important to remove the effect of non-conducting woody tissue on the basal area to LAI relationship, so sapwood area was used as the predictor. Thus, in our study two regression relations were used to obtain a LAI for each stand. First, the sapwood area at breast height was related to the leaf area of the destructively sampled trees for each species (Table 2a). Secondly, for each major species in each stand a relation was obtained between sapwood area and basal area based on the coring results of the first five tallied trees in each temporary sample plot (Table 2b). Thus, for each stand, direct LAI estimates (Table 1) were obtained first by predicting sapwood area from basal area and subsequently by predicting leaf area from sapwood area. An r^2 of 0.98 was obtained between mean basal area and direct LAI on a stand basis.

At the same time that direct LAI measurements were undertaken, measurements of the stem dimensions were also taken. The total stem surface area (lateral stem area) was regressed against basal area and height for the felled trees. The total stem surface area was then predicted for all trees in a stand by assuming that tree height was the average of the sample height measurements. This resulted in a mean height weighted by basal area.

The LAI-2000 measurements were performed in July 1992. Two intercalibrated instruments were used for all measurements. One unit was located in a large open area to make the above-canopy measurements, and the second instrument was carried along the transects to make the below-canopy measurements. Some of the stands contained a deciduous understory. To minimize the contribution of the understory, LAI-2000 measurements were taken at ≈2 m above the ground. To ensure that the conclusions of this study would not be influenced by the contribution of the understory, all measurements with the LAI-2000 were repeated after leaf-off at the end of October 1992. Some needle loss, particularly of the older foliage, had occurred since the July measurements.

The AgVision system was used to measure the shoot ratios necessary to correct for the underestimation of the LAI-2000 measurements (Gower and Norman 1991). The shoot ratio is a measure of needle clumping on the shoot and is defined as the projected one-sided area of all the needles belonging to a shoot divided by the silhouette area of that shoot with its needles still on. The technique to measure the shoot ratio was the same as described in Gower and Norman (1991) except that in our study, shoot ratios were measured for both old and current-year foliage. As in Gower and Norman (1991), the silhouette area was evaluated by measuring

TABLE 1. Summary of the stands examined.* The stand closure was 100% for all stands except for J1 and J5, which had a stand closure of 90%.

Stand name	Predominant species	Density (stems/ha)	Mean dbh (cm)	Basal area (m^2/ha)	Overstory LAI (m^2/m^2)	Stem : leaf area ratio† (%)
R1	red pine	430	29.5	29.3	2.9	8.6
R2	red pine	850	25.5	43.3	4.9	9.9
R3	red pine	1269	24.0	57.3	6.2	11.9
J1	jack pine	1299	13.0	17.3	1.6	19.4
J2	jack pine	1368	16.1	28.0	2.2	18.4
J3	jack pine	1510	13.2	20.7	1.7	22.9
J4	jack pine	2705	9.8	20.5	1.5	33.0
J5	jack pine	781	16.9	17.5	2.0	10.0

* Stands J4 and J5 are natural stands; all other stands are plantations. Three temporary sample plots were established in plantations and four in natural stands.
† One-half total stem area divided by overstory LAI and converted into a percentage.

the projected area of the shoot by holding the twig (to which the needles are attached, thus forming the shoot) parallel to the glass plate. Four measurements of projected area were taken on each shoot. The first position of the shoot was chosen randomly and the following three measurements were each done after a rotation of 90° about the twig axes with respect to the previous position. In July, shoot ratio measurements were performed on shoots taken from the felled trees. The samples were taken from the fourth to fifth whorl from the top of the trees. In October, a shotgun was used and upper crown branches were selected.

Results and Discussion

LAI-2000 measurements for the eight stands studied are listed in Table 3a. Fig. 1a illustrates a plot of direct LAI vs. LAI-2000 measurements for both the July and October readings. The LAI-2000 underestimated direct LAI values for the three red pine stands and J5.

TABLE 2. Results of model fitting.

