



Comparison and sensitivity analysis of instruments and radiometric methods for LAI estimation: assessments from a boreal forest site

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Abstract

Retrievals of LAI from inversion of canopy radiometric measurements, using the Li-Cor LAI-2000 Plant Canopy Analyzer and the Decagon AccuPar Ceptometer (a linear quantum probe) were analyzed and compared. Field data were collected from 34 sites in the boreal forest of interior Alaska, and sensitivity tests were conducted to estimate the effect of a variety of measurement conditions on the LAI retrievals. We also tested the response of estimated LAI to different values of the theoretical parameters in the retrieval algorithms. Uncertainty in the incident radiation level was magnified by the LAI retrieval, meaning that even small errors in this measurement significantly affected the LAI estimates. Changes in solar zenith angle over long data acquisition times also contributed to the errors. The most important quality control factors for accurate retrieval of LAI from field measurements were the incident radiation and solar zenith angle. A series of sensitivity tests showed that extreme values of leaf angle distribution could change LAI estimates, but our multi-angle measurements produced results consistent with a spherical leaf angle distribution. Alternative methods taken from the literature for post-processing of the data from the two instruments produced similar results for the LAI-2000, but widely different results for the Decagon AccuPar. Retrievals from the two instruments had an overall correlation coefficient $r = 0.88$, ($P < 0.01$). Agreement was considerably better in aspen stands ($r = 0.85$, $P < 0.01$, $N = 43$) than in spruce ($r = 0.56$, $P < 0.05$, $N = 22$). Some of the variability was attributed to spatial heterogeneity within stands, particularly sparse spruce canopies. Overall, our results suggest the retrievals were robust, and largely comparable between instruments over a range of measurement conditions, provided variability in measurement conditions was adequately characterized.

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1. Introduction

Accurate, repeatable measurements of canopy leaf area index (LAI) are useful for many models of vegetation photosynthesis in forest ecosystems (Goetz and

Prince, 1998; Gower et al., 1999; Liu et al., 1997). LAI is also used to estimate exchanges of water and energy between vegetation and the atmosphere (Canadell et al., 2000; Sellers et al., 1986). Direct measurement of LAI is, however, laborious and so used mainly for cultivars that are harvested annually. To facilitate field estimation of LAI, a great deal of research has gone into development of indirect optical radiometric meth-

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ods. In addition to a large body of theoretical work, there are several commercially available instruments to assist in the rapid estimation of LAI over relatively large areas using various sampling methods (Welles and Cohen, 1996). These instruments employ the same elementary theory of canopy transmission of radiation, but the theoretical and methodological implementations differ in the optimal conditions for measurement, the ancillary information required for LAI retrieval, and the mathematical means employed to account for canopies that often diverge in important ways from theoretical assumptions.

We used two different instruments, a Decagon AccuPar Ceptometer (Decagon Devices, Pullman, WA, USA) and a Li-Cor LAI-2000 Plant Canopy Analyzer (Li-Cor, Inc., Lincoln, NE, USA) to estimate LAI at 34 sites in interior Alaska. Supplemental field measurements were taken to estimate the uncertainty in various parameters used for retrieval of LAI from radiometric measurements. We used our field data to construct tests to estimate the sensitivity of the retrieved LAI to various types of random and systematic error. We then performed a detailed comparison of LAI retrieved by both instruments using simultaneously acquired measurements. The results presented here are relevant to both the field measurement protocols necessary for accurate use of these instruments, as well as the theoretical aspects of LAI retrieval from radiometric measurements.

2. Background: theory and application of indirect LAI retrieval

LAI is an index of canopy density that relates the foliage surface area of a canopy to the ground area beneath the canopy (Ross, 1981). It can be more strictly defined as one-half the total green leaf area per unit ground surface area. This definition, while simple, does not directly translate into light-intercepting surface area or associated biophysical processes. However, this definition allows simple calculation of projected leaf area, with few assumptions (Lang, 1991; Chen and Black, 1992; Li and Strahler, 1992). Projected leaf area is relevant to radiometric estimation of LAI because the interaction of canopy elements with incoming solar radiation is central to the indirect LAI estimation approach.

2.1. Mathematical basis for LAI retrieval by radiometric inversion

Transmission of light through a partially transparent medium is described by Beer's law,

$$I_{\text{trans}} = I_0 e^{-\varepsilon bc} \quad (1)$$

where I_{trans} is the intensity of transmitted light, I_0 the intensity of incident light, ε the absorptivity of medium, b the pathlength through medium and c the concentration of absorbent.

This equation can be adapted to estimate canopy light transmission for a given canopy density. In the case of light measured beneath the canopy at a specific angle, $I_{\text{trans}}(\theta, \phi)$, the variables of Eq. (1) take the following forms and dependencies:

- (1) Intensity of the incident hemispheric light source I_0 varies as a function of wavelength λ , zenith angle θ and azimuth angle ϕ .
- (2) Absorptivity ε includes both the reflective properties of the canopy materials and the effects of leaf orientation. To adapt this equation into a useful form, we will divide this into two terms. The first designates only the material absorptive properties and will be designated $a(\lambda)$. The second term is the leaf projection function, which describes the effects of leaf orientation, and is designated as $G(\theta, \phi)$.
- (3) Assuming the canopy is spatially continuous, pathlength b will be related to θ and canopy height z by $b = z/\cos \theta$.
- (4) With the equation in this form, concentration c is equal to canopy density. If we remove the canopy height z from the equation, c becomes LAI L , and our formula looks like this:

$$I_{\text{trans}}(\theta, \phi, \lambda) = I_0(\theta, \phi, \lambda) e^{-a(\lambda)G(\theta, \phi)L/\cos \theta} \quad (2)$$

If we arrange this equation in terms of transmission $\tau = I_{\text{trans}}/I_0$, we obtain

$$La(\lambda)G(\theta, \phi) = -\ln \tau \cos \theta \quad (3)$$

The right-hand side of Eq. (3) contains the easily measurable canopy transmission. The left-hand side contains the desired canopy structural information. This equation is the basis for estimation

of canopy structural properties from inversion of radiometric measurements. To estimate LAI from canopy light transmission, one or more measurements of transmission are needed, together with a model to account for the absorptivity $a(\lambda)$ and the leaf orientation function $G(\theta, \phi)$. The two methods described in this paper use different approaches to achieve this, which determine the measurement method, the optimal conditions for measurement, and the additional information required in order to calculate the LAI. The methods used to retrieve LAI from the LAI-2000 Plant Canopy Analyzer and the Decagon AccuPar instrument are discussed in detail below.

2.2. Problems with the radiometric inversion method

Retrieval of LAI by radiometric inversion offers several advantages over direct sampling of leaf area, allowing rapid non-destructive sampling over large areas. However, the inversion as described above makes some assumptions about the structural and radiative properties of plant canopies that are at odds with what is observed in real canopies. These problems have been analyzed in the literature, and methods proposed to correct the resulting bias in LAI, either with additional information about the canopy, or with changes to the sampling methodology. The most significant problems are discussed below, together with the corrections proposed in the literature.

