# Estimating forest canopy bulk density using six indirect methods

**Robert E. Keane, Elizabeth D. Reinhardt, Joe Scott, Kathy Gray, and James Reardon**

**Abstract:** Canopy bulk density (CBD) is an important crown characteristic needed to predict crown fire spread, yet it is difficult to measure in the field. Presented here is a comprehensive research effort to evaluate six indirect sampling techniques for estimating CBD. As reference data, detailed crown fuel biomass measurements were taken on each tree within fixed-area plots located in five important conifers types in the western United States, using destructive sampling following a series of four sampling stages to measure the vertical and horizontal distribution of canopy biomass. The six ground-based indirect measurement techniques used these instruments: LI-COR LAI-2000, AccuPAR ceptometer, CID digital plant canopy imager, hemispherical photography, spherical densiometer, and point sampling. These techniques were compared with four aggregations of crown biomass to compute CBD: foliage only, foliage and small branchwood, foliage and all branchwood (no stems), and all canopy biomass components. Most techniques had the best performance when all canopy biomass components except stems were used. Performance dropped only slightly when the foliage and small branchwood canopy biomass aggregation (best approximates fuels available for crown fires) was employed. The LAI-2000, hemispherical photography, and CID plant canopy imager performed best. Regression equations that predict CBD from gap fraction are presented for all six techniques.

**Résumé :** La densité apparente de la canopée (DAC) est une caractéristique importante de la cime qui est nécessaire pour prédire la propagation d'un feu de cime mais qui est cependant très difficile à mesurer sur le terrain. Les auteurs présentent ici un travail de recherche exhaustif dont le but était d'évaluer six techniques indirectes d'échantillonnage pour estimer la DAC. Les données de référence proviennent de mesures détaillées de la biomasse des combustibles dans la cime prises sur chaque arbre dans des placettes à superficie fixe situées dans cinq types importants de forêt résineuse de l'ouest des États-Unis en utilisant une approche destructrice après avoir procédé à une série d'échantillonnages en quatre étapes pour mesurer la distribution verticale et horizontale de la biomasse dans la canopée. Les six techniques indirectes de mesure sur le terrain comprenaient les instruments suivants : le LAI-2000 de LI-COR, le ceptomètre d'AccuPAR, l'imageur digital du couvert végétal CID, la photographie hémisphérique, le densiomètre sphérique et l'échantillonnage par point. Ces techniques ont été comparées à quatre regroupements de la biomasse de la cime pour calculer la DAC : feuillage seulement, feuillage et petites branches, feuillage et toutes les branches (sans la tige) et toutes les composantes de la biomasse de la cime. La plupart des techniques offraient la meilleure performance lorsque toutes les composantes de la biomasse de la canopée, à l'exception de la tige, étaient utilisées. La performance diminuait juste un peu avec l'utilisation du regroupement de la biomasse de la canopée composé du feuillage et des petites branches (regroupement qui fournit la meilleure approximation des combustibles disponibles pour les feux de cime). Le LAI-2000, la photographie hémisphérique et l'imageur digital du couvert végétal CID ont eu la meilleure performance. Des équations de régression qui prédisent la DAC à partir de la proportion d'ouvertures sont présentées pour les six techniques.

[Traduit par la Rédaction]

## Introduction

Successful fire-suppression programs in the western United States and Canada over the last 70 years have reduced fire occurrence in many fire-prone forests, resulting in excessive buildups of fuels, especially tree crowns, which has in turn increased the probabilities and intensities of future severe crown fires (Mutch 1994; Ferry et al. 1995; Kolb et al. 1998; Keane et al. 2002). Crown fires have become especially common in dry, low-elevation forests that, prior to European settlement (ca. 1900), frequently experienced nonlethal surface fires or mixed-severity fires that rarely burned overstory tree crowns and were somewhat easy to control (Kolb 1998; Arno et al. 2000). Therefore, it is very important that the forest canopy characteristics be quantified to assess crown fire hazard, prioritize treatment areas, and design treatments to reduce crown fire potential.

