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Ground and remote estimation of leaf area index in Rocky Mountain forest stands, Kananaskis, Alberta

R.J. Hall, D.P. Davidson, and D.R. Peddle

Abstract. Leaf area index (LAI) is an important measure of canopy structure that is related to biomass, carbon and energy exchange, and is an important input to ecological and climate change models. LAI can be estimated using algorithms applied to airborne and satellite imagery, with ground-based measurements of LAI being required for calibration and validation. A variety of methods exist for ground-based and remote estimation of LAI, and this can lead to confusion and uncertainty regarding selection of methods, experimental design, and instrumentation. As a contribution towards clarifying these protocols, this paper investigated and compared three optical methods and an allometric technique for ground-based estimation of LAI, and these were related to remote LAI estimates derived from the compact airborne spectrographic imager (*casi*) using three vegetation indices (normalized difference, weighted difference, and soil-adjusted vegetation indices, or NDVI, WDVI, and SAVI, respectively) and subpixel-scale spectral mixture analysis (SMA). The study was conducted in the Kananaskis region of Alberta in the Canadian Rocky Mountains and considered four species compositions within a montane ecological subregion: lodgepole pine, white spruce, composite deciduous (aspen and balsam poplar), and mixedwood (mixture of deciduous and lodgepole pine or white spruce). LAI data were obtained in the field using a LI-COR, Inc. LAI-2000 instrument, a tracing radiation and architecture of canopies (TRAC) system, an integrated (LAI-2000 and TRAC) method, and an allometric technique that used the ratio of sapwood basal area to leaf area. A subsample of plots was assessed with hemispherical photographs and LAI-2000 data from which similar effective leaf area index (eLAI) values were derived for two of the four species analyzed. The results highlight the importance of ensuring that samples represent the range of stand structures and canopy architecture inherent in the species group being assessed. Foliage clumping was observed to be similar in both coniferous and deciduous species and an important element to measure. LAI estimates were influenced by the field methods used to estimate LAI, species and their canopy architecture, and the form of the vegetation index or subpixel-scale mixing derived from the *casi* image. Of the three vegetation indices, the SAVI was the statistically strongest predictor of LAI for mixedwood species, but all were poor LAI estimators for lodgepole pine and deciduous species. The subpixel-scale scene fractions from SMA provided the best prediction of LAI for white spruce compared with the three vegetation indices. The result for white spruce provides an encouraging basis for further investigation of SMA as a sampling tool to scale from field to high-resolution airborne and satellite imagery for local to landscape-level biophysical estimation.

Résumé. L'indice de surface foliaire (LAI) est une mesure importante de la structure du couvert qui est reliée à la biomasse, aux échanges de carbone et d'énergie et qui constitue une donnée d'entrée importante pour les modèles écologiques et de changement du climat. L'indice LAI peut être estimé à l'aide d'algorithmes appliqués sur des images aéroportées ou satellitaires à condition d'avoir des mesures au sol de LAI pour l'étalonnage et la validation des données. Il existe une variété de méthodes pour l'estimation de LAI à partir du sol ou par télédétection et cette situation peut entraîner une certaine confusion et une mesure d'incertitude quant à la sélection des méthodes, du concept expérimental et de l'instrumentation. À titre de contribution visant à clarifier ces protocoles, le présent article a étudié et comparé trois méthodes optiques et une technique allométrique pour l'estimation de LAI à partir du sol et celles-ci ont été mises en relation avec des estimations de télédétection dérivées du capteur *casi* (« compact airborne spectrographic imager ») utilizant trois indices de végétation (l'indice normalizé NDVI, l'indice pondéré WDVI et le SAVI ajusté pour l'effet de sol) et l'analyse SMA (« spectral mixture analysis » ou analyse des spectres mixtes) à l'échelle du sous-pixel. L'étude a été menée dans la région de Kananaskis, en Alberta, dans les Montagnes Rocheuses canadiennes et visait quatre mélanges

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d'espèces à l'intérieur de la sous-région écologique du Montane : le pin tordu, l'épinette blanche, une forêt de feuillus composite (peuplier faux-tremble et peuplier baumier) et une forêt mixte (mélange de feuillus et de pin tordu ou d'épinette blanche). Les données LAI ont été obtenues sur le terrain à l'aide d'un instrument LI-COR, Inc. LAI-2000, d'un système TRAC (« tracing radiation and architecture of canopies » ou traçage du rayonnement et de l'architecture des voûtes de végétation), d'une méthode d'intégration (LAI-2000 et TRAC) et d'une technique allométrique utilizant le ratio de la surface terrière de l'aubier par rapport à la surface foliaire. Un sous-échantillon des parcelles a été évalué à l'aide de photographies hémisphériques et des données LAI-2000 à partir desquelles des valeurs similaires de surface foliaire effective (eLAI) ont été dérivées pour deux des quatre espèces analysées. Les résultats mettent en évidence l'importance de s'assurer que les échantillons représentent toute la gamme des structures de peuplement et d'architectures du couvert inhérentes au groupement des espèces sous évaluation. Il a été possible d'observer que l'agrégation du feuillage était similaire pour les conifères et les espèces de feuillus et constituait un élément important à mesurer. Les estimations de LAI ont été influencées par les méthodes utilizées sur le terrain pour estimer le LAI, les espèces et l'architecture de leur couvert, ainsi que par le type d'indice de végétation ou le mixage à l'échelle du sous-pixel dérivé de l'image *casi*. Des trois indices de végétation, le SAVI s'est avéré statistiquement le plus fort pour la prévision de LAI dans le cas des espèces de forêt mixte, mais tous étaient faibles au plan de l'estimation de LAI pour ce qui est des pins tordus et des espèces de feuillus. Les fractions de scène, à l'échelle du sous-pixel, obtenues à l'aide de la technique SMA ont fourni les meilleures prévisions de LAI pour l'épinette blanche comparativement aux trois indices de végétation. Le résultat observé pour l'épinette blanche fournit une base encourageante pour des recherches ultérieures basées sur l'utilization de la technique SMA en tant qu'outil d'échantillonnage dans le contexte de la mise à l'échelle d'une variété d'images, à partir des images au sol jusqu'aux images aéroportées et satellitaires à haute résolution, pour l'estimation biophysique de l'échelle locale à l'échelle du paysage.

[Traduit par la Rédaction]

Introduction

Leaf area index (LAI) is an important measure of canopy structure that is related to many biological and physiological processes associated with the terrestrial biosphere (Welles, 1990). LAI has been defined as one half the total intercepting area per unit ground surface area (Chen and Black, 1992). It has been related to canopy interception, transpiration, net photosynthesis, gas, water, carbon, and energy exchange, net primary productivity, and biomass (Gholz, 1982; Pierce and Running, 1988; Gower and Norman, 1991). LAI has been recognized as the most important attribute of vegetation structure for characterizing forest canopies over large areas at broad spatial scales using satellite remote sensing data (Running and Coughlan, 1988). Thus, many ecosystem models have been developed to be sensitive to and driven by LAI estimates (Running and Coughlan, 1988; Running and Hunt, 1993; Liu et al., 1997). Airborne and satellite remote sensing data have been used to estimate LAI based on relationships between remote sensing data and LAI measurements obtained from the field (White et al., 1997; Peddle et al., 1999; Peddle and Johnson, 2000; Johnson, 2000). An improved understanding of the various methods for estimating LAI in the field and through remote sensing is therefore important when inferences are to be made about its magnitude and spatial distribution over the landscape.

In this paper, we compare ground-based and airborne remote sensing image analysis methods for estimating LAI. It was not possible to obtain absolute measures of LAI because of restrictions on destructive sampling in the study area. Instead, the lack of actual LAI measures was addressed, to the extent possible, using relative comparisons among three field methods for estimating LAI and through the use of allometric relationships derived independently of the optical field methods tested. Having three different optical field methods in addition to an allometric method is uncommon, and this provided the unique opportunity for systematic comparisons in addition to partially mitigating the lack of absolute LAI data, a situation that is often a reality in forestry remote sensing over large areas. The essence of our approach, therefore, drew on the availability of the different LAI estimation methods, with the rationale that if the values of LAI from these various methods were relatively similar, then we would have greater confidence in their accuracy and in their utility for scaling with remote sensing. Our interest was in comparing methods that may be used for mapping the relative pattern and distribution of LAI over the landscape based on a model that describes the relationship between the remote sensing image and the ground-based optical estimates of LAI. This approach was considered a more practical and achievable goal than attempting to estimate the actual LAI value at particular locations on the ground because of the lack of actual leaf area information that could only be obtained from destructive sampling. Regarding destructive sampling, we note that variability in LAI occurs depending on how and where the destructive sampling of individual trees for a given species is carried out, such as sampling a representative range of tree sizes, and recognizing the local influence of abiotic and biotic factors on allometric coefficients (Gower et al., 1999). Furthermore, the absolute measurement of LAI over the full areas corresponding to the pixel spatial resolution of airborne and particularly most satellite sensors is difficult and often impractical or impossible to obtain by destructive sampling (unless associated with a clear-cutting operation). This is less of an issue with ground-based optical methods, since the full area of forest plots can be measured, or the density of subsampling controlled (e.g., purposive or regular sampling protocols and profiling techniques). The use of site-specific measures of absolute LAI by destructive sampling is further confounded by issues of positional control in relating field measurements to its exact corresponding pixel area within an image. As a result, ground-based LAI information for use in remote sensing image analysis and validation is almost always based on some form of sampling within actual pixel areas, giving rise to the issue of its appropriate representation of forest stands. As a result, even absolute measurements of LAI for remote sensing validation are challenged and sometimes compromised by issues of spatial scale, positional accuracy, and field sampling intensity.

The plethora of ground-based optical, allometric, and remote sensing approaches for estimation of LAI has resulted in some need to understand the variation in LAI estimates that may arise from these methods for different species and stand conditions (White et al., 1997; Gower et al., 1999). Accordingly, in this research, we have investigated this to the extent possible for a complex, mountainous environment in the Canadian Rockies. Here, we present results from a variety of ground-based methods, each with different inherent sampling strategies and protocols, and we compare these among themselves and also against LAI estimation from airborne compact airborne spectrographic imager (*casi*) remote sensing imagery (Davidson, 2002). The objectives of this study were (*i*) to assess the variation in ground-based estimates of LAI as a function of tree species and LAI estimation techniques for potential use in remote sensing studies, and (*ii*) to compare the ground-based LAI estimates with those obtained from several remote sensing LAI algorithms for four different species types in a particular ecological subregion in Alberta.