2.2.1. Foliage in canopies is not distributed randomly either vertically or horizontally

Clumping of canopy elements at scales from boles to needles on shoots will result in a canopy transmission greater than predicted from the random model, and thus an underestimate of LAI (Begue, 1993; Chen and Cihlar, 1995a; Fassnacht et al., 1994; Smith et al., 1993). The non-random spatial distribution of canopy elements results in a distribution of canopy gap sizes very different from that predicted (Chen and Cihlar, 1995a). Chen and Cihlar also described how the distribution of observed canopy gap sizes could be measured, and employed this distribution to correct indirect estimates of LAI (Chen and Cihlar, 1995b). A large body of work deals with the application of these methods to a variety of forest types (Chen, 1996; Chen et al., 1997a; Fassnacht et al., 1994; Gower et al.,

1999; Kucharik et al., 1997, 1999; Smith et al., 1993; Walter et al., 2003). Some forests, such as Douglas fir, were found to have similar clumping indices over a wide range of stand characteristics (Smith et al., 1993). Other forests displayed substantial dependence of clumping indices on stand age, stocking density, and other stand characteristics (Dufrene and Breda, 1995; van Gardingen et al., 1999).

A simpler approach, proposed by Lang and Xiang, takes multiple spatial samples of the area of interest, and imposes a quasi-random model on the observations by using the geometric mean of the samples rather than the arithmetic mean (Lang and Xiang, 1986). This method requires a modification of experimental design to ensure spatial sampling effectively captures the relevant scales of foliage clumping, but does not demand additional information about the canopy beyond the radiometric measurements. This method is implemented for both the LAI-2000 and the Decagon AccuPar for this paper.

2.2.2. Optical retrieval of LAI does not account for light absorption by non-photosynthetic canopy elements

LAI estimated from the equations above is actually a plant area index, since absorption by stems and branches contributes to the radiometric measurements. This factor can lead to positive bias in estimated LAI (Barclay et al., 2000; Kucharik et al., 1998a). Kucharik et al. measured surface area of branches and stems in several different forest types, and modeled light absorption for all canopy elements separately. They concluded that branch area is unlikely to cause a large bias in retrieved LAI, because (1) branch area is small compared to leaf area and (2) more than 90% of branch area was shaded by foliage in all species studied. They warn, however, that stems, which have a surface area comparable to that of branches, may not be preferentially shaded by foliage. They did not quantitatively determine the amount of light interception by stems.

2.2.3. Radiative properties of leaves are greatly simplified

The model used to derive Eq. (3) treats leaves only as absorbers, ignoring leaf transmission and scattering, and all second-order radiative effects. Scattering of light within canopies and light transmission through leaves can be significant sources of bias in radiometric

measurements of canopy light interception, leading to an overestimate of canopy transmission, and underestimation of LAI (Leblanc and Chen, 2001; Roujean, 1999; Spanner et al., 1994). These effects are strongly dependent on wavelength, and manifest themselves differently for the LAI-2000 and the Decagon Accu-Par. These problems are discussed in the sections below pertaining to each instrument.

2.3. Retrieval of LAI using the LI-COR LAI-2000 Plant Canopy Analyzer

The LAI-2000 measures incoming radiation using a fisheye lens apparatus. The hemisphere is divided into five zenithal bands or annuli, each of which is directed onto a separate photoelectric sensor. Each annulus measures the complete range of ϕ , though in the field, the azimuthal field of view is often restricted to avoid shadowing effects (see Section 3.2). The instrument also employs a light filter such that $320 \text{ nm} < \lambda < 490 \text{ nm}$ (LI-COR, 1991). In this frequency range, leaves are effectively black (non-reflecting and non-transmitting) and $a(\lambda) = 1$. Thus, for this instrument, the left-hand term of Eq. (3) becomes $LG(\theta)$, which is equivalent to the number of contacts made by a solid probe passing through the canopy at an angle θ (Warren Wilson, 1960). Miller (1967) demonstrated that if $\tau(\theta)$ can be determined through the range $[0, \pi/2]$, then LAI can be calculated as

$$L = 2 \int_0^{\pi/2} -\ln \tau(\theta) \cos \theta \sin \theta d\theta \quad (4)$$

Applying Eq. (4) to calculate LAI then only requires some method of performing the integration across the range of θ . Diffuse lighting conditions are encouraged for this method, for two reasons. First, penetration of the sun's direct beam into the canopy will result in a higher level of light scattering off of leaf surfaces, which could bias the LAI retrieval (Leblanc and Chen, 2001). Second, in direct sunlight conditions, the annulus containing the sun effectively measures the transmission only at $\theta_{\text{sun}}, \phi_{\text{sun}}$, rather than over the entire angular range. This results in some distortion of the estimated $G(\theta)$ function. Note that 90° azimuthal view restrictors were employed in this study to minimize this effect (see Section 3.2).

Two different methods are commonly used to achieve an accurate integration over θ using the

LAI-2000. The first calculates the LAI as a weighted sum of the measured canopy transmission, using the angular ranges of each annulus to calculate fixed weighting factors. This method is built into the software packaged with the LAI-2000. Several authors have noted a bias in the software implementation because the fifth (lowest) annulus, which measures radiation in the range $61^\circ < \theta < 74^\circ$, is used to estimate transmission in the range $61^\circ < \theta < 90^\circ$. This assumption further increases the weight of the fifth annulus in the summation, and also introduces a negative bias in estimated LAI based on predicted behavior of the leaf area projection function. Leblanc and Chen (2001) estimate this bias at around -8% .

A second method used to achieve the integration over θ was proposed by Lang, based on an assumption of linearity in the leaf projection function $G(\theta)$ (Lang, 1987). This approach assumes $G(\theta)$ is approximately linear with θ and has a value near 0.5 at $\theta = 1 \text{ rad}$ (57.3°) over a wide range of canopy and leaf structures, thus LAI should approximate $2(a + b)$, where a and b are the slope and intercept of the linear approximation of $G(\theta)$. Lang (1987) tested this function using measurements of direct radiation from the sun's beam at multiple zenith angles, and found that the assumption of linearity in $G(\theta)$ produced small error in estimated LAI ($< 6\%$), even with a narrow angular range of measurements ($\Delta\theta = 10^\circ$). However, the error associated with using this method with the LAI-2000 will not necessarily be this low, because the angles measured by the LAI-2000 are not centered around 45° , as were the measurements in all of Lang's (1987) trials (Planchais and Pontailier, 1999). This approach reduces the problem of overemphasis of the lower annuli in estimation of LAI by weighting all annuli equally in a linear regression to obtain the slope and intercept of $G(\theta)$.

Several authors have found that the LAI-2000 produces estimates of LAI systematically lower than those obtained from direct measurements and destructive sampling (e.g. Kűßner and Mosandl, 2000; Leblanc and Chen, 2001). Leblanc and Chen (2001), attribute this effect to "contamination" in the lowest ring caused by scattering of light within the canopy, resulting in a higher apparent transmission. This negative bias is often reduced by disregarding the annuli closest to the horizon, and calculating LAI with four, three or even just the two highest annuli (Cutini et al., 1998; Pokorny

and Marek, 2000; Soudani et al., 2001). This approach, however, does not always increase the estimated LAI, for example, Chen (1996) found a decrease in estimated LAI with the elimination of the lowest annulus. A theoretical and experimental analysis of this effect concluded that the magnitude of light scattering in the wavelength region used by the LAI-2000 is too small to cause large underestimation of LAI (Planchais and Pontailler, 1999). Furthermore, the increase in LAI with elimination of rings has been shown to be a consequence of the shape of the leaf projection function $G(\theta)$, resulting in positive errors in LAI retrievals using restricted angular ranges (Planchais and Pontailler, 1999).