One canopy characteristic important for crown fire propagation is canopy bulk density (CBD), defined as the mass

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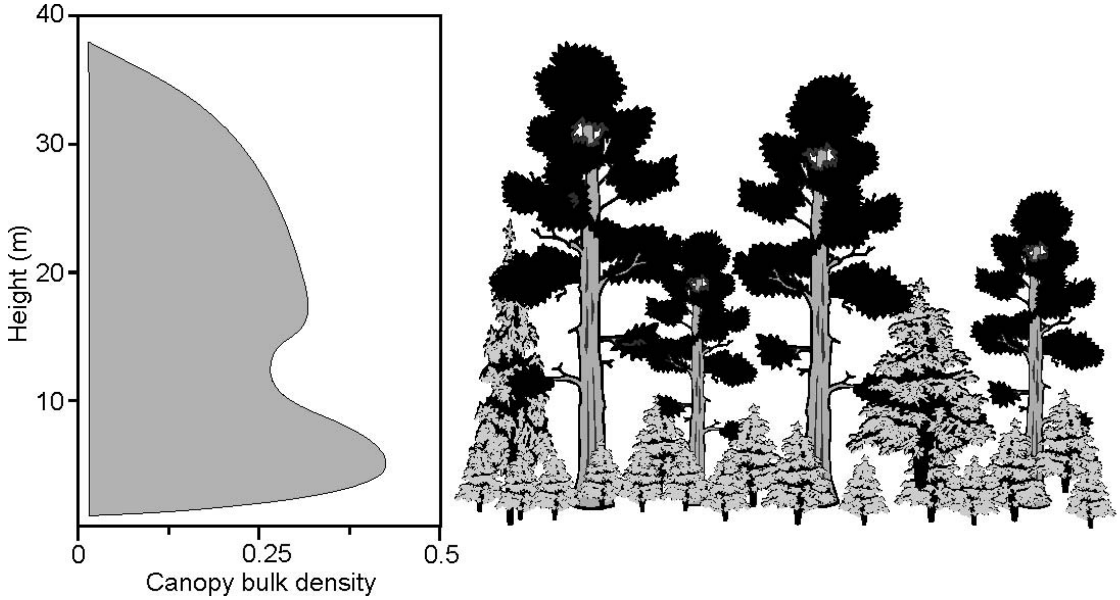
**Fig. 1.** Crown bulk density profile for a hypothetical stand. The crown bulk density averaged across the entire profile is 0.2 kg·m$^{-3}$, but one canopy layer at about 5 m high has a bulk density of 0.4 kg·m$^{-3}$.




per unit volume of canopy biomass that would burn in a crown fire (primarily foliage and twigs less than 3 mm in diameter) (see Fig. 1) (van Wagner 1977; Alexander 1988; Finney 1998*b*). A number of fire behavior and effects models require estimates of CBD and several other canopy fuel characteristics (namely canopy base height, stand height, and canopy cover) to accurately simulate crown fires, including the models FIRETEC (Linn 1997) and NEXUS (Scott 1999). The fire growth model FARSITE (Finney 1998), currently used by many fire management agencies, requires CBD and the other canopy characteristics to be mapped across the simulation landscape at high spatial resolution to predict crown fire behavior. Unlike the other canopy characteristics, standardized field methods do not exist for sampling CBD. Fire managers urgently need an efficient field sampling technique to estimate CBD for simulating crown fire behavior to facilitate design, implementation, and monitoring of canopy fuel treatment projects.

We evaluate six indirect techniques for their ability to estimate forest CBD for fire management applications. For reference data, we measured crown biomass on all trees within fixed-area plots using destructive sampling following a series of cutting treatments on five study sites representing common western United States conifer types. We evaluated six ground-based, optical, indirect measurement methods for estimating CBD. These methods use equipment for estimating leaf area index (LAI) and canopy gap fraction. Results from CBD estimates are compared across the six indirect techniques, and regression equations are developed so that these methods can be used in the field. Recommendations on their use are discussed.

## Background

### Current methods

Canopy bulk density (CBD) is difficult to measure because it requires detailed knowledge of the vertical distribution of crown biomass (Alexander 1988) (Fig. 1). Direct methods of destructively sampling tree biomass by vertical canopy layers are expensive and time intensive (Gary 1978; Scott and Reinhardt 2002). We found only two studies that measured vertical canopy fuel distribution. Sando and Wick (1972) computed CBD for 0.3-m canopy layers across a lodgepole pine forest vertical profile, and Gary (1976, 1978) intensively sampled thinned and unthinned 80-year-old lodgepole pine stands to determine crown biomass distribution and structure.

The most popular method for estimating CBD uses measurements of tree diameter, height, and crown base height for all trees in a stand to calculate crown biomass distribution from allometric crown biomass equations (Keane et al. 1998, 2000). Reinhardt and Crookston (2003) used the Sando and Wick (1972) approach in combination with Brown's (1978) crown equations to estimate canopy bulk density from stand inventory data (tree density, species, diameter at breast height (dbh; diameter at 1.37 m), height, crown base height). However, crown biomass equations are not available for all tree species, size classes, and stand conditions, so this method is impractical for many forested ecosystems. Johnson et al. (1989) developed crown fuel component biomass equations for lodgepole pine and white spruce using tree height and crown width but did not predict the vertical distribution of canopy fuels. The allometric approach for predicting CBD has not been previously validated and is restricted to those forest types with appropriate biomass equations.