Species	Stand	Model*	Mean squared error
a) Leaf area vs. sapwood area			
Jack pine	all	la = 0.1113(sa)	7.74
Red pine	all	la = 0.1513(sa)	7.10
White pine	all	la = 0.7252(sa)	3.71
b) Sapwood area vs. basal area			
Red pine	R1	sa = 0.6864(ba)	61.44
Red pine	R2	sa = 0.7440(ba)	35.13
Red pine	R3	sa = 0.7188(ba)	47.03
Jack pine	J1	sa = 0.8092(ba)	12.74
Jack pine	J2	sa = 0.7201(ba)	15.90
Jack pine	J3	sa = 0.7171(ba)	24.26
Jack pine	J4	sa = 0.6672(ba)	30.14
Jack pine	J5	sa = 0.7704(ba)	34.69
White pine	J5	sa = 0.3965(ba)	71.72

* la = leaf area (m^2), sa = sapwood area at breast height (cm^2), ba = basal area at breast height (cm^2).

For the other jack pine stands, the LAI-2000 slightly overestimated the direct LAI values. The October LAI-2000 values are consistently lower than the July values. The seasonal variation in LAI is a combination of several factors that could partially cancel each other out. These factors include an increase in needle size as a consequence of full elongation that occurred since July, needles falling off (in particular in the fall) and also seasonal variations in the shoot ratio.

Shoot ratios for old and current-year shoots for both the July and October measurements are listed in Table 3b. In all cases, the average shoot ratios for current-year shoots are larger than for old shoots. Red pine shoot ratios are considerably larger than the jack pine ratios. The average shoot ratio obtained for red pine is almost twice as large as that obtained by Gower and Norman (1991), which was 1.5 ± 0.41. This suggests that the shoot ratios may be specific to local growing conditions. The shoot ratios for both jack pine and red pine are higher in October than in July; however, the differences are less than one standard deviation, and consequently this result needs further validation.

To correct for clumping of needles on shoots, the LAI-2000 measurements were multiplied by the shoot ratios (Fig. 1b). Since the contribution of the current year needles was low (current-year dry needle mass was 13% of the total dry needle mass for the felled jack pine trees and 10.6% for the felled red pine trees), the LAI-2000 readings were multiplied by the old shoot ratios rather than by the current year shoot ratios. The corrected LAI-2000 values all consistently overestimated direct LAI measurements.

In the jack pine stands, woody components (stems and branches) contributed significantly to the LAI-2000 values that measure plant area index (includes all aboveground components). Table 1 includes a stem : leaf area ratio (square metre per square metre), defined as one-half of the total stem surface area divided by the direct leaf-area index. For the stands where the

TABLE 3. Summary of LAI-2000 measurements and shoot ratios.

a) LAI-2000 measurements (mean ± 1 SD).

Stand	July LAI	October LAI
R1	2.19 ± 0.35	1.96 ± 0.22
R2	2.70 ± 0.16	2.48 ± 0.07
R3	3.17 ± 0.30	3.02 ± 0.29
J1	2.26 ± 0.14	2.12 ± 0.13
J2	2.76 ± 0.13	2.53 ± 0.14
J3	2.05 ± 0.10	1.95 ± 0.06
J4	2.06 ± 0.47	1.94 ± 0.38
J5	1.75 ± 0.38	1.53 ± 0.35

b) Shoot ratios. N = number of trees sampled.

	July				October			
	Old shoots		Current-year shoots		Old shoots		Current-year shoots	
Species	Mean ± 1 SD	N	Mean ± 1 SD	N	Mean ± 1 SD	N	Mean ± 1 SD	N
Jack pine	1.90 ± 0.10	13	2.79 ± 0.47	12	2.40 ± 0.21	4	2.95 ± 0.53	4
Red pine	2.67 ± 0.58	4	3.29 ± 0.47	4	3.11 ± 0.14	4	3.65 ± 0.94	4