2.4. Retrieval of LAI using the Decagon AccuPar Ceptometer

The Decagon AccuPar Ceptometer is a probe consisting of 80 PAR quantum sensors arranged at 1-cm intervals beneath a light-diffusing shield. Each sensor measures radiation in the range $400 \text{ nm} < \lambda < 700 \text{ nm}$. The LAI retrieval used by this instrument differs in several important ways from that of the LAI-2000:

1. In the range of wavelengths measured by this instrument, leaf reflectance and scattering cannot be ignored, and must be included in the canopy light transmission model.
2. For diffuse radiation, the integration across θ is effectively done by the sensor itself. Because the ceptometer does not partition incoming radiation by zenith angle, the leaf angle projection function $G(\theta)$ need only be included for direct beam radiation.
3. Information about leaf orientation cannot be inferred from ceptometer measurements, because the measurement cannot be divided by zenith angle.

The model for retrieval of LAI from the ceptometer measurements of canopy light transmission is derived and simplified from a model of canopy light transmission by Norman and Jarvis (1975). The first published version of this retrieval comes from Norman (1988) (from Welles, 1990):

$$L = \frac{[f_b(1 - \cos \theta) - 1] \ln \tau}{0.72 - 0.337 f_b} \quad (5)$$

where f_b is the beam fraction: the fraction of direct (non-diffuse) radiation, τ the canopy transmittance (transmitted PAR/incident PAR) and θ_s the solar zenith angle.

In Eq. (5), the beam fraction f_b partitions the incoming radiation between direct and diffuse. The mechanisms employed to account for leaf angle distribution, canopy light transmission, and scattering are more explicit in a more detailed retrieval included in the manual for the ceptometer instrument (Decagon Devices Inc., 2001):

$$L = \frac{[(1 - (1/2K))f_b - 1] \ln \tau}{A(1 - 0.47f_b)} \quad (6)$$

This retrieval includes the following additional terms: A is a term for primary and secondary canopy absorption, and K is the canopy extinction coefficient. A is empirically related to the leaf absorptivity a by:

$$A = 0.283 + 0.785a - 0.159a^2 \quad (7)$$

The canopy extinction coefficient K incorporates the leaf angle distribution function, and the solar zenith angle. For an ellipsoidal leaf angle distribution, K is described by

$$K = \frac{(x^2 + \tan^2 \theta_s^2)^{1/2}}{x + 1.744(x + 1.182)^{-0.733}} \quad (8)$$

where x is the leaf angle distribution parameter (ratio of horizontal to vertical axes of ellipsoidal leaf distribution) (Campbell, 1986).

This retrieval is considerably more versatile than Eq. (5), but with the substitutions $a = 0.64$ and $x = 1.0$ (spherical leaf angle distribution), Eq. (6) is equal to Eq. (5). Literature values for a range between 0.85 and 0.90 for the species relevant to this study (Campbell and Norman, 1998; Dorman and Sellers, 1989). Thus, LAI retrievals using Eq. (5) will differ significantly from those using the longer version. We examined the magnitude of the discrepancy with a sensitivity test, as described in Section 4.1.1.5.

Under entirely diffuse illumination ($f_b = 0$), Eqs. (5) and (6) both simplify to

$$L = -\frac{\ln \tau}{A} \quad (9)$$

This is equivalent to the result obtained from Eq. (4) assuming a spherical leaf angle distribution ($G(\theta) =$

0.5), with a correction in the denominator for incomplete absorption of radiation by leaves.

Canopy non-randomness is just as much a problem for the AccuPar as for the LAI-2000. Analyses of this problem with the AccuPar have mostly dealt with proper application of the log-averaging method (Cohen et al., 1997; Lang and Xiang, 1986). With multiple spatial measurements or using only the 80 measurements taken simultaneously by the AccuPar, a quasi-random model can be applied to canopy units larger than the averaging length. This may not be sufficient, however, especially in conifer stands where clumping of needles on shoots occurs at a scale even

smaller than the 1 cm minimum measurement unit of the ceptometer instrument (Chen et al., 1997b).

3. Methodological approach

3.1. Study area and sampling design

The study area, in the Delta Junction region of interior Alaska, lies about 150 miles southeast of Fairbanks (Fig. 1). Thirty-four sites were selected for a comprehensive examination of post-fire succession and carbon dynamics, with species composition

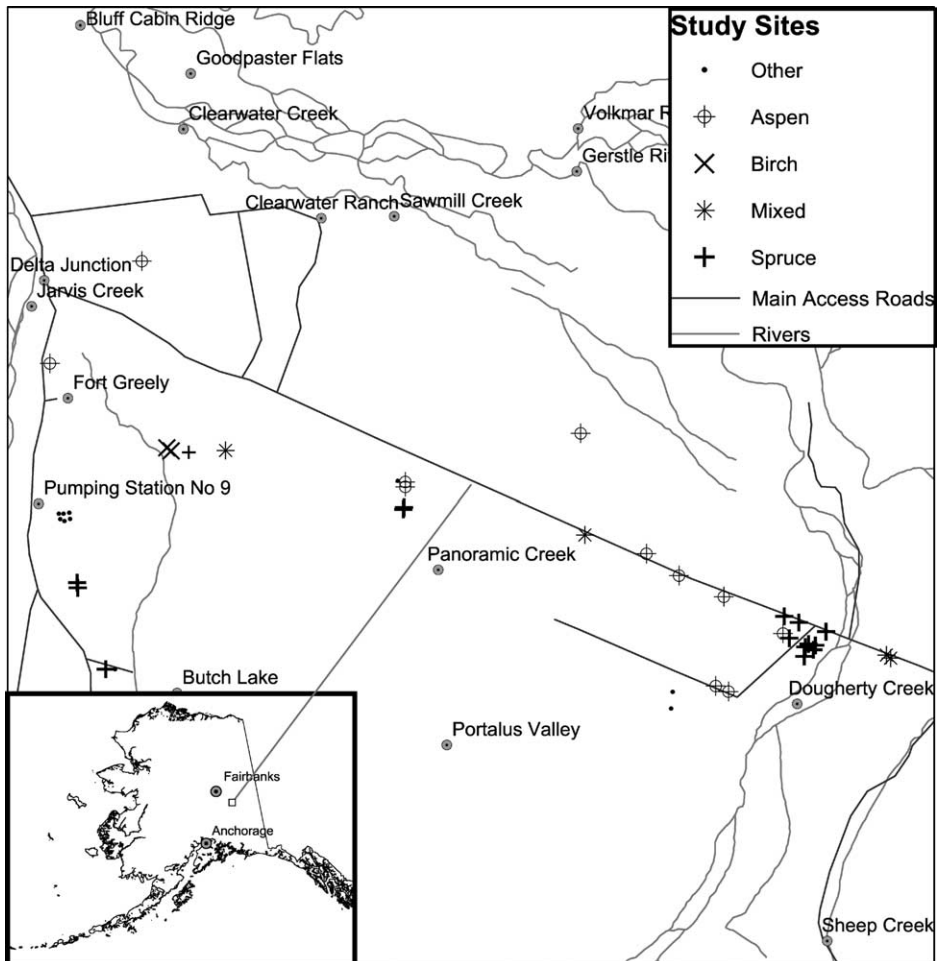


Fig. 1. The study area in interior Alaska, with specific measurement locations and stand types indicated.

dominated by black spruce (*Picea mariana*), quaking aspen (*Populus tremuloides*), and paper birch (*Betula papyrifera*). The sites encompass a broad range of age classes, basal area, stem density, and canopy closure, each influenced by a complex interplay of fire severity, topographic position, microclimate and edaphic conditions.