Because the vertical distribution of CBD is highly variable in a stand, average values across the canopy profile may not adequately represent the fuel conditions required for crown fire propagation (Fig. 1). Crown fire spread may depend only on a few dense canopy layers with high CBD. Vertical canopy fuel characteristics are associated with species composition and stand structure where shade-tolerant species tend to occupy the lower canopy and tend to have higher proportions of flammable foliage and fine fuel than shade-intolerant, early-seral species (Brown 1978; Roberts and Long 1992; Keane et al. 2002). Therefore, any estimate of CBD must describe those canopy layers that account for crown fire spread.

## Theory

Gap fraction is defined as the proportion of the sky visible when viewed from below the canopy, and it has been successfully used to estimate leaf area index (LAI) in croplands, shrublands, and forests (Welles 1990; Chason et al. 1991; Chen et al. 1993; Martens et al. 1993; Dufrene and Breda 1995; Nilson 1999). LAI is linearly related to foliar crown biomass by specific leaf area (unit leaf area per dry mass), if it is assumed that biomass of branches supporting foliage is proportional to needle biomass (Brown 1978). Therefore, the gap fraction of a canopy should be related to the amount of crown biomass and CBD based on the following theory.

Each ray of radiation passing through the vegetation canopy has a chance that it will be intercepted by foliage or supportive tissue, and this chance is proportional to path length, foliage density (FD, foliage area per canopy volume, $m^2 \cdot m^{-3}$), and foliage orientation ($G$) (Welles and Norman 1991; Nilson 1999). In a horizontally homogeneous canopy of infinitely thin, planar leaves, the transmittance or gap probability, $T$, can be represented by the equation

$$[1] \qquad T(\theta, \phi) = e^{[-(\mathrm{FD})G(\theta,\phi)S(\theta,\phi)]}$$

where $T(\theta, \phi)$ represents the gap fraction (the probability that a ray of light will not be intercepted at zenith angle $\theta$ and azimuth angle $\phi$), $S(\theta, \phi)$ is the path length of the ray through the canopy, and $G(\theta, \phi)$ is the foliage orientation (assumed to be one for infinitely thin planar leaves for simplicity) (Welles and Norman 1991; Stenberg et al. 1994). A solution for foliage density comes from Miller (1967) as

$$[2] \qquad \mathrm{FD} = 2\int_0^{\pi/2} \frac{-\ln T(\theta)}{S(\theta)} \sin\theta \mathrm{d}\theta$$

This assumes random distribution of canopy elements (foliage, stems, branches) in all directions, so the azimuth angle $\phi$ is dropped (Welles and Norman 1991). Foliage density is directly related to CBD by canopy height ($z$, m) and specific leaf area constants (SLA, $m^2 \cdot kg^{-1}$) which are species specific (Pierce et al. 1994), given the equation CBD = FD × SLA for each canopy layer across canopy height ($z$). Then, path length $S$ is computed from canopy height and zenith angle $\theta$ in the equation $S(\theta) = z/\cos\theta$. Combining these relationships and summing across $n$ zenith angles $\theta$, we get the equation

$$[3] \qquad \mathrm{CBD} = \frac{2}{\mathrm{SLA}} \sum_{i=1}^{n} \frac{-\ln T_i \sin\theta_i \cos\theta_i}{z}$$

where $T_i$ is the gap fraction measured at zenith angle $\theta_i$ and $z$ is canopy height. Estimation of CBD from eq. 3 is highly influenced by many factors, including foliage orientation (represented by the function $G(\theta,\phi)$) (Stenberg 1996*a*; Kucharik et al. 1998), foliage clumping (Fassnacht et al. 1994; Stenberg 1996*a*), SLA changes over canopy depth, and the measurement error of the gap fraction (Martens et al. 1993). This equation indicates that CBD can be estimated from three variables: gap fraction, stand height, and specific leaf area.

There are three common methods for estimating gap fraction. It can be optically estimated directly from digital hemispherical images taken below the canopy looking up or above the canopy looking down (Chen et al. 1993; Frazer et al. 1997; Nilson et al. 1999). Gap fraction can also be estimated as a proportion of foliage intercepts using active remotely sensed imagery, such as Lidar (Magnussen and Boudewyn 1998), or sampling techniques that compute gap fraction from a proportion of foliage intercepts (Clark and Seyfried 2001). Finally, gap fraction can be estimated indirectly as the fraction of radiation reaching the forest floor (i.e., below-canopy radiation divided by above-canopy radiation) measured in specific wavelength ranges (Nel and Wessman 1993).