Overview of LAI estimation methods

Ground-based methods

Indirect, nondestructive methods of estimating LAI in the field include allometric techniques and the use of various optical instruments. Allometric techniques are often based on empirical relationships between LAI and mensurational data such as sapwood area, basal area, and crown closure (Snell and Brown, 1978; Buckley, 1999). Allometric equations relate species-specific cross-sectional sapwood or basal area to individual tree leaf area, and these equations have been developed for a variety of tree species (Kaufmann and Troendle, 1981; Waring et al., 1982; Gower et al., 1997; White et al., 1997). The actual leaf area is usually derived by destructive sampling of individual tree portions or from foliage collected in litter traps. Direct estimation methods with tree allometry and litterfall are difficult and time-consuming and may not result in accurate and unbiased LAI estimates (Chason et al., 1991; Cutini et al., 1998). Collecting litterfall of conifer species is particularly difficult because needles may be retained for more than 1 year. Allometric equations are based on the pipe model theory that states, for a given unit of leaves, there must be a continuation of conductive tissue of constant cross-sectional area that services the foliage above (Waring et al., 1982). The use of allometric relationships between sapwood or tree basal area and leaf area has been shown to be stand specific and dependent on season, age, stand density, tree crown size, and climatic differences (Gholz et al., 1976; Pearson et al., 1984; Mencuccini and Grace, 1995; Gower et al., 1997). For these reasons, indirect, optical methods have been developed as an alternative approach that can offer more rapid and consistent estimates of leaf area and can be used over areas that are larger than the individual tree (Fassnacht et al., 1994; Chen et al., 1997b; Cutini et al., 1998).

Optical methods of estimating LAI use the inversion of gap fraction data or the precise measurement of the geometric distribution of openings. This information is used to estimate LAI based on the percentage of radiation transmitted through the canopy. These estimates are termed effective LAI (eLAI) because leaves in plant canopies are often not randomly distributed in space and optical methods will underestimate the actual LAI in canopies whose spatial arrangement of foliage is clumped (Chen et al., 1997b). The LAI-2000 plant canopy analyzer (LI-COR, Inc., 1990) instrument estimates LAI in this way. The LAI-2000 is an optical instrument that measures the light penetration through the canopy using five quantum detectors arranged in concentric rings, thereby capturing the light attenuation at several zenith angles (LI-COR, Inc., 1990). Chen and Cihlar (1995) took a further step with the development of the tracing radiation and architecture of canopies (TRAC) instrument, which accounts for not only canopy gap fraction but also canopy gap size distribution (the dimensions of a gap). The canopy gap size distribution is used to derive a clumping index that quantifies the effects of the nonrandom spatial distribution of foliage that often occurs in stands with mixedwood and conifer species. Along with measures of within-shoot clumping, Chen et al. (1997b) recommended integrating the eLAI measurement of the LAI-2000 with the clumping index (gap size) of the TRAC to produce a more theoretically definitive estimate of LAI that accounts for both gap fraction and gap size distribution. The TRAC has been used in support of LAI mapping from satellite images (Chen et al., 1997b; 2002) and in the assessment of ice-storm damaged sugar maple (*Acer saccharum* Marsh.) stands (Olthof et al., 2001).

Hemispherical canopy photography is another indirect method for estimating LAI. Using a 180° fish-eye camera lens with a digital or film camera system, photographs are acquired that image the position, size, and shape of the gaps in the forest canopy (Frazer et al., 1997). Ground-level photographs are usually taken below the canopy looking skyward using a camera mounted on a tripod to ensure camera orientation and stability. To date, film-based systems have been used most frequently and require the intermediate step of digital scanning of the analogue photographs. Current hemispherical photography systems, however, are increasingly moving towards digital technology because it bypasses the expense and time associated with photographic film and allows previewing of the digital photograph immediately in the field before selection (Frazer et al., 2001; Hale and Edwards, 2002). From the resulting photograph, gap fraction data are derived for the assessment of canopy architecture parameters such as openness, leaf area, and foliage inclination angle using specialized computer software (Rich, 1990; Frazer et al., 2001; Hale and Edwards, 2002).

For all of these ground-based LAI estimation methods, the species composition and structure of the forest canopy and the possible influence of the understory are factors that will influence LAI measurement. The assumption of randomly distributed foliage in a canopy that is made by several of the indirect methods described (e.g., LAI-2000, hemispherical photography) may be valid for closed canopy deciduous forests, but this assumption may be invalid for open canopy boreal coniferous and mixedwood forests (Chen et al., 1997b). Given the inherent variation within and between species, the use of forest or land cover classification maps has been recommended to stratify the landscape in efforts to provide a more judicious basis for LAI sampling and measurement (Cihlar et al., 1997). Boreal forests are often relatively open with considerable understory vegetation that will contribute to the overall LAI of a given stand when observed from above by a remote sensor. Although the influence of understory is not as significant in stands with a denser overstory canopy, it can create difficulties in determining overstory LAI in open stands. Careful timing of field sampling to account for differences in vegetative phenology is one approach that can mitigate the influence of understory vegetation on overstory LAI estimation. These issues are of critical importance with respect to using airborne and satellite imagery for estimating LAI. The methods used to measure LAI in the field for stands of varying composition and structure serve the dual role of being both a basis for developing empirical relationships between image-based reflectance values and LAI and a source of independent, mutually exclusive validation. This is particularly important when these image-based LAI estimates are further scaled and used for mapping LAI over large areas.

Remote sensing methods

In the efforts to obtain spatially comprehensive and detailed estimates of LAI for generating large-area map products, the relationship between satellite or airborne image reflectance and LAI has been explored in numerous studies (Chen, 1996a; Cihlar et al., 1997; Fassnacht et al., 1997; White et al., 1997; Gower et al., 1999; Pellikka et al., 2000; Peddle et al., 2001a; Chen et al., 2002). Remote sensing images and the subsequent modeling of leaf area have also been used to provide information to help monitor ecosystem functioning at regional to global scales (Sellers and Schimel, 1993).

Among the remote sensing sensors that have been most frequently used in the estimation of LAI are coarse- and medium-resolution satellites such as the National Oceanic and Atmospheric Administration (NOAA) advanced very high-resolution radiometer (AVHRR), Systeme pour l'Observation de la Terre (SPOT) VEGETATION, and Landsat thematic mapper (TM) (Badhwar et al., 1986; Fassnacht et al., 1997; White et al., 1997; Chen et al., 2002). Examples of other sensors that have been used to estimate LAI include image data derived from digital video cameras (Law, 1995), multiband vegetation imager (Kucharik et al., 1997), *casi* (Wulder et al., 1998; Fernandes et al., 2002), digitally scanned aerial photographs (Pellikka et al., 2000), and the along-track scanning radiometer (North, 2002). While much interest has been directed at the mapping of LAI with these sensors, the ability to detect change in LAI is also important because of the suitability of multitemporal remote sensing imagery for monitoring vegetation condition at periodic intervals. The calibration of remote sensing data and its multitemporal radiometric stability is therefore important when assessing the performance of a given LAI estimation algorithm and its consistency over time (Cihlar et al., 1997). Additional considerations for mapping LAI from remote sensing include establishing a sampling framework that represents the full range of LAI and ecological conditions within an area of interest, analyzing mixedwood stands separately from pure-species stands, employing vertical stratification if vegetation in the understory is an issue, and understanding the role of seasonal dependence on image–LAI relationships (Franklin, 2001). In addition to these considerations, the choice of image analysis algorithms (e.g., vegetation indices, mixture analysis, modeling), pixel scale, spectral and radiometric resolution, geometric correction, radiometric calibration, temporal stability, and image data source are also factors that will influence the ability to estimate, map, and monitor LAI over the landscape (Cihlar et al., 1997). In this study, the selection and role of vegetation indices and alternatives were of particular interest and relevance.

Vegetation indices and band ratios have typically been used to incorporate information from remote sensing platforms by combining two or more spectral bands (Qi et al., 1994). Most vegetation indices utilize the red and near-infrared (NIR) spectral bands for retrieving vegetation information (Baret and Guyot, 1991; Chen, 1996a). One of the earliest and most widely used vegetation indices is the normalized difference vegetation index (NDVI); however, it is only based on measurements of the entire pixel field of view and does not account for subpixel-scale reflectance from scene components that may include soil, vegetation, and shadow components (Richardson and Wiegand, 1977). This issue led to the development of the weighted difference vegetation index (WDVI) (Clevers, 1989) and the soil-adjusted vegetation index (SAVI) (Qi et al., 1994), which attempts to reduce the effects of reflectance from the soil or ground surface that forms part of the background to the vegetation canopy.

Spectral mixture analysis (SMA) is an approach that explicitly deals with subpixel scales by deriving the fraction of background, sunlit canopy, and shadow components within a pixel. Under the premise that it is these primary components that contribute to the observed reflectance at the pixel scale, these fractions can then be related to forest biophysical and structural variables. Compared to vegetation indices, improvements in estimating LAI have been reported using mixture analysis and modeling applied to airborne and satellite imagery in montane and boreal forest stands in Canada and the United States (Hall et al., 1995; 1996; Peddle et al., 1999; 2001a; Peddle and Johnson, 2000).

For forestry applications, *casi* provides a high spatial resolution and a finer and more varied spectral resolution than satellite imagery (Niemann, 1995; Coops et al., 1998). This sensor has been used to predict LAI (Gong et al., 1995; Wulder et al., 1996), forest stand age (Niemann, 1995), soil properties, and disturbance (Coops et al., 1998). It provides a means of extracting forest information at scales that may be more pertinent for forest management at regional scales than the use of archival satellite data. As well, with the emerging availability of higher spatial and spectral resolution satellite imagery, the use and application of airborne imagery such as *casi* has additional relevance. These factors form the rationale for evaluating the potential of SMA for estimating LAI based on its relationship with ground-based observations of LAI.

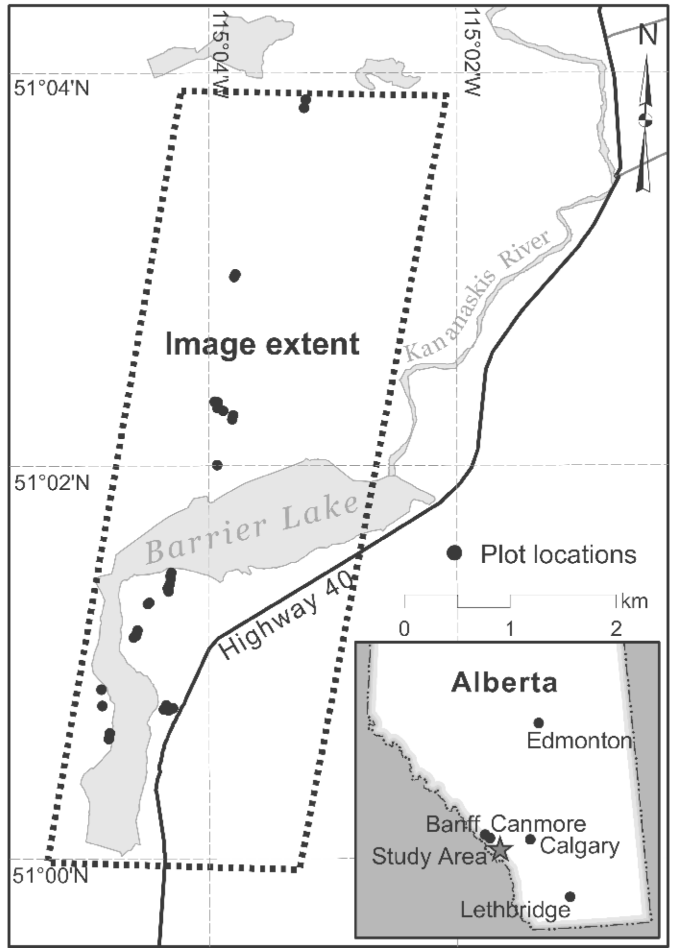

Figure 1. Location of the study area in Alberta, Canada.