The field measurement protocol was designed to ensure a consistent and repeatable set of measurements in each dominant forest type within the study area. The sites were spatially variable, thus some compromise was necessary in order to achieve a representative sampling scheme both within and between sites. We were most interested in capturing spatial variation across the study area, but also repeated measurements to capture temporal variability in measurement conditions (sun angle, etc.). In separate work we report on below-canopy light sensors that were run over a period of months, collecting and averaging data at 15 min intervals.

Hand-held instrument measurements were taken in two different spatial arrangements. Ten of the sites were of a “grid” design, where 8 points were laid out at 50-m intervals. In these, we collected below-canopy measurements at 1-m intervals along 10-m transects centered on each point. This strategy was developed to facilitate comparison with other field measurements. The remaining 24 sites were 100-m transects, with below-canopy measurements taken at 10-m intervals along each transect. These sites were established to extend the range of conditions over which data were collected. Each site was located using GPS, and marked for repeat visits.

3.2. Data acquisition

Data acquisition included replicate measurements of incident radiation both above and below the canopy. The ceptometer was used to measure the fraction of direct versus diffuse radiation using a shaded versus sunlit cell comparison. A 90° azimuthal view restrictor was used on the LAI-2000, oriented toward the opposite sky quadrant from the sun’s position. This view restrictor was used for both above- and below-canopy measurements. When possible, the incident radiation and the beam fraction were measured at the beginning and end of each acquisition. In every case, the time was recorded in the field at the beginning and end of

each data acquisition. Solar zenith angles were calculated offline from the site locations and recorded acquisition times using the algorithm of Paltridge and Platt (1976), which is accurate to within 0.05°.

Our measurement strategy was designed to optimize the conditions for LAI retrieval by each of the two instruments. Measurements were preferentially acquired during overcast conditions, because of potential error in the LAI-2000 retrieval caused by direct illumination. When it could be avoided, measurements were not acquired when sky conditions were anisotropic (e.g. partial cloud cover), or when sky conditions were changing. Also, because the LAI-2000 responds non-linearly to light interception by foliage closer than 10 cm to the sensor, we avoided inclusion of ground cover vegetation. LAI measurements for both instruments were taken at the lowest possible point above the ground cover. In different sites, this selection represented a different fraction of the total plant canopy. In early succession sites, for instance, the lower canopy was predominantly willow (*Salix* spp.) and alder (*Alnus* spp.), with very little ground cover. In these sites, our measurements included almost all light interception by vegetation. In contrast, ground cover in the mature black spruce stands consisted primarily of low stature vegetation such as low bush cranberry (*Vaccinium vitis*), and mosses (primarily *Sphagnum* and *Hylocomium* spp.). While these account for a substantial portion of the total vegetation cover, and affect total canopy reflectance (Goetz and Prince, 1996), they could not be included in our measurements of canopy light interception and transmission.

3.3. LAI retrieval and sensitivity analyses

LAI derivation from indirect radiometric measurements is still an evolving science. As described in Section 2, many corrections have been proposed to enhance comparability and stability of LAI measurements, employing a range of ancillary canopy information. In order to explore the assumptions of the retrieval techniques, we performed a sensitivity analysis of each instrument and a comparison between the two instruments. In addition to exploring the assumptions for each instrument in these boreal forest stands, we explore some of the proposed corrections to LAI using general literature estimates, where nec-

essary, for canopy properties (e.g., light absorptivity coefficient) of the species types involved.

For the LAI-2000, multiple measurements of canopy transmission were averaged using the log-averaging technique described by Lang and Xiang (1986). Baseline estimated LAI values were calculated using the method of Lang (1987), also known as the slope–intercept method. All annuli were included in these calculations. For the ceptometer, baseline LAI was computed using Eq. (6), with input parameters calculated as follows:

- $x = 1$ (spherical leaf angle distribution assumed),
- $a = 0.9$ (leaf absorptivity),
- f_b is the arithmetic mean of all measurements of beam fraction,
- PAR_a is the arithmetic mean of all measurements of incident PAR,
- PAR_b the geometric mean of all measurements of below-canopy PAR,
- $\tau = PAR_b / PAR_a$.

In this study, because our PAR_a measurements were taken only at the beginning and end of each collection, we found it preferable to first calculate a mean value of PAR_a to use for every PAR_b measurement. The log-averaging method of reducing bias caused by canopy non-randomness requires that after τ is calculated from each pair of PAR_a and PAR_b measurements, the geometric mean of the pairs is used to calculate the value of τ which will be employed in the retrieval (Lang and Xiang, 1986). We implement this method by using the geometric mean of PAR_b in the calculation of τ .

The LAI retrieval algorithm for the ceptometer incorporates variables measured in the field (PAR_a , PAR_b , f_b , θ), as well as theoretical parameters (a , x). We used our field measurements to estimate systematic and random errors in these inputs. To test the sensitivity of the LAI retrieval to various sources of uncertainty in the model, we designed tests based on the use of our collected data, to supply realistic estimates of uncertainty under the observed measurement conditions. Each sensitivity test consisted of reprocessing all acquisitions for the instrument in question, incorporating one modification to the baseline retrieval for each test. Sensitivity tests were developed based on field data and theoretical considerations. Sensitivity of estimated LAI determined from these

tests is different from a purely analytical solution of sensitivity, because there is significant correlation between input variables, which strongly restricts the range of possible inputs (e.g. θ is negatively correlated with both f_b and PAR_a). We believe these tests are more useful than a purely analytical estimate of uncertainty for determining how measurement conditions affect the information obtained from these instruments in the field.

4. Results and discussion

A total of 113 data acquisitions were made in 34 sites using the Decagon AccuPar Ceptometer, 108 acquisitions were made in 31 sites using the Li-Cor LAI-2000 Plant Canopy Analyzer. Measurements taken simultaneously with the two instruments provided a data set of 89 matched acquisitions from 25 sites for direct comparison of the two instruments.

Estimated LAI in the study sites ranged from 0.1 to 4.1 for the ceptometer, and from 0.1 to 3.8 for the LAI-2000. Statistics of estimated LAI for each instrument are shown in Table 1. The distribution of field measurements of f_b , PAR_a and θ for ceptometer retrievals and the matched data (Figs. 2–4) reflect the data acquisition conditions for LAI-2000, with 96% occurring in diffuse light conditions, i.e., with <20% direct illumination. A number of ceptometer acquisitions taken with $f_b > 30\%$ are included in the sensitivity studies described below, but are not included in the instrument comparison data set because the LAI-2000 instrument was not used under predominantly direct illumination conditions. Data collected during periods with higher f_b values were also characterized by higher values of incident PAR.