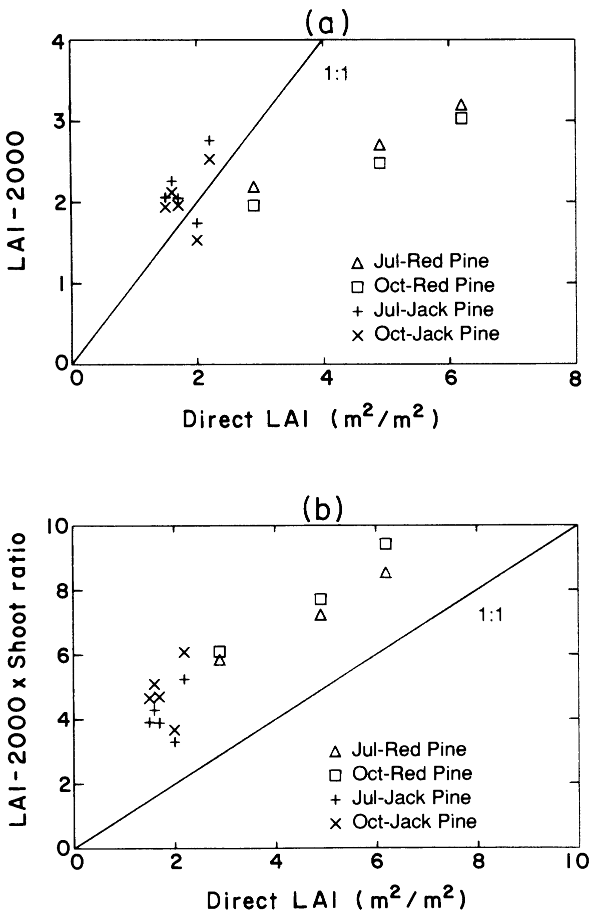

FIG. 1. (a) Comparison of LAI-2000 Plant Canopy Analyzer values with direct LAI estimates obtained from dimensional analysis. Measurements for July and October of 1992 are shown for three red pine plantations and five jack pine stands (three plantations and two natural stands). (b) Comparison of LAI-2000 Plant Canopy Analyzer values multiplied by shoot ratios (as given in Table 3b) with direct LAI estimates obtained from dimensional analysis.

LAI-2000 underestimated direct LAI (R1–R3 and J5, see Fig. 1a), the stem : leaf area ratio is ≈10%, whereas for the cases where the LAI-2000 overestimated LAI (J1–J4), the stem : leaf area ratio ranged between 19 and 33%. The highest value was for stand J4, which resulted from regeneration after a fire and had a very high density of trees (Table 1). The 30-yr-old jack pine stands have relatively more stem area than the 60-yr-old stand, J5 (Table 1). Although it was suggested that LAI-2000 measurements should be made at the base of the live crown in cases where there is a large percentage of woody area with respect to plant area (J. M. Norman, 1991, *personal communication*), climbing the 30-yr-old jack pine trees was unsafe and not practical, especially in a natural stand. Even for the red pine stands, it appears that a simple product of LAI-2000 values and shoot ratios does not lead to a correct estimate of direct LAI. From Fig. 1b one may notice, however, that the corrected LAI-2000 values consistently overestimated direct LAI by between 2 and 3 m^2/m^2.

The results of our study indicate that in coniferous stands (LAI of 3–6 m^2/m^2 for our red pine stands) the technique developed by Gower and Norman (1991) is not necessarily applicable, hence one may not simply take the shoot ratios measured by Gower and Norman and multiply them by LAI-2000 measurements to obtain an absolute value of LAI (as was done by Gong et al. 1992). In the case of forest stands that have a significant woody biomass component (relative to LAI), a further correction factor should be applied.

It appears that the LAI-2000 could be useful to measure relative variations (temporal and spatial) of LAI. Provided woody biomass does not vary considerably within a year, LAI-2000 measurements should reflect the change in the amount of leaf area over a season. However, in coniferous stands, the problem may be complicated by seasonal variation in shoot ratios (Table 3b). Further studies are needed to determine how shoot ratios vary within a year.

Recently, questions have been raised as to what leaf area is actually measured by radiometric sensors. According to Chen and Black (1992; see also Lang 1991), for leaves that have no concave area, are not bent, and for which a random leaf angular and spatial distribution is assumed, the leaf area obtained from radiation measurements should be approximately equal to one-half the total leaf area. Thus, the results obtained with a LAI-2000 (multiplied by a factor of two) should be compared with direct projected LAI measurements that have been transformed to total leaf area. Since in this study the needles were put unconstrained on a glass plate, the direct LAI values should be multiplied by π to obtain total leaf area (Grace 1987). The two sets of measurements would then strictly be comparable provided that (1) a foliage clumping index does not have to be taken into account and (2) woody components may be neglected. In our study a clumping index has to be taken into account in all stands. Branch and trunk contributions could probably be neglected for the red pine stands and the mature jack pine stand. The question also remains open as to how these woody components should be subtracted from the plant area index to obtain the leaf area index, considering the nonrandom distribution of the woody components. Further theoretical developments and experiments are needed to answer these outstanding issues.

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