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An assessment of ground reference methods for estimating LAI of boreal forests

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ABSTRACT

The amount of green leaf area, quantified by the leaf area index (LAI), is one of the key factors determining ecosystem net primary production and energy exchange between land surfaces and the atmosphere. LAI can be measured indirectly using optical methods that are based on the tight relationship between LAI and canopy light transmittance, or through allometric regression models. Until now there has been very little research to compare LAI estimated by the two different approaches. In this study we compare optically-based estimates of LAI to estimates produced using local foliage biomass models for three boreal tree species. Our study is based on 661 Scots pine, Norway spruce and Silver birch stands in the southern boreal zone in Finland. Routine stand inventory and LAI-2000 Plant Canopy Analyzer measurements were performed in all stands. We used three allometric foliage mass models to calculate foliage masses for each stand. The foliage mass estimates were then converted to LAI using specific leaf area (SLA) values. A theoretical stem diameter distribution was also used together with the only diameter-dependent foliage mass models. Optical LAI was corrected for shoot-level clumping (i.e., the clumping of needles into shoots). Finally, we estimated LAI from measured canopy gap fractions by inverting a canopy radiation model. Allometric foliage mass models produced significantly different foliage mass estimates (and the LAI estimates based on them). Among the allometric methods, however, the most sophisticated in terms of input tree variables agreed fairly well with each other and also with the clumping-corrected optical methods. The results indicate a need for caution when using foliage biomass or LAI estimates calculated using different models, especially if the estimates are to be used as an input for other models. The simple shoot-level clumping correction of optical LAI showed the best fit with allometric LAI. Our results support the use of a simple shoot-level clumping correction instead of more complicated correction methods in optical LAI estimation in coniferous forests.

1. Introduction

Leaf area index (LAI) is defined as the hemisurface area of green leaves (needles) per unit horizontal ground surface area (Chen and Black, 1992). Thus, it is a measure of the amount of photosynthetically active tissue in a forest stand. The LAI of the tree-layer of a forest can be measured indirectly using optical methods (fisheye photography, LAI-2000 Plant Canopy Analyzer) that are based on the tight relationship between LAI and canopy light transmittance. LAI can also be estimated through allometric regression models. Allometric equations are based on relationships between woody structures (e.g. tree height and stem diameter) and foliage mass. These regression models take easily measurable tree variables as an input and produce an estimate of dry foliage mass, which can be converted to stand-level LAI using species-specific values of the specific leaf area (SLA) and stand density.

Each method for estimating LAI has its drawbacks (e.g., Gower et al., 1999; Bréda, 2003; Jonckheere et al., 2004). Optical LAI estimation methods tend to underestimate LAI in forests, especially in coniferous forests, because the canopy structure is clumped (Smith et al., 1993; Stenberg et al., 1994; Stenberg, 1996). This happens despite the fact that instruments such as the LAI-2000 cannot separate between leaf area and woody area and thus theoretically would give an estimate of the total plant area index (PAI) instead of LAI (Stenberg et al., 2003). There have been many attempts to correct the underestimation of LAI using different correction factors, i.e. shoot- and stand-level clumping corrections (Gower and Norman, 1991; Smith et al., 1993; Stenberg et al., 1994; Stenberg, 1996; Chen, 1996). Because the clumping of needles into shoots allegedly accounts for a major part of the total clumping effect (Stenberg, 1996), the shoot-level clumping factor, also used in this study, has become a popular option to correct optical LAI estimates in, for example, remote sensing applications (e.g., Heiskanen et al., 2012). A more sophisticated clumping correction method is provided by canopy radiation models (e.g., Nilson, 1999), which take measured canopy transmittance values and forest variables as an input. However, these models require several forest variables that are seldom measured in forest inventories.

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The allometric models also have their drawbacks because the models are often size-, stand- and site-specific, i.e. they depend on the representativeness of the measured data, and local climate and soil properties. Unlike optical methods, allometric models are not applicable for monitoring seasonal changes in foliage biomass and hence LAI. The green biomass of a canopy can be converted to LAI using canopy averaged values of SLA. However, SLA is a rarely measured variable and varies with canopy position and season. In birch, for example, the seasonal changes in SLA may result in ±24% variation in allometric LAI values (Sellin and Kupper, 2006). In Finland, the foliage biomass of pine stands reach their largest values at the end of the growing season (Jalkanen, 1986), whereas for spruce the seasonal variation is even smaller because the needle fall is more uniform over the year (Viro, 1955). Although the seasonal variation of LAI in coniferous stands has not been extensively investigated, fluctuations of 5–15% in optical LAI have been reported in case studies (Rautiainen et al., 2012; Heiskanen et al., 2012).

Until now there has been very little research to compare optical *in situ* LAI measurements, LAI obtained from allometric foliage mass models and LAI obtained from the inversion of canopy radiation models. Jonckheere et al. (2005) investigated the relationship between optical LAI and allometric LAI. For their study stands, the allometric and shoot-level clumping corrected LAI values were two times larger than the optical LAI. They concluded that optical LAI estimation methods are very sensitive to different correction factors. Stenberg et al. (2003), on the other hand, analyzed the effect of branches and stems on optical LAI in two experiments, where LAI of two Scots pine stands was gradually reduced by removing branches or whole trees. They observed that the ratio of optical LAI to direct estimates of LAI obtained through allometric relationships ranged from 0.63 to a value of 1.16 which was obtained in the last step of branch removal experiment when the sum of the stem and branch area indices was almost as large as LAI. The ratio of optical LAI to PAI, on the other hand, remained relatively stable (at 56–69%) in both experiments.