Table 1
Number of collections and overall means for estimated LAI for this study. All data used in this study are included here

Species	Decagon		LAI-2000	
	<i>n</i>	Mean (range)	<i>n</i>	Mean (range)
Aspen	47	1.03 (0.22–2.33)	46	1.38 (0.3–2.72)
Birch	4	3.39 (2.81–4.21)	5	3.73 (3.6–3.84)
Mixed	3	1.78 (1.31–2.23)	6	1.95 (0.71–2.43)
Other	32	0.67 (0.09–1.83)	18	0.91 (0.13–1.99)
Spruce	27	1.23 (0.25–4.51)	33	1.40 (0.35–3.34)
All	113	1.08 (0.09–4.51)	108	1.45 (0.13–3.84)

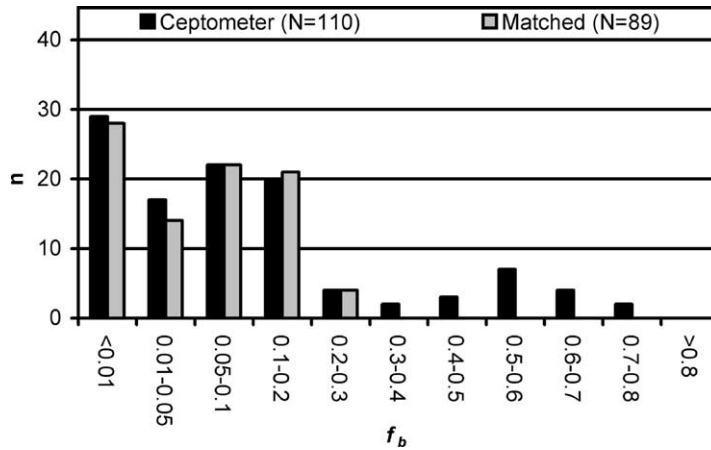


Fig. 2. The distribution of direct versus diffuse illumination conditions for collections in this study. The preference for mostly diffuse conditions in our protocol is evident. The ‘matched’ collections are collections where both instruments were used simultaneously.

4.1. Error estimates for retrieval parameters

4.1.1. Decagon AccuPar Ceptometer

Uncertainty in the estimated LAI as derived from the ceptometer data arises from several sources. The variables measured in the field have uncertainties both from instrument error as well as possible changes in measurement conditions during data acquisition. The theoretical variables required by the ceptometer retrieval also present a source of uncertainty, as their

values depend on canopy properties. Below we present and discuss the results of uncertainty in each component of the LAI retrieval algorithm, and the sensitivity tests used to determine the resulting level of uncertainty in the estimated LAI. The sensitivity tests and the calculated sensitivities are summarized in Table 2.

4.1.1.1. Incident PAR. Variability in the PAR_a measurement, critical to the estimate of τ and LAI, reflects changing illumination conditions during the field

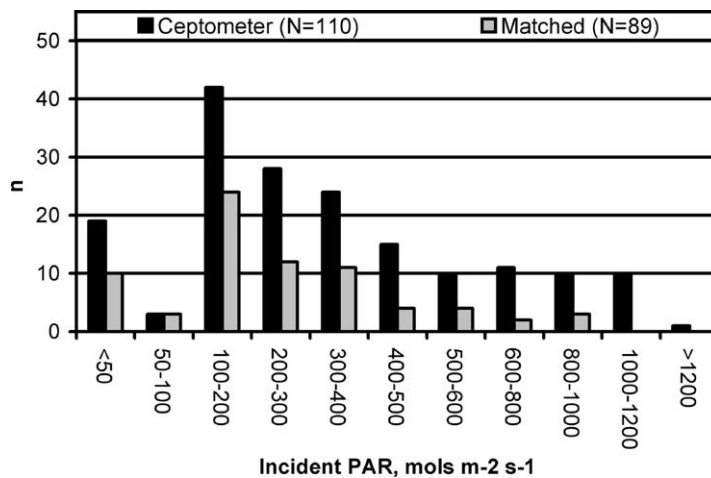


Fig. 3. The distribution of measured incident PAR for collections in this study. Since the matched collections tend to be those with the more diffuse illumination, the matched data set has slightly lower average incident PAR relative to the overall mean for collections with the Decagon AccuPar Ceptometer.

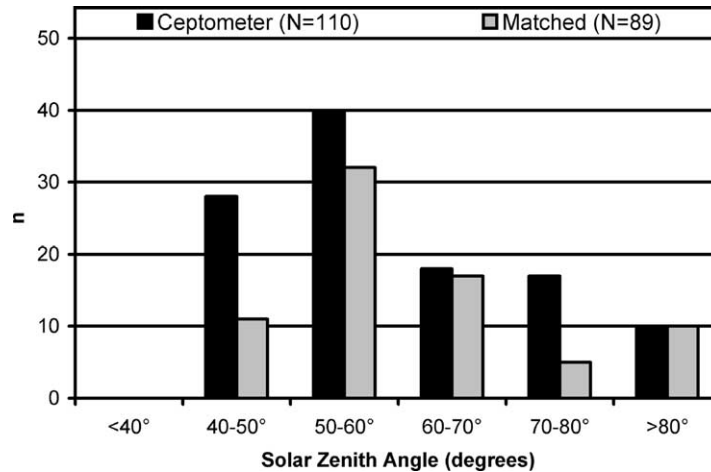


Fig. 4. The distribution of solar zenith angle for collections in this study. At this latitude, the minimum solar zenith angle at the summer solstice is 42° .

data acquisition period. The distributions of recorded changes in PAR_a are shown in Fig. 5. Differences in PAR_a recorded at the beginning and end of data acquisition were less than 15% in 70% of collections.

To simulate uncertainty in incident PAR and estimate its effect on the retrieved LAI, we ran two simulations altering the field-recorded PAR_a values by 10%. We found that uncertainty in measured incident PAR is magnified in the uncertainty of the estimated LAI. The

Table 2
Results of sensitivity tests on the LAI retrieval for the Decagon AccuPar Ceptometer^a

Test	Mean sensitivity (%)
$PAR_a = 1.1 PAR_a$	0.12 (19)
$PAR_a = 0.9 PAR_a$	-0.13 (-21)
$f_b = f_b + 0.1$	0.04 (3)
$f_b = f_b - 0.1$	-0.02 (-2)
Time = time + 90 min	-0.01 (-1)
Time = time - 90 min	-0.06 (-4)
$\theta = \theta + 10^\circ$	-0.04 (-3)
$\theta = \theta - 10^\circ$	-0.02 (-1)
$x = 0.5$	0.08 (5)
$x = 1.5$	-0.03 (-2)
$a = 1$	-0.06 (-5)
$a = 0.64$ (Eq. (5))	0.13 (12)

^a For each test, a single variable in the retrieval was altered, and the LAI was recalculated for all collections. Mean sensitivity is given in LAI units. The numbers in parentheses are the mean sensitivity as a percent of the baseline retrieval. These tests are described in more detail in Section 4.1.

average absolute offset of LAI resulting from a 10% change in incident PAR was in the range 0.1–0.15, with limited sensitivity to measurement conditions and canopy properties. The impact of this offset is larger on acquisitions with low LAI: the average bias in sites with $LAI < 1.5$ was 22–25%, compared with 6–7% for sites with higher LAI. For our study, this means that the change in estimated LAI, for the majority of cases, magnified the effects of uncertainty in incident PAR. Given the distribution of estimated error in PAR_a (see Fig. 5), this seems likely to be the largest source of random error in our LAI estimates.

