Response of LAI-2000 estimates to changes in plant surface area index in a Scots pine stand

HEIKKI SMOLANDER¹ and PAULINE STENBERG²

¹ The Finnish Forest Research Institute, Suonenjoki Research Station, FIN-77600 Suonenjoki, Finland
² Department of Forest Ecology, P.O. Box 24, FIN-00014, University of Helsinki, Finland

Received March 16, 1995

Summary We assessed the accuracy with which the LAI-2000 plant canopy analyzer measured changes in leaf area index (LAI) and plant area index (PAI) in a 25-year-old Scots pine (Pinus sylvestris L.) stand. Stand density was 2100 stems ha⁻¹ and mean tree height was 8.7 m. Needle and branch areas of the stand were reduced progressively to zero by the stepwise removal of branches on all trees growing in a circular plot with a radius of 25 m. An LAI-2000 estimate was taken after each step reduction. The needle and branch surface areas removed at each step were estimated from direct measurements and were compared with the changes in the LAI-2000 estimates. Initially (before removal of branches), directly measured PAI was 5.2 (needles = 86%, branches = 8% and stems = 6%). The LAI-2000 estimate of total surface area was 66% of direct PAI and 77% of direct LAI. There was a nonlinear relationship between the LAI-2000 estimate and directly measured PAI, such that their ratio (equivalent to the clumping factor) increased from 0.66 to 1.05 with decreasing PAI. At the last measurement, when only stems were left, the LAI-2000 estimate agreed well with the direct measurement of PAI.

The LAI-2000 underestimated the direct measurement of LAI at the first three steps when LAI was > 2 and the proportion of woody area was small (< 20%). However, because the LAI-2000 estimate included stem and branch areas, it overestimated the direct measurement of LAI at the last three measurements when the proportion of woody area was large (> 20%).

Keywords: foliage clumping factor, leaf area index, Pinus sylvestris, specific needle area, STAR.

Introduction

The LAI-2000 plant canopy analyzer (Li-Cor, Inc., Lincoln, NE) often underestimates leaf area in coniferous stands because of the grouping of needles into shoots and branches (e.g., Gower and Norman 1991, Smith et al. 1993, Stenberg et al. 1994). Gower and Norman (1991) proposed that the LAI-2000 gives an estimate of shoot silhouette area index (SSAI) rather than LAI (cf. Fassnacht et al. 1994, Stenberg 1995) and recommended that the instrument reading be multiplied by a correction factor to account for the grouping of needle area on shoots. Stenberg et al. (1994) derived a theoretical relationship between the correction factor and the silhouette to total needle area ratio (STAR) of shoots.

Gower and Norman (1991) obtained a linear relationship between direct estimates of leaf area index and LAI-2000 estimates multiplied by a species-dependent correction factor for red pine (Pinus resinosa Ait.), white pine (Pinus strobus L.), European larch (Larix decidua Mill.) and Norway spruce (Picea abies (L.) Karst.). Stenberg et al. (1994) applied a constant correction factor to LAI-2000 estimates and found that the corrected estimates agreed well with sapwood-area-based estimates of leaf area in several Scots pine (Pinus sylvestris L.) stands; however, when measurements were made in the same stands later in the autumn, the decrease in LAI as a result of litterfall was only partly detected by the LAI-2000.

We have tested the accuracy with which the LAI-2000 measures changes in leaf and plant area indices in a Scots pine stand. Needle and branch areas of the stand were decreased gradually by the stepwise removal of all branches and LAI-2000 measurements were made after each step. The needle and branch areas removed at each step were estimated by direct measurements and compared with the changes in the LAI-2000 estimates.

Materials and methods

Measurements were made between August 30 and October 30, 1993, in a circular plot with a 25 m radius, situated in a 25-year-old Scots pine stand near Suonenjoki Research Station (62°39' N, 27°05' E) in central Finland. The stand was established by planting to a density of 2100 stems ha⁻¹ on a site of medium fertility. Mean height and diameter of the trees were 8.7 m and 11.8 cm, respectively. All trees other than the Scots pine (a few broad-leaved and Norway spruce trees), and dead branches below the live crown were removed from the experimental plot and from a 10-m buffer zone.

Below-canopy measurements with the LAI-2000 analyzer were made about 1 m above the ground in a grid of 6 × 6 points at 1.5-m intervals, marked by stakes located in the center of the plot (Figure 1). Above-canopy measurements were taken automatically every 15 s from a 9-m-high platform in the stand. A 90° view restrictor was used in all measurements to prevent
direct sunlight from reaching the sensor and to occlude the operator from the area of view.