Methods

Study area

The study area was located in the Bow Valley and Bow Valley Wildland provincial parks in Kananaskis Country, Alberta, Canada. Field and remote sensing data were collected during the summers of 1998 and 1999 for a study area centred at 51°1′13″N, 115°4′20″W and straddling Barrier Lake in a montane ecological subregion located on the eastern slopes of the Canadian Rocky Mountains (**Figure 1**). The montane is characterized by varying soils and forests owing to the diverse climatic and variable topographic conditions (extensive relief and geomorphology) that typify this ecological zone (Achuff, 1992). The study area covers approximately 77 km^2 and a full range of terrain aspects and slopes. Dominant softwood tree species in the area include lodgepole pine (*Pinus contorta* var. *latifolia* Dougl ex. Loud.), white spruce (*Picea glauca* (Moench) Voss), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and subalpine fir (*Abies lasiocarpa* (Hook) Nutl.). The dominant deciduous tree species include trembling aspen (*Populus tremuloides* Michx.) and balsam poplar (*Populus balsamifera* L.), with lesser amounts of white birch (*Betula papyrifera* Marsh.). Representative stands were chosen from the study area to encompass pure stands of lodgepole pine, white spruce, and mixedwood and composite deciduous (aspen and balsam poplar). Mixedwood stands were considered as those with a secondary or tertiary species that made up greater than 20% of the overstory canopy (Archibald et al., 1996).

Field plot measurements

A total of 42 plots distributed over the study area (**Figure 1**), each of dimensions 10 × 10 m, were established, of which eight were lodgepole pine, seven were white spruce, 15 were mixedwood, and 12 were composite deciduous. All field measurements were taken when the trees were at the same stage of phenology and at maximum photosynthetic capacity for a given growing season between 7 July and 25 August in 1998 and 1999. The plots were located with the assistance of forest inventory maps available for the study area and, although the stand types within a given species were intentionally selected for variability to represent a range of LAI, a given plot was established well within a given stand type to minimize variation at a particular site. This process was similar to that of Dantec et al. (2000), in which plots were carefully positioned to be well within a given stand in as homogeneous condition as possible with respect to species composition and structure as defined by height, stem density, and canopy closure. In each plot, basic forestry measurements were obtained for each tree, including species composition, height using a digital hypsometer and diameter at breast height (dbh). Tree increment cores were also collected to determine sapwood basal area. Two cores were collected from each tree, and candidate trees were selected as two to three trees per species in each plot. Crown closure was estimated using a spherical densitometer as the average of five measurements whose locations included plot centre and one reading located 2–3 m away from each plot corner along a diagonal toward plot centre similar to the method employed by Gerylo et al. (1998). Within each plot, LAI estimates were derived using published allometric functions and the LI-COR, Inc. LAI-2000 (Welles, 1990) and TRAC (Chen et al., 1997b) instruments and an integrated LAI-2000 and TRAC approach. On a subsample of plots, hemispherical photographs were acquired and processed to assess their relative similarity in eLAI estimates compared with those from the LI-COR, Inc. LAI-2000.

Allometric estimation of leaf area index

The transition zone between the sapwood and heartwood on the increment cores, where visible, was marked on each tree core extracted from each plot. For each of those trees, sapwood widths were averaged and sapwood area calculated as the difference between the stem basal area at breast height and the heartwood area. Stem basal area at breast height was calculated based on the diameter of each tree inside the bark. The inside bark diameter was determined based on diameter outside bark – diameter inside bark (DOB/DIB) models developed by Huang (1994) for each species in this montane ecological subregion. Since it was not possible to core all the trees in every plot, the sapwood area for the entire plot was determined by extrapolation. Using the various tree data, regression models were built to relate sapwood basal area to tree basal area for each species within the study area. A composite deciduous group was created because of the relatively small occurrences of balsam poplar trees in the study area and their similarity with trembling aspen.

Regression models for estimating sapwood basal area by species were determined and tested through the creation of a fitting and a validation sample. The validation sample set was based on a random sample of 25% of the trees for each species, with the remaining sample comprising the fit data set for determining regression model parameters. The regression models were chosen based on the magnitude of the coefficient of determination (r^2), root mean square error (RMSE), the standardized residual plots, and the statistical significance of each model. The regression models were then applied to the uncored trees within the plots to determine a plot level sapwood basal area estimate. Leaf area of each stand (**Table 1**) was estimated using published allometric equations of sapwood basal area to leaf area for montane ecosystems in the Rocky Mountains as summarized by White et al. (1997). The summed leaf area was then divided by the plot ground area of 100 m^2 (10 × 10 m) to estimate the LAI for each of the plots.

Table 1. Projected leaf area to cross-sectional sapwood area values extracted from White et al. (1997).

Species	Leaf area/ sapwood area ($m^2 \cdot cm^{-2}$)	References
Lodgepole pine	0.14	Gower et al., 1987
White spruce	0.34	Waring et al., 1982
Trembling aspen	0.10	Kaufmann and Troendle, 1981

LAI-2000 and hemispherical photography

For each plot, overstory LAI was measured using the LAI-2000 at eight random locations within each plot. An outside canopy measure was taken in an open field immediately prior to the plot measurements to serve as the above-canopy measurement. Measurements were taken on overcast days or early–late in the day during diffuse light conditions for the same range of dates as those of the field data collection. To minimize the effects of slope and to reduce the incorrect weighting imposed on the fifth ring (61–74°) by Miller's theorem (Miller, 1967), the fifth ring was removed during the calculation of eLAI (Leblanc and Chen, 2001). For 34 of the 42 field plots, hemispherical photographs were available from a previous study (Davidson, 2002) to derive eLAI values that could then be compared with those determined from LAI-2000 measurements. Five bracketed-exposure hemispherical photographs were taken between 30 July and 21 August 1999 at dawn or dusk during diffuse light conditions. The stage of vegetation was equivalent to the timing of the field and *casi* image data collection. At the centre of the plots, the photograph with the highest contrast between sky and canopy was selected for digital scanning using an HP 4C 600 dpi optical scanner. Subsequently, eLAI was estimated from the digitized hemispherical photographs using the Gap Light Analyzer (GLA) software (Frazer et al., 1999), which includes terrain corrections based on inputs for local slope and aspect. The comparison of eLAI estimates between the two methods served as an indicator of the degree to which they might be expected to be similar across the four species.

TRAC

Using TRAC, 10 transects, oriented perpendicular to the solar plane, were established within each plot at approximately 1 m intervals. The TRAC transects were collected during sunny, cloud-free conditions at 2 h either side of solar noon during the same range in dates that the tree measurements and LAI-2000 data were being collected to ensure the vegetation was at the same stage of phenology. All measurements were therefore taken within a solar zenith angle range of 30–50°, which were within the preferred operating range for TRAC (Leblanc et al., 2002). Measurements were collected by walking at a rate of approximately 0.33 m/s. The TRAC values were postprocessed using software developed by the Canada Centre for Remote Sensing (Leblanc et al., 2002). A topographic normalization was completed based on a correction that transformed the length walked with the TRAC to the horizontal length actually captured by the TRAC (J.M. Chen, personal communication, 1999; S.G. Leblanc, personal communication, 2002). This resulted in a slope correction for LAI as follows:

$$L = L_{SL} \cos \theta_{SL} \quad (1)$$

where L is the final LAI, L_{SL} is the LAI calculated on the slope, and θ_{SL} is the slope angle (S.G. Leblanc, personal communication, 2002). Slope was measured within each plot. Postprocessing of the TRAC transect data resulted in computation of LAI and a clumping index value that was used in Equation (2) to compute an integrated estimate of LAI.

Integrated LAI-2000 and TRAC approach

Chen et al. (1997b) suggested that integrating the LAI-2000 eLAI estimate with the TRAC clumping index would result in a more accurate LAI estimate because it would account for both gap angular distributions at several angles from zenith and the gap size distribution function. The calculation is as follows:

$$\text{LAI} = (1 - \alpha)\,\text{eLAI}\,\frac{\text{Ve}}{\Omega} \quad (2)$$

where α is the ratio of woody area to total area, Ve is the ratio of needle area to shoot area, and Ω is the clumping index. The ratio of woody area to total area (α) converts the plant area index into LAI because branches and tree trunks intercept radiation transmission that results in inflated LAI values. Woody area to total area ratios were obtained from previously published values of similar stands from boreal forests (Chen, 1996b). The α values used were 0.28 for lodgepole pine, 0.17 for white spruce, and 0.20 for deciduous ratios. The terrain-adjusted eLAI was obtained from the LAI-2000. The ratio of needle area to shoot area (Ve) is the ratio of half the total needle area in a shoot to half the total shoot area. It is used to quantify within-shoot clumping (Chen, 1996b). This ratio is required because the needles in the shoots of conifer forests are tightly grouped, making it impossible to infer the needle surface area from optical measurements (Chen, 1996b). Lodgepole pine had a Ve of 2.08 and white spruce had a Ve of 1.27 as derived from a selection of shoot samples that were processed by the Canada Centre for Remote Sensing using methods described in Chen et al. (1997b). Deciduous species were assigned a Ve of 1.0 as reported by Chen et al. (1997a). This value was simple to apply when only a single species dominated the stand associated with a given plot. For plots that contained more than one species, such as mixed stands, the Ve value for the plot was the summation of the portion of total basal area by species based on reported results that leaf area and dbh (and thus basal area) are correlated for boreal species (Gower et al., 1997). The clumping index (Ω) was obtained using TRAC and was used to quantify clumping at scales larger than the shoot (Chen, 1996b). No slope corrections were needed, since both the LAI-2000 and TRAC data had been adjusted for slope effects prior to their use in this integrated approach.

Airborne image acquisition and processing

The *casi* imagery (Anger et al., 1994) was acquired over Kananaskis on 18 July 1998 by Itres Research Ltd., Calgary, who also performed the geocoding of the image. Their process was a scan line by scan line correction whereby each scan line was referenced and time-coded to the aircraft inertial navigation system to provide sequential x, y, and z positions for precise geocoding (M. Kerr, Itres Research Ltd., personal communication, 2003). For this 18-band, 2 m spatial resolution data set, an empirical radiometric correction to surface reflectance was performed based on Johnson (2000). The radiometric correction used four pseudo-invariant global positioning system (GPS) controlled calibration targets that were measured spectrally using an analytical spectral devices (ASD) full-range field spectroradiometer during the *casi* overflight and corrected to surface reflectance (Peddle et al., 2001b) with reference to a calibrated Spectralon white reference panel. The spectroradiometer measurements were subsequently related to *casi* image data using a linear spectral response function for each image band from which an empirical function was developed. The empirical function served to align the image data to the measured surface reflectance at the calibration target sites as identified in the image and measured on the ground. This process also corrected for any atmospheric effects, which were deemed to be minimal under the ideal image acquisition conditions. It was not possible to undertake biodirectional reflectance distribution function (BRDF) corrections because it was not part of the Itres Research Ltd. standard product. A C-correction (Teillet et al., 1982) was used for terrain normalization of the imagery using a high-resolution digital elevation model that had been resampled by Itres Research Ltd. to be equivalent to the pixel size of the image, based on the results of Meyer et al. (1993) and Johnson (2000).