4.1.1.2. Solar zenith angle. Solar zenith angles for acquisitions ranged from 45° to 85° (see Fig. 4). At the latitude of the study site, the minimum solar zenith angle at the summer solstice was 42° . Because the calculation of solar zenith angle was accurate to within 0.05° (Paltridge and Platt, 1976), the principal source of error in θ was the passage of time during the acquisition. For all cases where the beginning and ending times were recorded, the average time required for field data acquisition at a single site was 79 min, resulting in an average change in θ of 7.03° (Fig. 6).

The sensitivity tests of LAI estimation based on uncertainty in θ , as estimated by altering the acquisition times by 90 min before calculating θ , and in simulations altering the value of θ used to calculate LAI by 10° , we found that frequent measurements of solar

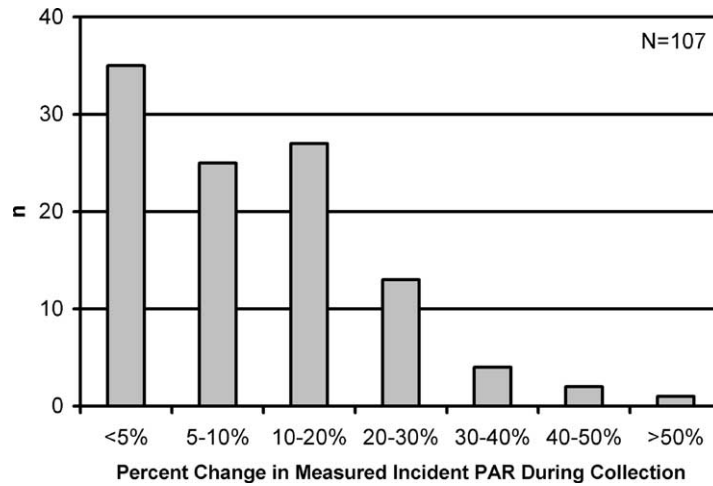


Fig. 5. The distribution of recorded changes in incident PAR calculated from measurements taken at the beginning and end of field data acquisition.

zenith angle were necessary under non-diffuse illumination. Given that the base retrieval uses the midpoint of the acquisition to calculate θ , LAI was not systematically biased, but the amount of random error introduced into the LAI retrieval by an error of 10° , corresponding to about 90 min at mid-day, can be substantial. For cases with $f_b > 0.5$, the 10° offset of θ resulted in a change in retrieved LAI of 5% or more in more than half of the cases.

4.1.1.3. Beam fraction. The distribution of values obtained for the beam fraction (shown in Fig. 2) clearly indicates the preference for overcast skies included in our measurement protocol. Over 80% of the ceptometer acquisitions, and 96% of the matched acquisitions, were taken with less than 20% direct illumination. Uncertainty in f_b , as in PAR_a , resulted both from measurement error as well as from changes in illumination conditions during data acquisition.

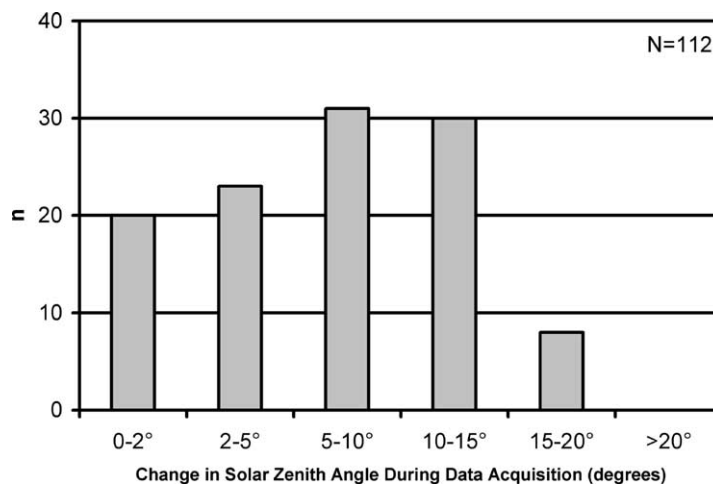


Fig. 6. The distribution of changes in solar zenith angle during field data acquisition. Angles were calculated from the beginning and end times for each acquisition.

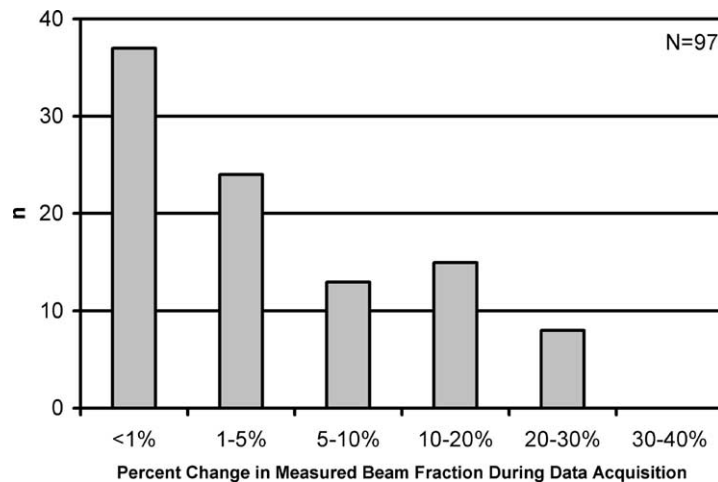


Fig. 7. The distribution of estimated change in the beam fraction of incident PAR during collections, calculated from measurements taken at the beginning and end of each collection.

Estimating this uncertainty using acquisitions with multiple recorded values showed that, in the majority of cases, the observed change in f_b was small (Fig. 7). In approximately 25% of cases, however, the beam fraction changed by more than 0.1 (10%) during the data acquisition period.

Testing the effects of uncertainty in f_b by altering the value of f_b used to calculate LAI by ± 0.1 we found that realistic levels of uncertainty in the measurement of beam fraction were unlikely to substantially affect the retrieved LAI. While f_b is the proportioning coefficient between the direct and diffuse terms of Eq. (3), as long as measurements are confined to conditions of primarily diffuse illumination, the difficulty in exact measurement of f_b does not affect the accuracy of the LAI retrieval. When only those data with $f_b > 0.5$ were considered, the sensitivity increased, but did not exceed an average bias of 5% for a change in f_b of ± 0.1 .

4.1.1.4. Leaf angle distribution. The theoretical inputs to the LAI retrieval used by the ceptometer represent certain assumptions about canopy structure and radiative properties. The leaf angle distribution is well-documented as a central feature in accurate retrievals of LAI from radiometric inversion (e.g. Barclay, 2001; Kucharik et al., 1998b; Welles and Norman, 1991). For the canopy types included in this study, Chen et al. (1997a) found that boreal aspen

canopies had $G(\theta)$ functions matching those predicted for canopies with a spherical leaf angle distribution ($x = 1$). Kucharik et al. (1998b), working in the same study area but with different instrumentation (the Multispectral Vegetation Analyzer), found a best-fit with theoretical models using a highly erectophile leaf angle distribution ($x \sim 0.4$).