After the first LAI-2000 measurement, the needle and branch areas were gradually reduced and a new LAI-2000 estimate was taken. The reduction was done in five steps, by removing one randomly selected branch of each whorl of each tree on the experimental plot and the buffer zone. At the last step, all remaining branches were removed (average number of branchers per whorl was 5.5). At each step, the branches removed from the experimental plot were collected in bags and transferred to cold storage (−4 °C) for further analysis. At the end of the experiment, all stems were removed from the circular plot and a final LAI-2000 measurement was made to check for a possible edge effect of the surrounding stand.

The total needle surface area (LAI) removed at each step was calculated from needle dry weight (48 h at 80 °C) and specific needle area (SLA), which was determined on a tree and a whorl basis from branches collected at Step 3 by the following procedure. The SLA was first determined separately for one branch of each whorl from 21 trees located in the center of the experimental plot (see Figure 1). The shoots were cut from the branch, and needles were removed from three randomly selected shoots. Needles were carefully mixed, and projected needle area and dry weight of a subsample (of about 3 g needle fresh weight) were measured. Total needle surface area was estimated as π times the projected needle area (see Johnson 1984). The SLA by whorls is shown in Figure 2.

The SLA of a tree was obtained as the mean of the SLA of its branches, weighted by the needle dry weight of each branch. The SLA for the whole canopy (SLA_c) was then estimated as the mean SLA of the sample trees, weighted by the total needle dry weight of the trees. Finally, the total needle area removed at each step was obtained by multiplying the dry weight of all the removed needles by SLA_c.

Litterfall was collected during the period of measurement and was taken into account in the LAI estimates. It was assumed that the litterfall occurring between two measurements was proportional to the standing LAI at that time.

The branch area index (BAI, total surface area) removed at each step was estimated from photographically recorded projected areas of the branches from the same 21 trees used to determine SLA. The total surface area of a branch was estimated as the projected area multiplied by π. In addition, the stem surface areas of the same 21 trees used to determine SLA_c were estimated from stem diameter measurements made at 1-m intervals, and assuming each section to be a cylinder. Plant area index (PAI, total surface area) is the sum of needle, branch and stem area indices.

**Principle of the LAI-2000**

The LAI-2000 estimate is based on the assumption that the canopy consists of regions of randomly distributed leaves or needles of convex shape that are uniformly oriented with respect to azimuth. Thus, it can be shown that leaf area index, which is assumed to be equivalent to half of the total needle surface area \( L = \frac{LAI}{2} \), is obtained as (Miller 1967, Lang 1991, Chen and Black 1992, Stenberg et al. 1994):

\[
L = -2\int_0^{\pi/2} \ln[T(\theta)]\cos\theta \sin\theta d\theta,
\]

where \( T(\theta) \) is the canopy transmittance (gap fraction) at the zenith angle \( \theta \).

The optical sensor of the LAI-2000 plant canopy analyzer comprises five detectors, arranged in concentric rings, that measure radiation (below 490 nm) from different sections of the sky. Canopy transmittance for these different sections is
computed as the ratio of below-canopy and above-canopy readings for each detector ring, and the LAI-2000 estimate of leaf area index is calculated from these transmittance values as:

\[
\text{LAI-2000} = -2 \sum_{j=1}^{5} \frac{1}{n} \left[ \sum_{i=1}^{n} \ln(tr(i,j)) \right] \cos \theta_j w_j,
\]

where \(tr(i,j)\) denotes the ratio of below- and above-canopy readings for the detector ring \(j\) taken at location \(i\), \(\theta_j\) is the zenith angle corresponding to ring \(j\), and \(w_j = \sin \theta_j \Delta \theta\) is the weight attributed to ring \(j\).

Theoretically, if the canopy were comprised solely of leaves, the LAI-2000 estimate would correspond to one half of the total leaf surface area index (LAI/2) (Equations 1 and 2). However, because the instrument sees not only the leaves but also branches and stems, the LAI-2000 estimate includes the woody area and logically should correspond more closely to one half of the total surface area index of all the plant components (PAI/2). Discrepancies between the LAI-2000 estimate and PAI/2 would indicate a nonrandom distribution of foliage, e.g., caused by clumping of needles on shoots.

In this paper, all indices are expressed on a total surface area basis and, consequently, all LAI-2000 estimates have been multiplied by 2.

**Results**

Initially (before removal of branches), direct estimates of LAI and PAI were 4.5 and 5.2, respectively (0.3 from stems and 0.4 from branches) (Figure 3). At each step, the amount of PAI removed was approximately the same, ranging from 0.9 to 1.1. When all stems had been removed, the LAI-2000 gave a zero value indicating that no edge effects were present.