Vegetation indices

In this study, three vegetation indices were chosen based on their performance for the prediction of forest biophysical parameters (including LAI) in other studies that each compared a total of 10 different vegetation indices (Chen, 1996a; Peddle et al., 2001a). Based on those results, NDVI, WDVI, and SAVI (**Table 2**) were computed from the 2 m imagery. All vegetation indices were derived using *casi* bands that ranged over red (640–680 nm) and near-infrared (NIR: 790–875 nm) wavelengths that corresponded as closely as possible in this study to Landsat TM – enhanced thematic mapper plus (ETM+) bands 3 (red: 630–690 nm) and 4 (NIR: 760–900 nm), respectively. The soil or background spectral component reflectance value needed for WDVI and SAVI was the same as the background end-member spectra used in the spectral mixture analysis.

Spectral mixture analysis

Linear spectral mixture analysis (SMA) (Adams et al., 1993) was used to derive the subpixel-scale fractions of background, sunlit canopy, and shadow using a constrained least squares approach (Shimabukuro and Smith, 1991; Hall et al., 1995) applied to the same *casi* image data as those used in deriving the vegetation indices. End-member spectra were measured in the field using the ASD full-range field spectroradiometer (Johnson, 2000). The sunlit canopy end member was the

Table 2. Vegetation index equations based on near-infrared (NIR) and red (R) spectral bands.

Vegetation index	Equation	Reference
Normalized difference vegetation index, NDVI	$\frac{\text{NIR} - \text{R}}{\text{NIR} + \text{R}}$	Rouse et al., 1973
Weighted difference vegetation index, WDVI	$\text{NIR} - a\text{R}, \quad \text{where} \quad a = \frac{\text{NIR of soil}}{\text{R of soil}}$	Clevers, 1989
Soil-adjusted vegetation index, SAVI	$\frac{(\text{NIR} - \text{R})(1 + L)}{\text{NIR} + \text{R} + L}, \quad \text{where } L = 1 - 2.12(\text{NDVI} \times \text{WDVI})$	Qi et al., 1994

spectra for the appropriate species (lodgepole pine or white spruce) depending on the species composition of the plot recorded in the field. The background end member was obtained from spectroradiometer measurements of the aggregated background found on the forest floor that included pine grass (*Calamagrostis rubescens* Buckl.), step moss (*Hylocomium splendens* (Hedw.) B.S.G.), and buffalo berry (*Shepherdia canadensis* (Nutt) L.). Similar to the sunlit canopy end member, the composition and aggregation of the background end member was species specific. The shadow end member was the darkest apparent reflectance obtained from the samples of canopy and background end members as measured in the field. The apparent reflectance (Miller et al., 1997; Peddle et al., 2001b) of the background and canopy targets was determined from spectral measurements of the vegetation targets in complete shadow with respect to an illuminated and calibrated reference panel. In this study, the apparent reflectance of pine grass spectra was used as the shadow end-member reflectance. In the present study, the SMA was not able to encompass deciduous or mixedwood species plots, since appropriate end members were not available, thus only conifer plots were tested. To quantify the accuracy of the subpixel fractions, Johnson (2000) produced a supervised maximum likelihood (ML) classification of the 60 cm *casi* imagery to separate the image into three classes (background, sunlit canopy, and shadow). This ML classification was used for scene fraction validation (Peddle and Johnson, 2000) of the new fractions produced using the end member set at the 2 m image resolution from which an excellent level of correspondence was found.

Statistical analyses

Means and standard deviations were calculated for LAI estimates from each instrument by species, and scatterplots were also undertaken to compare the relative relationships among the instruments. The estimation of eLAI from rings 1–4 of the LAI-2000 was statistically compared, using a paired *t* test, to determine if there was a statistical difference among the eLAI results from the LAI-2000 with the subset of hemispherical photographs. A two-way factorial analysis of variance (ANOVA) was undertaken using the Statistical Package for the Social Sciences statistical software (SPSS Inc., 1999) to determine if differences existed in LAI instrumentation and by species, and if its interaction significantly influenced the LAI estimate. Tukey's honestly significantly different (HSD) multiple-mean comparison tests were conducted if statistical differences in LAI instrumentation and species were observed. The remote sensing based LAI estimates from the vegetation indices for each of the four species were also compared. Although a more robust statistical model fitting approach such as a linear nonparametric Thiel–Sen regression approach (Kendall and Stuart, 1967) would be preferable for LAI mapping, a simple linear regression method was selected for quantifying the statistical relationship between each vegetation index and the various ground-based LAI measures (the same was done for the SMA shadow fractions). The use of jackknife and bootstrap procedures for more robust estimation of standard errors and confidence limits when validation data are not available and distributional assumptions may not be true (Sokal and Rohlf, 1995) were also considered, but sample sizes were too small for these procedures to be viable. The linear regression model approach combined with scatterplots therefore served as a preliminary indicator of the image–LAI relationships for the purposes of this study. The comparison of simple linear regression models was based on the magnitude of the r^2 and RMSE values and the statistical significance of each model. All statistical tests in this study were performed at the 5% probability level.

Results

Stand mensurational information

Lodgepole pine stands were characterized by relatively small basal areas and tree heights and were among the most variable for stem densities (**Table 3**). White spruce exhibited the largest basal areas and tree heights while having much smaller stem densities compared with the other species. Both mixedwood and deciduous stands had highly variable crown closures and stem densities, but similar basal areas. Mixedwood stands had the highest stem density and the widest range in tree heights. The latter was attributable, in part, to the composition of the mixedwoods being primarily white spruce and deciduous species. An indicator of the variability in structure evident through tree stem distribution and understory vegetation by overstory species is evident in the sample field photographs depicted in **Figure 2**. Of particular note is that open stands (**Figures 2a**, **2d**) tend to result in more vigorous understory vegetation growth compared to more dense stands (**Figures 2b**,

2c) that would contribute to the apparent LAI observed on the image. The very different structural characteristics among the species must be considered when assessing the results from the different LAI estimation methods tested.

Ground-based LAI

Based on the subsample of field plots where hemispherical photographs were available, there was no statistical difference in eLAI estimates between the LAI-2000 and hemispherical photographs for white spruce ($P = 0.10$) and deciduous ($P = 0.29$) species. Conversely, there were statistical differences in eLAI estimates for lodgepole pine ($P = 0.02$) and mixedwood ($P = 0.00$) species.

Tree basal area and sapwood basal area were highly correlated and statistically significant for lodgepole pine ($r = 0.95$, $P = 0.001$), white spruce ($r = 0.87$, $P = 0.001$), and

Table 3. Descriptive statistics for field plots by species or species group.

	Lodgepole pine	White spruce	Mixedwood	Deciduous
No. of plots	8	7	15	12
Min. crown closure (%)	25	46	29	26
Max. crown closure (%)	52	66	80	75
Min. stem density (stems/ha)	600	1000	1300	700
Max. stem density (stems/ha)	4400	2500	4900	4400
Min. tree height (m)	10.3	19.0	5.2	6.8
Max. tree height (m)	14.0	22.6	20.5	14.8
Min. basal area (m^2/ha)	14.7	32.9	14.0	20.5
Max. basal area (m^2/ha)	45.8	77.0	65.6	65.6
Min. elevation (m)	1369	1315	1315	1374
Max. elevation (m)	1435	1642	1390	1552
Min. slope (°)	5.2	0.1	1.4	2.9
Max. slope (°)	36.2	33.5	40.5	14.9

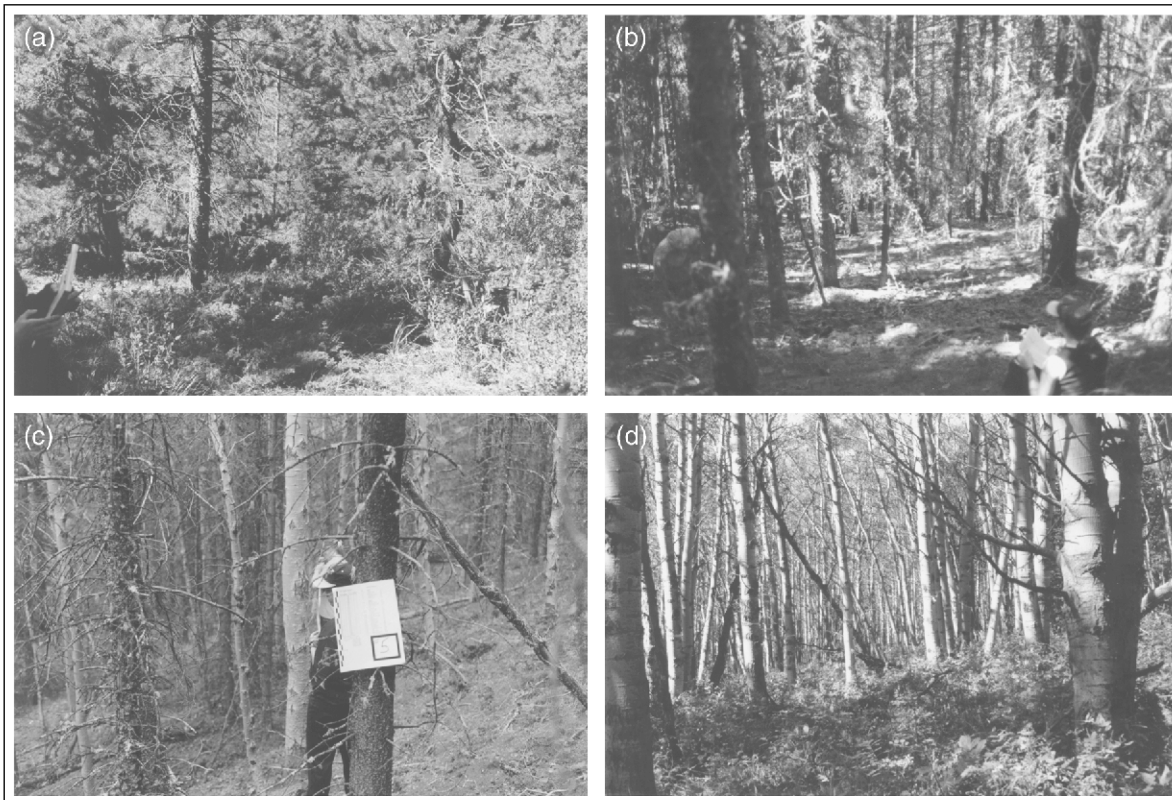

Figure 2. Field photographs illustrating the variation in structure and understory composition by species or species group. (a) Pure lodgepole pine stand 12 m tall with a crown closure of 45%, density of 2600 stems/ha, and LAI of 1.7. (b) Pure white spruce stand 22 m tall with a crown closure of 55%, density of 1200 stems/ha, and LAI of 2.6. (c) Mixed species stand 22 m tall with a crown closure of 54%, density of 2600 stems/ha, and LAI of 4.0. (d) Pure deciduous stand 16 m tall with a crown closure of 45%, density of 1600 stems/ha, and LAI of 1.1.

deciduous (r = 0.89, P = 0.001) species. A nonlinear model was selected for estimating sapwood area that was based on the strongest model (highest r^2 and lowest RMSE) that characterized the patterns found within the data (**Table 4**). An overlay of the fitted nonlinear regression model to the scatterplot of the data used in **Table 4** showed that the function fit the trend of the data across all species (R.J. Hall, unpublished data). From these functions, a test with validation data resulted in no statistical differences in sapwood basal area estimation for the lodgepole pine (P = 0.96), white spruce (P = 0.08), and deciduous species (P = 0.68).