Our results suggest that the role of the leaf angle distribution parameter x is small in mostly diffuse lighting conditions, but significant and non-trivial to correct for. Applying a leaf angle distribution $x = 0.5$ to our data, corresponding to strongly erectophile foliage, raised LAI by an average of 5% versus the baseline ($x = 1$). When limited to acquisitions with $f_b > 0.5$, however, this bias increased to nearly 20%. In the case of planophile foliage distribution ($x = 1.5$), the effects on estimated LAI were smaller (-2% for all acquisitions, -8% for $f_b > 0.5$), but still large enough to require a concerted effort to determine the correct value for the sites being studied. The strong dependence of this sensitivity on measurement conditions makes it difficult to apply a simple correction.

4.1.1.5. Leaf absorptivity and alternate retrieval. The leaf absorptivity term a accounts for all non-absorptive responses of the canopy, that is, scattering, reflection, and transmission. These complex radiative processes are represented in a very simple form in Eq. (6), and potentially subject to considerable

differences based on canopy properties, as well as measurement conditions. The importance of this parameter to the LAI retrieval is evident from Eq. (9). For this study, we used a baseline value for a of 0.9, which is consistent with literature values reported for the species relevant to this study (Campbell and Norman, 1998; Dorman and Sellers, 1989). The retrieval published in Welles (1990), shown above as Eq. (5), is mathematically equivalent to our baseline retrieval, but with leaf absorptivity $a = 0.64$. Chen et al. (1997b) report estimates derived from ceptometer measurements in central Canada and processed with Eq. (5), which we assessed in relation to our data.

We conducted two sensitivity tests to estimate the effect on retrieved LAI of this parameter, setting a to 1.0 (corresponding to perfectly black foliage) and 0.64 (corresponding to Eq. (5)). The results of these tests suggest that the leaf absorptivity a is an important parameter for accurate retrieval of LAI using the AccuPar instrument. The assumption that leaves are black and do not reflect, transmit, or scatter light at the relevant frequencies produces a negative bias in retrieved LAI of about 5% relative to the base case ($a = 0.9$). Using the retrieval from Eq. (5) leads to LAI estimates about 12% larger than the base case. This bias is consistent across the range of estimated LAI and f_b in this study.

4.1.2. Li-Cor LAI-2000 Plant Canopy Analyzer

As discussed above, many of the assumptions about canopy structure and radiative properties which are explicitly included in the ceptometer retrieval are built-in to the retrieval used by the LAI-2000, and are difficult to test in post-processing. However, our data did enable us to test some alternative post-processing practices proposed in the literature for estimating LAI from LAI-2000 measurements. Leblanc and Chen (2001) found that the entirety of the variance in retrieved LAI ($r^2 = 0.99$) was contained in the measurement of the fourth annulus ($47\text{--}58^\circ$ from zenith). They contend, based on their measurements, that the fourth annulus can effectively be used alone under diffuse conditions, with only a very small bias relative to the retrieval from all five annuli (about 5% in Leblanc and Chen's data). Our comparison (Fig. 8) generally supports this observation, although the scatter is somewhat larger in our data. The agreement between LAI calculated from five annuli and using only the fourth annulus implies that $G(\theta)$ is constant, which corresponds to a spherical distribution of leaf angles. The robustness of this phenomenon across different forest types (Leblanc and Chen's study was done in a mixed deciduous-conifer forest in Ontario) suggests that strong deviations from spherical leaf angle distribution are uncommon in these forests, and not as critical a factor for LAI

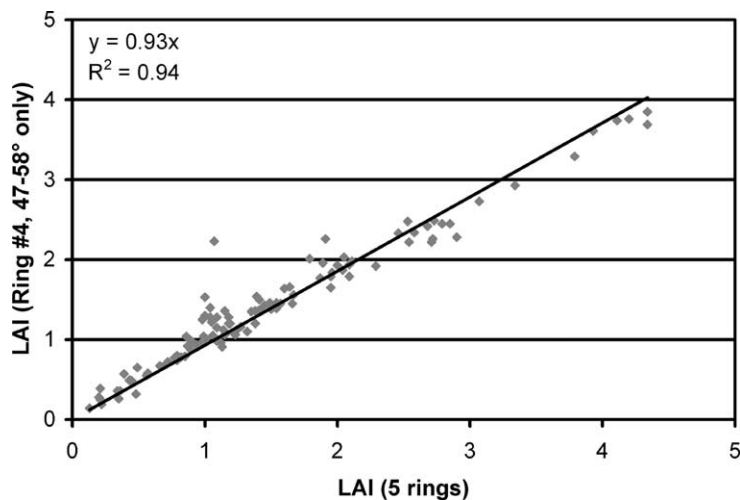


Fig. 8. Comparing the LAI retrieval from all five annuli to that derived using only the fourth annulus. The best-fit line was calculated using ordinary least squares regression, and the resulting line and its equation are shown in the graph.

Table 3
Statistics on collections in the comparison data set^a

Canopy species	<i>n</i>	AccuPar mean (range)	LAI-2000 mean (range)	Correlation coefficient
Aspen	43	0.99 (0.22–2.33)	1.38 (0.3–2.72)	0.85
Birch	5	3.40 (2.81–4.21)	3.73 (3.6–3.84)	0.53
Mixed	4	1.89 (1.31–2.23)	2.19 (1.87–2.43)	0.97
Other	15	0.77 (0.14–1.83)	0.90 (0.13–1.99)	0.95
Spruce	22	0.92 (0.25–1.55)	1.33 (0.35–2.33)	0.57
All	89	1.11 (0.14–4.21)	1.45 (0.13–3.84)	0.89

^a For each species, the number of matched collections by each instrument is shown, as well as the mean and range for each retrieval, and the coefficient of correlation between the two instruments.

measurements, at least under mostly diffuse illumination.

We also compared the baseline LAI retrieval with the alternate method using a weighted summation of $\tau(\theta)$ values, which is sometimes used in place of the slope–intercept method (LI-COR, 1991). The two estimates varied by an average of 4%, with close agreement ($r^2 = 0.99$), and no significant bias (slope of OLS regression = 0.98).

4.2. Instrument comparison

Comparison statistics for the matched data acquisitions using the two instruments (Table 3 and Fig. 9) show that, overall, the correlation between the retrievals is high ($r = 0.88$), but results for dif-

ferent canopy types vary. On average, the LAI-2000 retrieval was 20% higher than LAI derived from the ceptometer. The magnitude of the discrepancy did not have a significant trend (e.g., heteroscedasticity) with LAI magnitude. Tests for correlation for each species type in the comparison data set suggest that the two instruments responded similarly to the range of conditions in aspen stands ($r = 0.85$, $N = 43$), but responded differently to variability in spruce stands ($r = 0.57$, $N = 22$). One possible reason for this concerns the azimuthal view represented by each measurement: the LAI-2000 was used with a 90° azimuthal view restrictor, while the ceptometer responds to conditions in the entire field of view. Many of our spruce sites had sparse canopies, which would have greater azimuthal variation in light transmission, resulting in