## Indirect measurement techniques

This study evaluated six common indirect methods to estimate CBD. All methods use canopy gap fraction to compute a canopy characteristic, such as leaf area index or canopy cover, from readily available instruments and sampling techniques. We selected these methods based on their ability to be used in extensive fuel sampling efforts and their success in measuring other canopy characteristics. The instruments were the LI-COR LAI-2000 and AccuPAR ceptometer, which estimate gap fraction by the fraction of below- and above-canopy radiation; the CID digital plant canopy imager (CIDpci), hemispherical photographs, and spherical densiometer, which compute gap fraction from digital images; and point sampling using vertical line intercept protocols (Table 1).

Perhaps the most commonly used instrument to indirectly measure LAI is the LAI2000 plant canopy analyzer (LAI2000) (LI-COR 1992). The LAI2000 estimates gap fraction as the fraction of radiation transmitted through the canopy at five zenith angles (7°, 23°, 38°, 53°, and 68° from vertical) measured with five concentric lenses on a handheld wand (Welles and Norman 1991). Stenberg et al. (1994) note that the instrument does not sense leaf area, but rather leaf and shoot silhouette area, which includes stems, branches, reproductive organs, and arboreal lichens and mosses, which may be a desirable trait when estimating CBD. As a result, the LAI2000 tends to underestimate LAI in stands with high leaf area (>5.0 LAI) because supporting tissue may block clumped foliage (White et al. 1998). Correction factors to adjust LAI2000 measurements have been developed for many ecosystems (Gower and Norman 1991; Smith et al. 1993; Stenberg et al. 1994; Smolander and Stenberg 1996; White et al. 1998), but Sampson and Allen (1995) note that species-specific correction factors will not necessarily correct bias in LAI2000 measurements because of high variability in the spatial distribution of species and crown structure. Ideal conditions for using the LAI2000 are uniformly cloudy days or near dawn or dusk (LI-COR 1992; Peper and McPherson 1998).

The AccuPAR Sunfleck Ceptometer (ceptometer) is a linear ceptometer consisting of a wand containing 80 sensors at 1-cm intervals that measure photosynthetically active radiation in the 400–700 nm wavelength range (Decagon 1987). The sensor arrangement attempts to mitigate effects of foliar clumping by detection of sunflecks, and a microprocessor scans the 80 sensors and calculates the arithmetic radiation average (Peper and McPherson 1998). Gap fraction and LAI can be computed using the Campbell and Norman (1989) method or by the division of measurements taken inside and

**Table 1.** Description of the six indirect measurement techniques used to estimate canopy characteristics in this study.

| Instrument[a] | Company | Estimated cost | Ease of use | Method |
|---|---|---|---|---|
| *LAI2000* | LI-COR | $4200 | Moderate | Gap fraction estimated from canopy transmittance for five zenith angles |
| *Ceptometer* | AccuPAR | $2900 | Easy | Gap fraction estimated at various azimuth angles |
| Digital plant canopy imager (*CIDpci*) | CID, Inc., Vancouver, Washington, USA | $4200 | Moderate | Gap fraction estimated from digital imagery taken with a high-resolution camera on a wand connected to a computer that processes the imagery |
| Hemispherical photography (*hemiphoto*) | Several companies provide instruments and software | $600–$2500 | Moderate | Gap fraction estimated from upward-pointing digital photography analyzed using special software |
| Spherical densiometer (*densiometer*) | Available at many forestry suppliers | $100 | Easy | Gap fraction estimated by counting empty grid pixels in an upward-pointing convex mirror |
| Point sampling (*point*) | Available at many forestry suppliers | $40 | Easy | Gap fraction estimated by the number of vertical line transects that do not intercept foliage |

[a]Italicized names are the labels used to represent the indirect techniques in this paper.

outside the canopy. The main problem with the ceptometer, as with most quantum sensors, is that the light environment under and above the forest canopy is constantly changing so it is difficult to synchronize clear-sky and below-canopy radiation measurements and it is difficult to obtain meaningful measurement replicates in the sample stand. Clear sky and low zenith angles are needed for the best ceptometer readings.