LAI estimates among the instruments were highly variable for each species or species group (**Figures 3**, **4**). White spruce had the highest LAI estimates of all the instruments and methods used, followed by the mixedwood, lodgepole pine, and deciduous species. TRAC gave the highest optical estimates of LAI for all species, followed by the allometric, integrated (LAI-2000 and TRAC), and LAI-2000 methods. The clumping indices for all species were similar (lodgepole pine mean (m) = 0.88, standard deviation (s) = 0.10; white spruce m = 0.89, s = 0.07; mixedwood m = 0.90, s = 0.06; deciduous m = 0.87, s = 0.10), and so were the ranges, with 0.69–1.00 for lodgepole pine, 0.64–0.99 for white spruce, 0.77–0.96 for mixedwood, and 0.69–1.00 for deciduous. For each species, there were different pairs of methods that appeared to result in relatively similar LAI estimates (**Figure 4**). For example, the integrated LAI-2000 and TRAC estimates of LAI were similar to the eLAI estimates from the LAI-2000 for deciduous species, but these same methods did not yield comparable results for the other species (**Figures 3**, **4**). Although sample size (**Table 3**) may have influenced the extent to which measurements among the various instruments and methods could be compared, it was obvious that the leaf area values did not compare linearly (**Figure 4**). Thus, the selection of LAI estimation method does have an influence on the LAI value to be derived for a given species, and clumping appears to be an important parameter to measure for all species.

LAI estimates were significantly different among the different species and instrument factors based on the ANOVA tests (**Table 5**). Tukey's HSD multiple-mean comparison tests summarized which LAI estimation technique was statistically different from the others (**Table 6**). The TRAC and allometric leaf area estimates across all species were significantly higher than those from the integrated and LAI-2000 methods. Although not statistically different, the integrated approach generally resulted in larger mean LAI estimates than those from the LAI-2000 instrument. This result was expected, since the integrated method incorporated a clumping measure in its LAI estimate, whereas the LAI-2000 only provides a measure of eLAI. While we recognized the TRAC, integrated, and allometric LAI measurement techniques were similar to one another and not directly comparable to the technique of estimating eLAI from the LAI-2000, it was of interest to determine their relative magnitudes across the four species. The instrument and species interaction factor was statistically significant, suggesting that LAI values will vary with species and measurement techniques (**Table 5**).

Remote sensing LAI estimation

Based on the simple linear models used to estimate LAI from the *casi* image, the spectral mixture analysis shadow fraction (SMA shadow fraction) generally resulted in stronger model fit statistics than the vegetation indices for the white spruce and lodgepole pine plots tested (Table 7, lodgepole pine and white spruce). Although none of the models fitted for lodgepole pine were statistically significant, SMA shadow fraction was generally a stronger predictor than the other vegetation indices. Spectral mixture analysis of the shadow fraction with high-resolution *casi* data was observed to be a generally stronger predictor of LAI than spectral-based vegetation indices.

There were insufficient end members for testing spectral mixture analysis for deciduous and mixedwood species. For the mixedwood species, SAVI resulted in statistically stronger models than the other vegetation indices (**Table 7**, mixedwood). Among the vegetation indices tested for deciduous species, there were no statistically significant models, and the r^2 values were all relatively low (**Table 7**, composite deciduous). Linear patterns from scatterplots among the remote sensing indices and SMA shadow fraction with LAI were not obvious for all species, and some nonlinear patterns appeared to occur, but this result was difficult to determine because of the relatively small sample sizes (D.P. Davidson,

Table 4. Regression models for the prediction of species-specific sapwood basal area (SA, cm^2) from tree basal area (BA, cm^2) determined through area estimates from diameter at breast height (dbh).

Species	N	r^2	RMSE (cm^2)	Equation	Parameter standard errors* Numerator	Parameter standard errors* Denominator
Lodgepole pine	54	0.92	32	$SA = \frac{4062BA}{6486 + BA}$	2929	5029
White spruce	44	0.84	48	$SA = \frac{707BA}{987 + BA}$	106	241
Deciduous (trembling aspen, balsam poplar)	64	0.83	41	$SA = \frac{-529BA}{-1267 + BA}$	115	184

*Standard errors for the numerator and denominator of the model listed in the equation column.

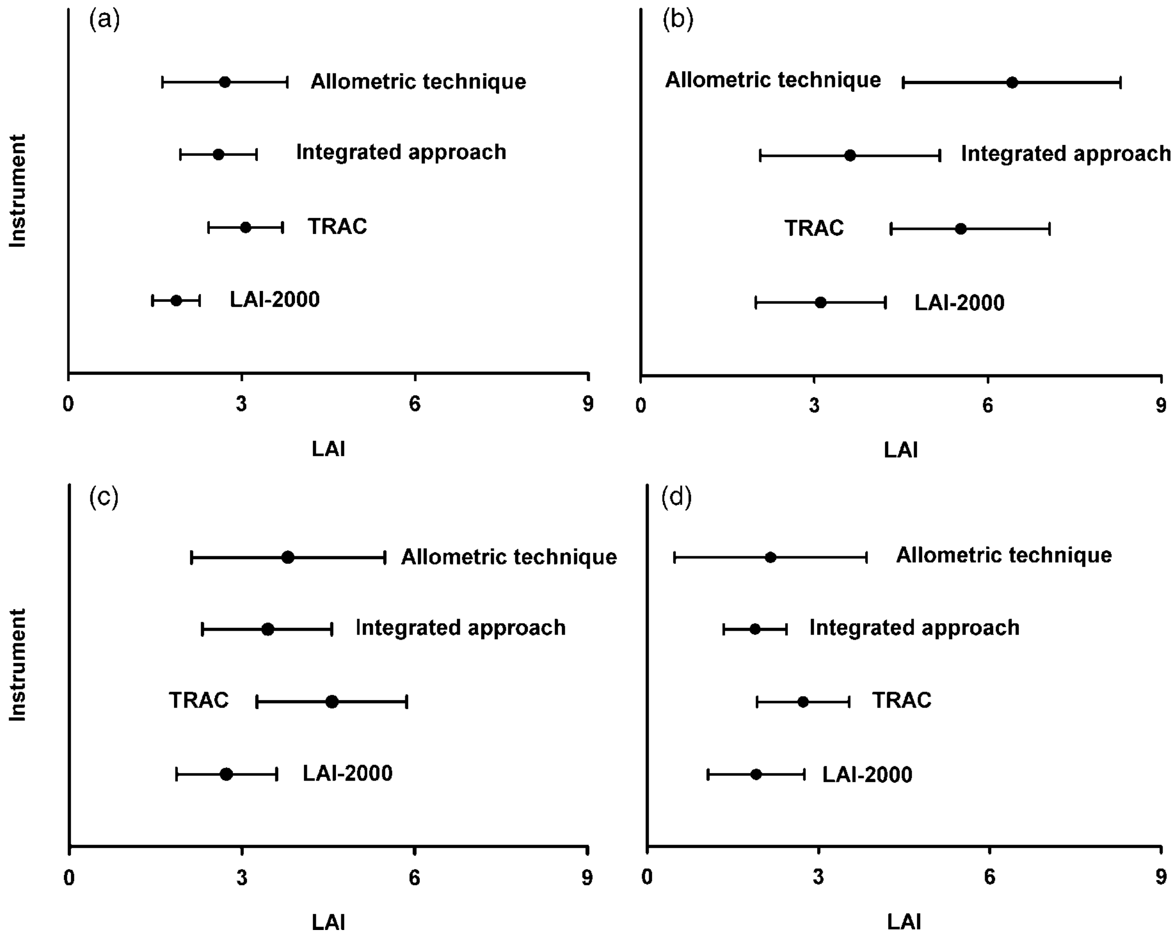

Figure 3. The mean and range in LAI values for each instrument or measurement technique by species: (a) lodgepole pine, (b) white spruce, (c) mixedwood, and (d) composite deciduous. The integrated approach is the integration of the LAI-2000 eLAI measurement with the clumping index derived from the TRAC.

unpublished data). Thus, the use of a linear regression model may not have been appropriate for some of the indices tested.

Discussion

The factors that influenced results obtained in this study and particularly for defining the relationship between LAI and the *casi* image included the methods used to estimate LAI in the field within the context of species and their structural composition, and the remote sensing algorithm that was related to LAI.

Ground-based LAI

The different assumptions inherent to the estimation of LAI from the allometric and optical techniques resulted in variable LAI estimates (**Figure 3**), even within a given species, that were statistically different from each other (**Table 5**). These results were not unexpected. Published allometric functions were used in this study because local allometric functions to estimate LAI by species were not available. The use of the sapwood area to leaf area estimates in previous studies has been shown to be species and stand specific and dependent on season, age, stand density, tree crown size, and climatic differences (Gholz et al., 1976; Pearson et al., 1984; Mencuccini and Grace, 1995). While recognizing that generation of local leaf area allometrics is both a time-consuming and tedious exercise, some means of validating the utility of published allometrics is necessary in future studies.

The LAI-2000 measures the gap fraction at several zenith angles (Chen et al., 1997b) but does not account for gap size distribution that has been reported to result in underestimation of LAI, especially for coniferous forest whose foliage is typically clumped at the shoot and canopy levels and because of woody elements (Gower and Norman, 1991; Fassnacht et al., 1994; Kucharik et al., 1998). The LAI-2000 only provides an estimate of eLAI, which explains why its magnitude was smaller than LAI estimates generated from the other methods. Of interest was the similarity in eLAI estimates between the LAI-2000 and hemispherical photographs for white spruce and deciduous species and the statistical differences for lodgepole pine and mixedwood species. These results may help to verify the estimation of eLAI for these two species in the absence of destructive samples and highlight the influence of sample size