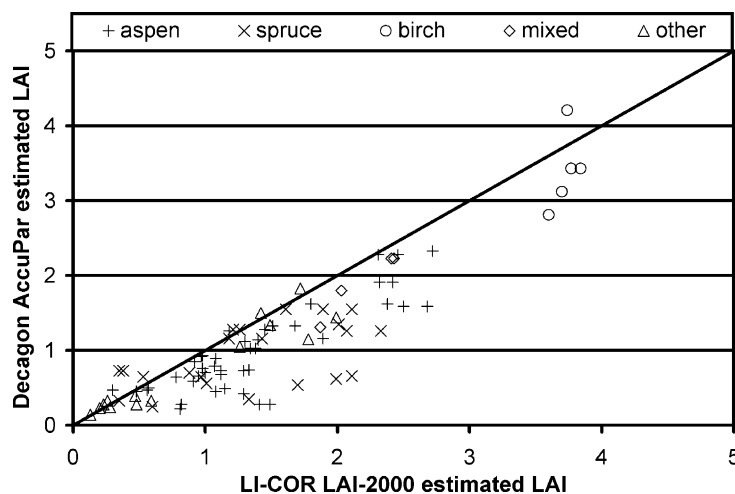


Fig. 9. Comparison of matched LAI retrievals from the Decagon AccuPar Ceptometer to those derived from the Li-Cor LAI-2000 Plant Canopy Analyzer. All retrievals were processed using the baseline method described in Section 3.3.

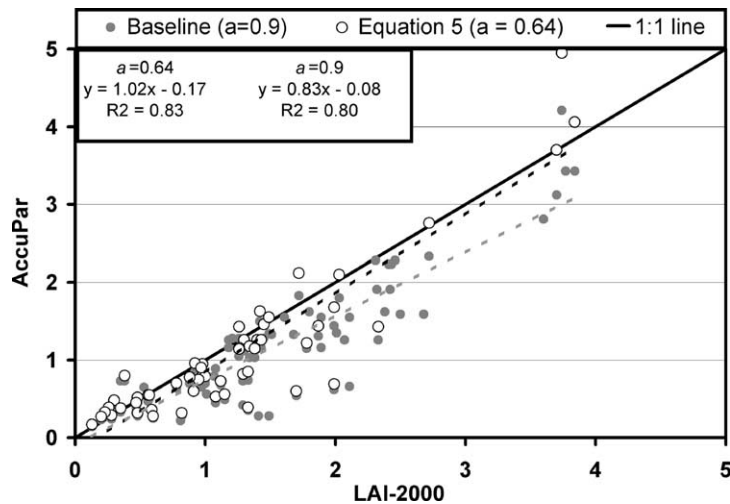


Fig. 10. Comparison of alternate retrievals for the AccuPar instrument versus the LAI-2000. The older retrieval (Eq. (5)) is equivalent to the baseline retrieval for this study, but with leaf absorptivity a of 0.64. The dashed lines in the graph are best-fit lines calculated using ordinary least squares regression. Their equations are shown in the graph. While the correlation between instruments does not improve, the slope calculated from least squares regression is very close to 1 for the $a = 0.64$ (Eq. (5)) case, whereas it is much lower than 1 for the baseline case with $a = 0.9$.

lower correlation between the two retrievals. We did not directly test the effect of varying the angular range and orientation of the view restrictor in this study.

Multiple regression of measurement variables (f_b , PAR_a , PAR_b , θ) against the residual differences between retrievals showed that f_b , PAR_a , and PAR_b were statistically significant at the $P < 0.05$ level, but the overall amount of variance explained was less than 6% for all variables combined. For acquisitions where data were collected to assess consistency of sky conditions, changes in PAR_a and f_b were tested for their correlation with the difference between the instruments. This test did not find that changes in PAR_a or f_b explained significant variance in the residuals. As an additional test, the correlation was recalculated, removing those acquisitions where PAR_a varied by more than 5%, and also those where f_b varied by more than 10%. This resulted in a somewhat higher correlation overall ($r = 0.94$), but application of those criteria reduced the size of the data set by more than 50%. The conditions of measurement, therefore, can affect the agreement between the two instruments, but no significant correlation could be identified between instrument comparison residuals and specific measurement conditions. Thus, while the quality control issues related to LAI retrieval identified above can be shown to affect the

agreement between the two instruments, there is no evidence that the two instruments respond differently to the range of measurement conditions encountered in this study.

Least squares regression of the two retrievals yielded a slope of 0.83 for the baseline cases. Comparing the baseline LAI-2000 retrieval to the AccuPar retrieval from Eq. (5) yields a best-fit line with a slope of 1.02 (see Fig. 10). This change reflects only a small improvement in the correlation between instruments.

5. Conclusions

Using two different optical instruments, the Li-Cor LAI-2000 Plant Canopy Analyzer and the Decagon AccuPar Ceptometer, to estimate LAI in 34 stands in interior Alaska, we conducted sensitivity tests to determine the uncertainty in retrieved LAI based on the measurement conditions of our study. We also tested different approaches for post-processing of radiometric data to determine LAI, and we performed a comparison of the two instruments' response to different canopies.

Based on our sensitivity tests, the most important factor for a field measurement protocol to measure

LAI was the consistency of sky conditions. An error of 10% in incident PAR, whether due to measurement error or changing conditions, could cause an even larger error in the estimated LAI. Errors caused by changing illumination conditions can be reduced by using a continuous measurement of incident PAR which is then matched to each below-canopy measurement to calculate canopy transmission for the retrieval. During long data acquisition periods, change in solar zenith angle could also significantly affect retrieved LAI. This error can be avoided by using several different measurements of zenith angle in post-processing. The beam fraction of incident radiation, while prone to some measurement error, was not likely to cause large biases in retrieved LAI. Tests of the sensitivity of the LAI retrieval to different values of the theoretical parameters employed in the retrieval showed that extreme values of the leaf angle distribution, corresponding to highly erectophile canopies, could cause large changes in retrieved LAI. Tests performed with the LAI-2000 data, however, showed that the variance in LAI was largely captured by measurements from a single angle, indicating that deviations from randomness, in the canopies we studied, were likely to be small. We tested the effect of the leaf absorptivity on the retrieved LAI, a critical parameter for the AccuPar instrument because it measures PAR (the LAI-2000 measures only at wavelengths <490 nm, in a spectral range where leaves are effectively black). Since the absorptivity is the sole variable in the parameterization of radiative behavior of leaves used by the AccuPar retrieval, the estimated LAI depends strongly on the absorptivity.

Finally, we tested an earlier published version of the LAI retrieval for the AccuPar instrument, which was used by Chen et al. (1997b). This version is mathematically equivalent to our baseline retrieval with leaf absorptivity set to 0.64. We found that results derived from this retrieval differ dramatically from those found using the baseline retrieval.

Comparison of the two instruments showed that overall, they responded in similar fashion to different canopy structures and densities. In the two largest samples from our study, aspen and spruce canopies, the two retrievals were much more highly correlated in aspen canopies than spruce. This may be caused by the sensitivity of the measurements to spatial heterogeneity in sparser canopies. The two instruments do

not have the same azimuthal range, so spatial heterogeneity has the potential to reduce correlation between their optical measurements. The average bias between the two instruments was different depending on which version of the retrieval for the AccuPar instrument was used.

Additional research is needed to better understand the impact of spatial heterogeneity on the two instruments, particularly since the observed systematic bias between them limits their interoperability and requires appropriate consideration for LAI monitoring and comparison activities, including validation of remotely sensed LAI estimates.

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