Optical methods can be used in a wide range of forest conditions and the results are known to be robust. Allometric methods are easy to apply if forest inventory data bases are available, yet tend to be site-specific. The use of canopy radiation models is a theoretically valid approach, but requires relatively large amounts of data or additional parameterization. Using an extensive forest inventory database, the aim of this study is: (1) to compare popular foliage mass models for three boreal tree species in Finland, (2) to compare optical *in situ* LAI and allometric LAI, and (3) to compare the optical and allometric LAI with LAI obtained from the inversion of a canopy radiation model.

2. Materials and methods

2.1. Stand inventory data

Our study sites Puumala (28°42′E, 61°31′N) and Saarinen (27°29′E, 62°40′N) are located in the southern boreal forest zone in Finland and comprise a total of 661 study stands (Table 1). The stands are dominated by Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst) and Silver birch (*Betula pendula* Roth). In both study sites, the stands formed a systematic grid in which the distance between measurements points (i.e., stand center points) was 50 m. The stands were classified into four groups (‘pine’, ‘spruce’, ‘birch’ and ‘mixed’) based on the dominant tree species. In pine, spruce and birch stands at least 70% of the trees (by stem count) belonged to the aforementioned species, respectively. For each stand, foliage masses were calculated according to species composition. Relascope sampling was carried out at the center of each stand, and a median tree was identified based on its diameter at breast height (dbh). For each stand, we measured trees per hectare (n) and basal area (ba), and for the median trees also dbh, tree height (h) and length of living crown (cl) (Table 1).

Table 1
The number of stands and their classification according to dominating (>70%) tree species, and a summary of forest variables for all study stands. Abbreviations: n = number of trees per hectare, ba = basal area (m^2/ha), dbh = diameter at breast height (cm), h = tree height (m) and cl = crown length (m).

	Pine	Spruce	Birch	Mixed
Stands	269	209	35	148
n_{avg}	1064	929	1127	713
n_{range}	47–3616	22–7898	89–3111	128–2625
ba_{avg}	16.4	20.4	13.9	19.2
ba_{range}	1–46	2–69	2–32	4–46
dbh_{avg}	14.0	17.3	9.1	13.1
dbh_{range}	4.5–25.2	4.1–34.1	2.6–17.8	6.1–26.3
h_{avg}	11.6	14.7	9.0	11.8
h_{range}	2.6–17.8	4.9–22.5	2.5–17.2	5.3–20.4
cl_{avg}	6.2	9.9	5.4	6.9
cl_{range}	1.4–10.9	2.7–19.1	1.8–9.9	3.1–14.3

2.2. Optical LAI measurements

The optical LAI measurements were conducted in July when leaves and needles are fully developed. The optical LAI for all stands was measured using two LAI-2000 Plant Canopy Analyzer units simultaneously (LI-COR, 1992). The LAI estimation method is based on the inversion of canopy transmittance according to Beer’s law (Monsi and Saeki, 1953). The instrument measures the transmittance in different directions through plant canopies in the blue wavelength region (320–490 nm), where the light scattering from leaves is minor. Thus, the transmittance values correspond to angular canopy gap fractions. The sensor’s field-of-view (FOV) extends over almost 150° and is divided into five concentric rings (i) centered at zenith angles θ_i that are given weights (W_i) according to the part of the hemisphere that they cover.

The optical LAI (LAI_{Opt}) was computed as (LI-COR, 1992):

$$LAI_{Opt} = \sum_{j=1}^{15}\left[-2\sum_{i=1}^{5}\ln[T_j(\theta_i)]\cos\theta_i W_i\right] \quad (1)$$

where $T_j(\theta_i)$ is the measured angular canopy gap fraction at point j. The measurements were performed at the center of the stand and at six meters distance in each cardinal direction. Three readings were made at each measurement point. The LAI-2000 units were intercalibrated before the measurements were carried out. The other unit was placed in an open field, while the other was operated below the canopy in the forest. A more detailed description of the measurements can be found in Rautiainen et al. (2009).

The optical LAI-2000 measurements were used to obtain two different LAI estimates: (1) the direct output of the instrument, i.e. optical LAI (LAI_{Opt}, Eqs. (1) and (2) a clumping corrected version of the optical LAI, i.e. LAI_{Opt} divided by a species-specific shoot-level clumping factor. The shoot-level clumping factor (SLC) is equal to 4 × STAR, where STAR is the mean silhouette to total leaf area ratio (Oker-Blom and Smolander, 1988; Thérézien et al., 2007). A STAR value of 0.147 was used for pine (Smolander et al., 1994); it is based on a large number of shoots representing different age and site fertility classes in Finland and Sweden. For spruce, on the other hand, STAR was set to 0.161 (Stenberg et al., 1995); it is based on data from the same study area as the SLA value we used for spruce. The clumping correction was not applied to deciduous species. We will refer to the direct output of the LAI-2000 device as LAI_{Opt} and the shoot-level clumping corrected value as LAI_{Slc} (Table 2).