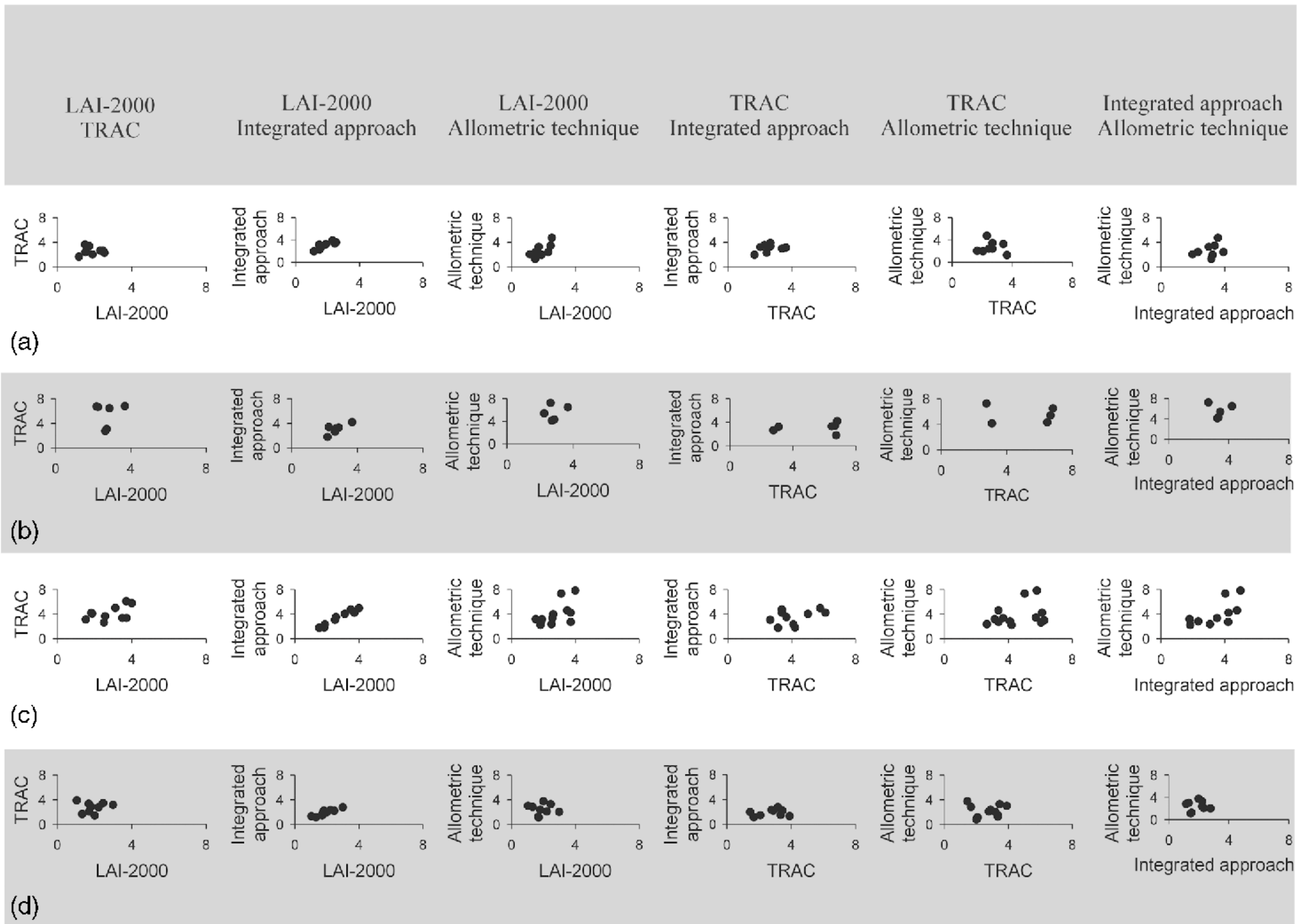

Figure 4. Pairwise scatterplots depicting the relationship between LAI measurement method: (a) lodgepole pine, (b) white spruce, (c) mixedwood, and (d) composite deciduous.

Table 5. Two-way factorial analysis of variance (ANOVA) for species type, instrument, and interactions.

	df	Mean square	*F*	*P*
Instrument	3	39.80	29.64	0.00*
Species	3	15.73	11.71	0.00*
Instrument × species	9	4.01	2.99	0.03*
Error	135	1.34		

Note: df, degrees of freedom; F, F statistic.
*Statistically significant at $P < 0.05$.

Table 6. Tukey's HSD multiple comparison test for LAI by instrument or method.

Instrument or method	*N*	Mean LAI
LAI-2000	36	2.40a
Integrated approach	34	3.01a
Allometric technique	42	3.77b
TRAC	39	3.78b

Note: Means followed by the same letter are not significantly different at $P < 0.05$.

and variation in stand structure that must be captured in the data for valid empirical comparisons to be made. Thus, recognizing that the method used for LAI estimation has a profound influence on its derived magnitude is critical towards its appropriate selection and use for mapping and modeling applications.

The higher LAI estimates by TRAC were attributed to the calculation of a clumping index, the determination of a gap size distribution, and the lower gap fraction estimate resulting from the optical measurement at one solar zenith angle (Chen and Cihlar, 1995; Leblanc and Chen, 1998; 2001). The clumping index calculation is considered more important in coniferous species where the assumption of a random distribution of leaves is not valid (Chen and Cihlar, 1995). In this study, however, the clumping index may be as important in deciduous species as in coniferous stands because of their similar magnitudes (**Figure 3**). Chen et al. (1997a) suggested that the assumption of foliage elements being randomly distributed within foliage clumps and these foliage clumps being randomly distributed in space is not necessarily true for aspen stands. Chen et al. calculated clumping index (Ω) values as 0.84, 0.75, and 0.70

Table 7. Coefficient of determination (r^2), root mean square error (RMSE), and significance ($P < 0.05$) for remote sensing image analysis of LAI (vegetation indices, spectral mixture analysis) regressed against the TRAC, LAI-2000, integrated LAI-2000 and TRAC, and sapwood area/leaf area for lodgepole pine, white spruce, mixedwood, and composite deciduous.

Instrument or method	N	NDVI			WDVI			SAVI			SMA shadow fraction		
		r^2	RMSE	P	r^2	RMSE	P	r^2	RMSE	P	r^2	RMSE	P
Lodgepole pine													
TRAC	7	0.10	0.67	0.44	0.11	0.67	0.43	0.01	0.71	0.94	0.22	0.63	0.24
LAI-2000	7	0.29	0.46	0.17	0.35	0.44	0.12	0.04	0.54	0.88	0.16	0.50	0.32
Integrated	7	0.30	0.58	0.16	0.33	0.56	0.14	0.03	0.69	0.91	0.37	0.55	0.11
Allometric	7	0.04	1.14	0.62	0.06	1.13	0.55	0.21	1.04	0.26	0.01	1.16	0.79
White spruce													
TRAC	4	0.01	2.13	0.90	0.00	2.13	0.99	0.23	1.88	0.42	0.02	2.12	0.84
LAI-2000	4	0.96	0.12	0.01*	0.89	0.20	0.02*	0.30	0.50	0.34	0.98	0.08	0.001*
Integrated	4	0.60	0.53	0.12	0.48	0.61	0.20	0.02	0.84	0.82	0.74	0.43	0.05*
Allometric	4	0.08	2.19	0.65	0.03	2.25	0.79	0.14	2.12	0.54	0.18	2.07	0.48
Mixedwood													
TRAC	10	0.01	1.30	0.93	0.03	1.29	0.69	0.44	0.98	0.06			
LAI-2000	11	0.02	0.87	0.68	0.11	0.83	0.31	0.41	0.68	0.04*			
Integrated	11	0.00	1.25	0.97	0.05	1.22	0.56	0.48	0.90	0.04*			
Allometric	11	0.03	1.96	0.61	0.10	1.88	0.34	0.70	1.08	0.01*			
Composite deciduous													
TRAC	10	0.06	0.85	0.49	0.05	0.86	0.54	0.04	0.86	0.59			
LAI-2000	9	0.11	0.60	0.39	0.10	0.60	0.42	0.22	0.55	0.20			
Integrated	9	0.10	0.56	0.42	0.07	0.56	0.48	0.16	0.54	0.28			
Allometric	11	0.04	0.98	0.56	0.02	0.99	0.71	0.02	0.99	0.90			

*Statistically significant at $P < 0.05$.

for different aspen stands within Prince Albert National Park, Saskatchewan, Canada. The clumping indices obtained in this study were consistent with those published by Chen et al., suggesting that foliage clumping can be important in the derivation of LAI values in deciduous stands.

LAI estimation by species using remote sensing

The structural properties of a tree can vary significantly by species, with the spatial distribution of trees within a stand having an important influence on the amount and distribution of light that reaches the forest floor. The differences in LAI among species can be attributed, in part, to the structural composition of the stand, including canopy architecture and morphology, leaf orientation and distribution, and stand structure attributes such as stem density, site quality, age class, a variety of abiotic and biotic factors, and woody elements (Pearson et al., 1984; Kucharik et al., 1998; Kollenberg and O'Hara, 1999; Gower et al., 1999).

The low R^2 and relative lack of statistical significance in the LAI models for lodgepole pine were likely attributed to the sensitivity of this species growth and stand dynamics to stand density and vegetative competition (Alexander et al., 1967; Lotan and Critchfield, 1990). Among all the species evaluated in this study, lodgepole pine was the most variable in terms of density (600–4400 stems/ha; **Table 3**). This sensitivity to the structure of lodgepole pine stands influences how the crown biomass is allocated along the tree, and this consequently influences the amount and spatial distribution of leaf area within the tree. Kollenberg and O'Hara (1999) suggested that stratifying lodgepole pine stands by age class or canopy strata may result in more accurate stand-level LAI estimations, and that leaf area dynamics will vary between even-aged and multi-aged stands. If this is not considered, then more difficulty may be expected for both ground-based and remote estimates of LAI for lodgepole pine compared with other species such as white spruce. Although the SMA shadow fraction was generally a stronger predictor of LAI than the other vegetation indices (**Table 7**, lodgepole pine), further study of lodgepole pine stand characterization, its measurement of leaf area, and its relation to remote sensing indices is needed to reliably map its quantity and spatial distribution.

LAI estimates for white spruce were the largest of all species (**Figure 3**). This was consistent with their mensurational descriptives, since this species was also the largest in the study area with respect to both tree height and basal area (**Table 3**). Although white spruce can grow on a diverse range of sites (Nienstaedt and Zasada, 1990), the relatively similar site conditions for white spruce in our study area may have contributed to its relatively narrow range of stand structures and distributions with respect to stem densities and crown closures compared with those of the other species (**Table 3**). Although no age data were collected, information from the Alberta Vegetation Inventory for the Kananaskis study area suggests that stands were largely mature, with ages that ranged from 100 to 150 years (R.J. Hall, unpublished data). The shadow fraction from SMA was the strongest predictor of leaf area for this species compared with remote sensing vegetation indices (**Table 7**, white spruce). This result is a significant finding because it suggests that for mature white spruce stands, LAI can be estimated from high-resolution *casi* data based on the shadow fraction as the predictor. Sampling a wider range of stands would provide the opportunity to verify if these results also apply to smaller and younger white spruce stands.

Mixedwood canopies consisted of mostly a mixture of trembling aspen, balsam poplar, and white spruce trees. These stands were the most variable from a structural perspective in terms of crown closure, stem density, tree height, and basal area (**Table 3**). The lack of sufficient end members for mixedwood and deciduous species negated the opportunity to evaluate spectral mixture analysis for LAI estimation in these cases. There were, however, encouraging results for prediction of LAI from SAVI (**Table 7**, mixedwood). The SAVI is essentially the NDVI with an adjustment to minimize the secondary backscattering effect of canopy-transmitted soil background reflected radiation (Bannari et al., 1995), and this index appears to offer potential in mixed species canopies.

For the deciduous stands, LAI was poorly predicted from any of the vegetation indices evaluated (**Table 7**, composite deciduous). Deciduous stands were the second most variable species group with respect to crown closure, tree height, and basal area (**Table 3**). Trembling aspen and balsam poplar can occupy a large range of sites and are also characterized by clonal differences (Perala, 1990; Zasada and Phipps, 1990) that result in structural variation that may not have been sufficiently sampled in this study.