There was a nonlinear relationship between the LAI-2000 estimates (i.e., \(2 \times \text{LAI-2000}\)) and the direct estimates of PAI (Figure 4). Before removal of branches, the LAI-2000 estimate was 3.4, i.e., 66% of direct PAI. The ratio (clumping factor) increased at each step (Figure 4), and was 1 at the last measurement when only stems were left.

At the first measurement (at full leaf area), the LAI-2000 estimate was 77% of direct LAI (Figure 5). The LAI-2000 also underestimated direct LAI at Steps 2 and 3. For Steps 1–3, i.e., when direct LAI was > 2 and the proportion of woody area was < 20%, the relationship between the LAI-2000 estimates and direct estimates of LAI appeared to be linear with a slope of 0.58. The LAI-2000 estimate was larger than the direct LAI at Steps 4–6 when the woody area was > 20%. Overestimation at Steps 4–6 occurred because the LAI-2000 estimates include stem and branch areas, and hence LAI is overestimated when the proportion of woody area is high.
Figure 6. Direct estimates of the decrease in PAI by components (columns) and the decrease estimated by the LAI-2000 during step-wise removal of branches (○).

The ratio between indirectly and directly estimated removal of plant surface area ($\Delta$LAI/2000/ΔPAI) increased with increasing branch removal. The LAI-2000 detected 48% of the removed PAI at Step 1 and 80% at Step 5 (Figure 6).

Discussion

The nonlinear relationship between the LAI-2000 and PAI measured directly (Figure 4) can be partly explained by the fact that the proportions of leaf area (LAI), branch area (BAI) and stem area (SAI) changed between measurements. The LAI-2000 gave a good estimate of SAI. However, because the spatial distribution of needles is clumped, the LAI-2000 underestimated needle area. Consequently, the slope of the relationship between the LAI-2000 estimate and direct PAI will decrease with increasing PAI, whenever LAI increases faster than SAI.

Although the LAI-2000 is commonly used to estimate LAI, it cannot separate leaf area from branch and stem areas. Consequently, if the proportion of woody area is large, the LAI-2000 estimate will be in error. Also, the intercept of the relationship between the LAI-2000 estimate and the true LAI will always be positive (Figure 5). Although the relationship is initially nonlinear, at large values of LAI (relative to woody area) the slope approaches a constant value. This value, which may be interpreted as the ratio of the decrease in needle area determined by the LAI-2000 to the actual decrease in needle area, will be $<1$ because of the clumping of needles on shoots. Stenberg et al. (1994) referred to this ratio as the shoot shading factor, and showed that it is equal to the mean STAR (STÅR, spherically averaged ratio of shoot silhouette area to total needle area) of shoots in the canopy multiplied by 4.

In this study, the slope of the relationship between the LAI-2000 estimate and direct LAI approached 0.58. This corresponds to a STAR of 0.145, which is a reasonable value (Oker-Blom and Smolander 1988, Smolander et al. 1994). The slope value of 0.58 is also very close to the value of the constant correction factor (0.57) used by Stenberg et al. (1994) to convert LAI to SSAI (shoot silhouette area index). Stenberg et al. (1994) were able to apply this constant correction factor to LAI-2000 estimates across a range of LAI values. However, this was not possible with our data because the relationship between the LAI-2000 estimates and direct LAI was nonlinear and had a positive intercept, hence the asymptotic value of the slope was not equal to the ratio of the LAI-2000 estimate to the true LAI and therefore could not be used as a correction factor.

We have identified problems in using the LAI-2000 to measure LAI in coniferous stands. Our results show that, in coniferous stands with a marked proportion of woody area, previously proposed techniques to convert an LAI-2000 estimate to a true LAI (e.g., Gower and Norman 1991, Stenberg et al. 1994) may not be applicable. In this experiment, the proportion of woody area was changed unnaturally, the proportion of branch area remained relatively constant (8%), but the proportion of stem area increased from 6 to 25%, and so at Steps 4–6 the proportion of woody area was larger than is common in young stands (e.g., Swank and Schreuder 1974). However, in older stands the proportion of woody area may be too high to be neglected. For such stands, the amount and distribution of woody area should be included in models designed to describe the relationship between the LAI-2000 estimate and the true PAI and LAI.

Foliage clumping at scales larger than the shoot, e.g., grouping of shoots in branches and crowns, may also have contributed to the nonlinear relationship between the LAI-2000 estimate and direct PAI obtained in this study. As the tree crowns were thinned by branch removal, the effect of clumping at scales larger than the shoot was reduced, whereas clumping within the shoots remained the same. Thus, reduced overall clumping with decreasing LAI may have resulted in an increase in the ratio between the LAI-2000 estimate and direct PAI.

References