Conclusions

Three aspects of LAI estimation and their interrelationships were investigated in this study, including the species, the method for ground-based estimation of LAI, and the relationship between the LAI and the acquired *casi* image. Study results verified that LAI values varied with species, structural composition of the species, and the ground-based allometric or optical measurement technique employed. Consequently, the relationship between the ground-based LAI and the algorithm applied to the remote sensing image will vary, thus pointing to the need to carefully select the appropriate method for estimating LAI from the ground. From the perspective of the image, previous studies have provided evidence of the utility of spectral mixture analysis and modeling for LAI estimation from Landsat TM satellite imagery and airborne radiometer and multispectral video data (Peddle and Johnson, 2000; Peddle et al., 2001a; 2003). This study has demonstrated further potential for estimation of LAI in white spruce stands using spectral mixture analysis of the shadow fraction for *casi* data at 2 m spatial resolution. Further research over a wider range of stand conditions is needed to assess the application of spectral mixture analysis to lodgepole pine, mixedwood, and deciduous species. These results were specific to the montane ecoregion in Kananaskis, Alberta, but may be applicable to other similar regions that could be verified by sampling from a larger area with greater ecological diversity. In terms of the potential application of these study results, while we recognize that it is less practical to employ contiguous *casi* data for large-area LAI mapping, its potential use as a sampling tool has not yet been fully explored. The use of *casi* data in models with ground-based, optical LAI data provides the potential for local area biophysical estimation and for scaling to coarser resolution data such as the Landsat TM and moderate-resolution imaging spectroradiometer (MODIS) imagery for LAI mapping at the landscape level.

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References

Achuff, P.L. 1992. *Natural regions, subregions and natural history themes of Alberta*. Parks Services, Alberta Environmental Protection, Edmonton, Alta.

Adams, J.B., Smith, M.O., and Gillespie, A.R. 1993. Imaging spectroscopy: interpretation based on spectral mixture analysis. In *Topics in remote sensing IV: remote geochemical analysis*. Edited by C.M. Pieters and P.A.J. Englert. Cambridge University Press, New York. pp. 145–166.

Alexander, R.R., Tackle, D., and Dahms, W.G. 1967. *Site indexes for Lodgepole Pine with correction for stand density: methodology.* U.S. Forest Service, U.S. Department of Agriculture, Washington, D.C., Research Paper RM-29.

Anger, C.D., Mah, S., and Babey, S. 1994. Technological enhancements to the compact airborne spectrographic imager (*casi*). In *Proceedings of the 1st International Conference on Airborne Remote Sensing*, 12–15 Sept. 1994, Strasbourg, France. Environmental Research Institute of Michigan, Ann Arbor, Mich. Vol. II, pp. 205–213.

Archibald, J.H., Klappstein, G.D., and Corns, I.G.W. 1996. *Field guide to ecosites of southwestern Alberta*. UBC Press, Vancouver, B.C., Special Report 8.

Badhwar, G.D., Macdonald, R.B., Hall, F.G., and Carnes, J.G. 1986. Spectral characterization of biophysical characteristics in a boreal forest: relationship between Thematic Mapper band reflectance and leaf area index for aspen. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. GE-24, pp. 322–326.

Bannari, A., Morrin, D., Bonn, F., and Huete, A.R. 1995. A review of vegetation indices. *Remote Sensing Reviews*, Vol. 13, pp. 95–120.

Baret, F., and Guyot, G. 1991. Potentials and limits of vegetation indices for LAI and APAR assessment. *Remote Sensing of Environment*, Vol. 35, pp. 161–173.

Buckley, D.S. 1999. Practical field methods of estimating canopy cover, PAR and LAI in Michigan oak and pine stands. *Northern Journal of Applied Forestry*, Vol. 16, pp. 25–32.

Chason, J.W., Baldocchi, D.D., and Huston, M.A. 1991. A comparison of direct and indirect methods for estimating forest canopy leaf area. *Agricultural and Forest Meteorology,* Vol. 57, pp. 107–128.

Chen, J.M. 1996a. Evaluation of vegetation indices and a modified simple ratio for boreal applications. *Canadian Journal of Remote Sensing*, Vol. 22, pp. 229–242.

Chen, J.M. 1996b. Optically-based methods for measuring seasonal variations of leaf area index in boreal conifer stands. *Agricultural and Forest Meteorology*, Vol. 80, pp. 135–163.

Chen, J.M., and Black, T.A. 1992. Defining leaf area index for non-flat leaves. *Plant, Cell and Environment*, Vol. 15, pp. 421–429.

Chen, J.M., and Cihlar, J. 1995. Plant canopy gap-size analysis theory for improving optical measurements of leaf-area index. *Applied Optics*, Vol. 34, pp. 6211–6222.

Chen, J.M., Blanken, P.D., Black, T.A., Guilbeault, M., and Chen, S. 1997a. Radiation regime and canopy architecture in a boreal aspen forest. *Agricultural Forest Meteorology*, Vol. 86, pp. 107–125.

Chen, J.M., Rich, P.M., Gower, S.T., Norman, J.M., and Plummer, S. 1997b. Leaf area index of boreal forests: theory, techniques and measurements. *Journal of Geophysical Research*, Vol. 102, No. D24, pp. 29 429 – 29 433.

Chen, J.M., Pavlic, G., Brown, L., Cihlar, J., Leblanc, S.G., White, H.P., Hall, R.J., Peddle, D.R., King, D.J., Trofymow, J.A., Swift, E., Van der Sanden, J., and Pellikka, P.K.E. 2002. Derivation and validation of Canada-wide coarse-resolution leaf area index maps using high-resolution satellite imagery and ground measurements. *Remote Sensing of Environment*, Vol. 80, pp. 165–184.

Cihlar, J., Chen, J., and Li, Z. 1997. On the validation of satellite-derived products for land applications. *Canadian Journal of Remote Sensing*, Vol. 23, pp. 381–389.

Clevers, J.G.P.W. 1989. The application of a weighted infrared–red vegetation index for estimating leaf area index by correcting for soil moisture. *Remote Sensing of Environment*, Vol. 29, pp. 25–37.

Coops, N., Ryan, P., and Bishop, A. 1998. Investigating *casi* response to soil properties and disturbance across an Australian eucalypt forest. *Canadian Journal of Remote Sensing*, Vol. 24, pp. 153–168.

Cutini, A., Matteussi, G., and Mugnozza, G.S. 1998. Estimation of leaf area index with the Li-cor LAI 2000 in deciduous forests. *Forest Ecology and Management*, Vol. 105, pp. 55–65.

Dantec, V.L., Dufrêne, E., and Saugier, B. 2000. Interannual and spatial variation in maximum leaf area index of temperate deciduous stands. *Forest Ecology and Management*, Vol. 134, pp. 71–81.

Davidson, D.P. 2002. *Sensitivity of ecosystem net primary productivity models to remotely sensed leaf area index in a montane forest environment*. M.Sc. thesis, Department of Geography, University of Lethbridge, Lethbridge, Alta.

Fassnacht, K.S., Gower, S.T., Norman, J.M., and McMurtrie, R.E. 1994. A comparison of optical and direst methods for estimating foliage surface area index in forests. *Agricultural and Forest Meteorology*, Vol. 71, pp. 183–207.

Fassnacht, K.S., Gower, S.T., MacKenzie, M.D., Nordheim, E.V., and Lillesand, T.M. 1997. Estimating the leaf area index of north central Wisconsin forests using Landsat Thematic Mapper. *Remote Sensing of Environment*, Vol. 61, pp. 229–245.

Fernandes, R.A., Miller, J.R., Hu, B., and Rubinstein, I.G. 2002. A multi-scale approach to mapping effective leaf area index in boreal *Picea mariana* stands using high spatial resolution CASI imagery. *International Journal of Remote Sensing*, Vol. 23, pp. 3547–3568.

Franklin, S.E. 2001. *Remote sensing for sustainable forest management*. Lewis Publishers, CRC Press, Boca Raton, Fla.

Frazer, G.W., Trofymow, J.A., and Lertzman, K.P. 1997. *A method for estimating canopy openness, effective leaf area index, and photosynthetically active photo flux density using hemispherical photography and computerized image analysis techniques*. Pacific Forestry Centre, Canadian Forest Service, Natural Resources Canada, Victoria, B.C., Information Report BC-X-373.

Frazer, G.W., Canham, C.D., and Lertzman, K.P. 1999. *Gap Light Analyzer (GLA): hemispherical photography and imaging software, users manual and program documentation*. Simon Fraser University, Burnaby, B.C., and the Institute of Ecosystem Studies, Millbrook, N.Y.

Frazer, G.W., Fournier, R.A., Trofymow, J.A., and Hall, R.J. 2001. A comparison of digital and film fisheye photography for analysis of forest canopy structure and gap light transmission. *Agricultural and Forest Meteorology*, Vol. 109, pp. 249–263.

Gerylo, G., Hall, R.J., Franklin, S.E., Roberts, A., and Milton, E.J. 1998. Hierarchical image classification and extraction of forest species composition and crown closure from airborne multispectral images. *Canadian Journal of Remote Sensing*, Vol. 24, pp. 219–232.

Gholz, H.L. 1982. Environmental limits on aboveground net primary production, leaf area, and biomass in vegetation zones of the Pacific Northwest. *Ecology*, Vol. 63, pp. 469–481.

Gholz, H.L., Fritz, F.K., and Waring, R.H. 1976. Leaf area differences associated with old growth forest communities in western Oregon Cascades. *Canadian Journal of Forest Research*, Vol. 6, pp. 49–57.

Gong, P., Pu, R., and Miller, J.R. 1995. Coniferous forest leaf area index estimation along the Oregon transect using Compact Airborne Spectrographic Imager data. *Photogrammetric Engineering and Remote Sensing*, Vol. 61, pp. 1107–1117.

Gower, S.T., and Norman, J.M. 1991. Rapid estimation of leaf area index in conifer and broadleaf plantations. *Ecology*, Vol. 72, pp. 1896–1900.

Gower, S.T., Grier, C.C., Vogt, D.G., and Vogt, K.A. 1987. Allometric relations of deciduous (*Larix occidentalis*) and evergreen conifers (*Pinus contorta* and *Pseudotsuga menziesii*) of the Cascade Mountains in Central Washington. *Canadian Journal of Forest Research*, Vol. 17, pp. 630–634.

Gower, S.T., Vogel, J.G., Norman, J.M., Kucharik, C.J., Steele, S.J., and Stow, T.K. 1997. Carbon distribution and aboveground net primary production for aspen, jack pine, and black spruce stands in Saskatchewan and Manitoba, Canada. *Journal of Geophysical Research*, Vol. 102, No. D24, pp. 29 029 – 29 041.

Gower, S.T., Kucharik, C.J., and Norman, J.M. 1999. Direct and indirect estimation of leaf area index, f_{APAR}, and net primary production of terrestrial ecosystems. *Remote Sensing of Environment*, Vol. 70, pp. 29–51.

Hale, S.E., and Edwards, C. 2002. Comparison of film and digital hemispherical photography across a wide range of canopy densities. *Agricultural and Forest Meteorology*, Vol. 112, pp. 51–56.

Hall, F.G., Shimabukro, Y.E., and Huemmrich, K.F. 1995. Remote sensing of forest biophysical structure using mixture decomposition and geometric reflectance models. *Ecological Application*, Vol. 5, pp. 993–1013.

Hall, F.G., Peddle, D.R., and LeDrew, E.F. 1996. Remote sensing of biophysical variables in boreal forest stands of *Picea mariana*. *International Journal of Remote Sensing*, Vol. 17, pp. 3077–3081.

Huang, S. 1994. *Ecologically based individual tree volume estimation for major Alberta tree species. Report 1: individual tree volume estimation procedures for Alberta: methods of formulation and statistical foundations.* Land and Forest Services, Forest Management Division, Alberta Environmental Protection, Edmonton, Alta.

Johnson, R.L. 2000. *Airborne remote sensing of forest leaf area index in mountainous terrain*. M.A. thesis, Department of Geography, University of Lethbridge, Lethbridge, Alta.

Kaufmann, M.R., and Troendle, C.A. 1981. The relationship of leaf area and foliage biomass to sapwood conducting area in four subalpine forest tree species. *Forest Science*, Vol. 27, pp. 477–482.

Kendall, M.G., and Stuart, A.S. 1967. *Advanced theory of statistics*. Vol. 2. Charles Griffin and Company, London.

Kollenberg, C.L., and O'Hara, K.L. 1999. Leaf area and tree increment dynamics of even-aged and multiaged lodgepole pine stands in Montana. *Canadian Journal of Forest Research*, Vol. 29, pp. 687–695.

Kucharik, C.J., Norman, J.M., and Murdock, L.M. 1997. Characterizing canopy nonrandomness with a multiband vegetation imager (MVI). *Journal of Geophysical Research*, Vol. 102, No. D24, pp. 29 455 – 29 473.

Kucharik, C.J., Norman, J.M., and Gower, S.T. 1998. Measurements of branch area and adjusting leaf area index indirect measurements. *Agricultural and Forest Meteorology*, Vol. 91, pp. 69–88.

Law, B.E. 1995. Estimation of leaf area index and light intercepted by shrubs from digital videography. *Remote Sensing of Environment*, Vol. 51, pp. 276–280.

Leblanc, S.G., and Chen, J.M. 1998. LAI measurements in deciduous and coniferous forests with two optical instruments. In *Proceedings of an International Workshop: Scaling and Modelling in Forestry: Applications in Remote Sensing and GIS*, 19–21 Mar. 1998, University of Montréal, Montréal, Que. pp. 119–125.

Leblanc, S.G., and Chen, J.M. 2001. A practical scheme for correcting multiple scattering effects on optical LAI measurements. *Agricultural and Forest Meteorology*, Vol. 110, pp. 125–139.

Leblanc, S.G., Chen, J.M., and Kwong, M. 2002. *Tracing radiation and architecture of canopies. TRAC manual version 2.1*. Canada Centre for Remote Sensing, Natural Resources Canada, Ottawa, Ont.

LI-COR, Inc. 1990. *LAI-2000 plant canopy analyzer: operating manual*. LI-COR, Inc., Lincoln, Nebr.

Liu, J., Chen, J.M., Cihlar, J., and Park, W.M. 1997. A process-based boreal ecosystem productivity simulator using remote sensing inputs. *Remote Sensing of Environment*, Vol. 62, pp. 158–175.

Lotan, J.E., and Critchfield, W.B. 1990. *Pinus contorta* Dougl. Ex. Loud, lodgepole pine. In *Silvics of North America. Volume 1: Conifers*. Edited by R.M. Burns and B.H. Honkala. U.S. Department of Agriculture, Forest Service, Washington, D.C., Agriculture Handbook 654, pp. 302–315.

Mencuccini, M., and Grace, J. 1995. Climate influences the leaf area/sapwood are ratio in Scots pine. *Tree Physiology*, Vol. 15, pp. 1–10.

Meyer, P., Itten, K.I., Kellenberger, T., Sandmeier, S., and Sandmeier, R. 1993. Radiometric corrections of topographically induced effects on LANDSAT TM data in an alpine environment. *Journal of Photogrammetry and Remote Sensing*, Vol. 48, pp. 17–28.

Miller, J.B. 1967. A formula for average foliage density. *Australian Journal of Botany*, Vol. 15, pp. 141–144.

Miller, J., White, P., Chen, J., Peddle, D., McDermid, G., Fournier, R., Shepherd, P., Rubinstein, I., Freemantle, J., Soffer, R., and LeDrew, E. 1997. Seasonal change in understorey reflectance of boreal forests and influence on canopy vegetation indices. *Journal of Geophysical Research, Special Issue: BOREAS*, Vol. 102, No. D24, pp. 29 475 – 29 482.

Niemann, K.O. 1995. Remote sensing of forest stand age using airborne spectrometer data. *Photogrammetric Engineering and Remote Sensing*, Vol. 61, pp. 1119–1127.

Nienstaedt, H., and Zasada, J.C. 1990. *Picea glauca* (Moench) Voss, white spruce. In *Silvics of North America. Volume 1: Conifers.* Edited by R.M. Burns and B.H. Honkala. U.S. Department of Agriculture, Forest Service, Washington, D.C., Agriculture Handbook 654, pp. 204–226.

North, P.R.J. 2002. Estimation of f_{APAR}, LAI, and vegetation fractional cover from ATSR-2 imagery. *Remote Sensing of Environment*, Vol. 80, pp. 114–121.

Olthof, I., King, D.J., and Lautenschlager, R.A. 2001. Leaf area index change in ice-storm-damaged sugar maple stands. *The Forestry Chronicle*, Vol. 77, pp. 627–635.

Pearson, J.A., Fahey, T.J., and Knight, D.H. 1984. Biomass and leaf area in contrasting lodgepole pine forests. *Canadian Journal of Forest Research*, Vol. 14, pp. 259–265.

Peddle, D.R., and Johnson, R.L. 2000. Spectral mixture analysis of airborne remote sensing imagery for improved prediction of leaf area index in mountainous terrain, Kananaskis, Alberta. *Canadian Journal of Remote Sensing*, Vol. 26, pp. 176–187.

Peddle, D.R., Hall, F.G., and LeDrew, E.F. 1999. Spectral mixture analysis and geometric optical reflectance modeling of boreal forest biophysical structure. *Remote Sensing of Environment*, Vol. 67, pp. 288–297.

Peddle, D.R., Brunke, S.P., and Hall, F.G. 2001a. A comparison of spectral mixture analysis and ten vegetation indices for estimating boreal forest biophysical information from airborne data. *Canadian Journal of Remote Sensing*, Vol. 27, pp. 627–635.

Peddle, D.R., White, H.P., Soffer, R.J., Miller, J.R., and LeDrew, E.F. 2001b. Reflectance processing of remote sensing spectroradiometer data. *Computers & Geosciences*, Vol. 27, pp. 203–213.

Peddle, D.R., Johnson, R.L., Cihlar, J., and Latifovic, R. 2003. Large area forest classification and biophysical parameter estimation using the 5-Scale canopy reflectance model in multiple-forward mode. *Remote Sensing of Environment*. In press.

Pellikka, P., Seed, E.D., and King, D.J. 2000. Modelling deciduous forest ice storm damage using aerial CIR imagery and hemispheric photography. *Canadian Journal of Remote Sensing*, Vol. 26, pp. 394–405.

Perala, D.A. 1990. *Populus tremuloides* Michx., Quaking Aspen. In *Silvics of North America. Volume 2: Hardwoods.* Edited by R.M. Burns and B.H. Honkala. U.S. Department of Agriculture, Forest Service, Washington, D.C., Agriculture Handbook 654. pp. 555–569.

Pierce, L.L., and Running, S.W. 1988. Rapid estimation of coniferous forest leaf area index using portable integrating radiometer. *Ecology*, Vol. 69, pp. 1762–1767.

Qi, J., Chehbouni, A., Huete, A.R., Kerr, Y.H., and Sorooshian, S. 1994. A modified soil adjusted vegetation index. *Remote Sensing of Environment*, Vol. 48, pp. 119–126.

Rich, P.M. 1990. Characterizing plant canopies with hemispherical photographs. *Remote Sensing Reviews*, Vol. 5, pp. 13–29.

Richardson, A.J., and Wiegand, C.L. 1977. Distinguishing vegetation from soil background information. *Photogrammetric Engineering and Remote Sensing*, Vol. 43, pp. 1541–1552.

Running, S.W., and Coughlan, J.C. 1988. A general model of forest ecosystem processes for regional applications: 1. Hydrologic balance, canopy gas exchange and primary production processes. *Ecological Modelling*, Vol. 42, pp. 125–154.

Running, S.W., and Hunt, E.R. 1993. Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models. In *Scaling physiological processes: leaf to globe*. Edited by J. Ehleringer. Academic Press, New York. pp. 141–158.

Sellers, P.J., and Schimel, D. 1993. Remote sensing of the land biosphere and biogeochemistry in the EOS era: science priorities, methods and implementation. *Global and Planetary Change*, Vol. 7, pp. 279–297.

Shimabukuro, Y.S., and Smith, J.A. 1991. The least-squares mixing models to generate fraction images derived for remote sensing multispectral data. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 29, pp. 16–20.

Snell, J.A.K., and Brown, J.K. 1978. Comparison of tree biomass indicators — DBH and sapwood area. *Forest Science*, Vol. 24, pp. 455–457.

Sokal, R.R., and Rohlf, F.J. 1995. *Biometry: the principles and practice of statistics in biological research*. 3rd ed. W.H. Freeman and Company, New York.

SPSS Inc. 1999. *SPSS for Windows, release 10.0.0*. SPSS Inc., Chicago, Ill.

Teillet, P.M., Guindon, B., and Goodenough, D.G. 1982. On the slope aspect correction of multi spectral scanner data. *Canadian Journal of Remote Sensing*, Vol. 8, pp. 84–106.

Waring, R.H., Schroeder, P.E., and Oren, R. 1982. Application of the pipe model theory to predict canopy leaf area. *Canadian Journal of Forest Research*, Vol. 12, pp. 556–560.

Welles, J.M. 1990. Some indirect methods of estimating canopy structure. *Remote Sensing Reviews*, Vol. 5, pp. 31–43.

White, J., Running, S., Nemani, R., Keane, R., and Ryan, K. 1997. Measurement and remote sensing of LAI in Rocky Mountain montane ecosystems. *Canadian Journal of Forest Research*, Vol. 27, pp. 1714–1727.

Wulder, M.A., Franklin, S.E., and Lavigne, M.B. 1996. High spatial resolution optical image texture for improved estimation of forest stand leaf area index. *Canadian Journal of Remote Sensing*, Vol. 22, pp. 441–449.

Wulder, M.A., LeDrew, E.F., Franklin, S.E., and Lavigne, M.B. 1998. Aerial image texture information in the estimation of northern deciduous and mixed wood forest leaf area index (LAI). *Remote Sensing of Environment*, Vol. 64, pp. 64–76.

Zasada, J.C., and Phipps, H.M. 1990. *Populus balsamifera* L.: balsam poplar. In *Silvics of North America. Volume 2: Hardwoods*. Edited by R.M. Burns and B.H. Honkala. U.S. Department of Agriculture, Forest Service, Washington, D.C., Agriculture Handbook 654, pp. 518–529.