Hemispherical photography (hemiphoto) is gaining popularity for the computation of leaf area and the exploration of canopy light dynamics (Neumann et al. 1989; Englund et al. 2000; Frazer et al. 2001). Hemispherical photographs are taken directly upwards from the ground to the canopy on a level tripod using a fish-eye lens and high-resolution film or digital photography (Frazer et al. 1997). Digital images are imported into a variety of analysis software to compute various vegetation indices and light regimes (Smith and Somers 1991; Inouye 2000; Frazer et al. 2000). Lens optics, exposure settings, scanner resolution, and nonlevel tripod can significantly affect digital photo quality (Walter and Himmler 1996). Hemiphotos can be taken under a wide variety of light conditions but Frazer et al. (2001) found the best results in uniformly overcast skies.

The CID CI-100 digital plant canopy imager (CIDpci) (CID, Inc., Vancouver, Washington, USA) takes a high-resolution digital image from a self-leveling camera mounted at the end of a probe, very much like the hemiphoto technique. The image is stored on the hard disk of a field computer for future processing. The CIDpci software allows various modifications, transformations, and masking of the digital image to enhance calculation of gap fraction, including dividing the image into a number of zenith and azimuth angle partitions. Gap fraction is computed from the fraction of sky visible in each partition. This instrument can be used under a wide variety of weather conditions from sunny to cloudy.

The spherical densiometer (densiometer) is commonly used to estimate crown closure for many forestry applications because it is inexpensive and relatively easy to use. It consists of a convex mirror with a grid of 24 squares etched into the glass, with each square containing four points. The densiometer is held level underneath the canopy, and canopy closure is computed as a tally of those points out of 96 that are covered by foliage (gap fraction = 1 – canopy cover). This device has had limited success because it is difficult to hold the instrument level and still during the tally process. It can be used under most weather conditions with minimal training.

Point intercept sampling techniques (point) have been used to estimate canopy characteristics, primarily canopy closure, for many forest and range communities (Battles et al. 1996; Groeneveld 1997). Most involve installing a number of sampling points in a grid and then recording whether a line extending directly down or up from the sample point intersects plant material (foliage or branches) (Jurik et al. 1986). We used a device that contains a prism with cross-hairs that allows an upward-looking view of the canopy while keeping the head level. The major limitation of point sampling is that it takes a large number of points to accurately describe gap fraction, and these points should be along a grid or random circuit to minimize bias.

Several studies have compared these methods and instruments for estimating LAI or some other crown characteristic. Dufrene and Breda (1995) evaluated the LAI2000, a Demon portable light sensor, and a net radiometer to compute LAI as calculated from litter-trap data and found the LAI2000 provided the best estimates. Chason et al. (1991) compared the LAI2000 and a direct beam sensor on a tram system with litterfall estimates of LAI and found that the LAI2000 performed well when measurements were scaled to correct for clumping. Martens et al. (1993) compared the ceptometer, another line quantum sensor, the LAI2000, and hemispherical photographs with direct biomass measurement and found the LAI2000 was easiest to use and performed the best in an orchard setting but was less reliable in a forest. The ceptometer tended to overestimate LAI, contrary to results from Pierce and Running (1988). An extensive evaluation study was done by Peper and McPherson (1998) where they compared a ceptometer, LAI2000, CIDpci, allometric equations, and hemispherical photography to estimate LAI. They found all methods appeared to underestimate LAI and none produced satisfactory estimates, but overall hemispherical photography seemed to perform the best. Similar results were found by Fassnacht et al. (1994) when they compared a ceptometer, LAI2000, and DEMON line sensor. The present study differs from other comparison studies in that we are testing instruments for estimation of CBD, not LAI. Because CBD includes the small supporting branches, these indirect methods may estimate CBD more accurately than LAI.

## Materials and methods

### General description

Five sites representing major conifer types in the western United States were selected for this study (Table 2). These sites historically experienced nonlethal surface or mixed-severity fire regimes but have recently become susceptible to crown fire because of a buildup of overstory and understory crown fuels, resulting from the lack of fires. Indirect measurements were taken at 25 points within a fixed-area plot located in a relatively homogeneous portion of the site based on crown fuel characteristics. The plot size was varied by study site to ensure adequate representation of stand conditions as judged from plot inventories of tree density data (Table 2).

To simulate a wide range of crown conditions, we removed approximately 25% of tree basal area from each plot in three sequential sampling stages to create four or five (Ninemile, Blodgett, and Tenderfoot sites had an extra treatment) different stand structures for each of the five sample sites, ultimately resulting in 23 observations (5 sites × 4 or 5 sampling stages). Each tree with dbh > 1 in. (1 in. = 2.54 cm) was tagged, and its dbh was recorded along with species and other descriptive attributes. An initial set of indirect measurements was taken once the grid was installed. Then, the smallest trees were destructively sampled until approximately 25% of the basal area was removed, and another set of indirect measurements was taken. This was repeated four times (25%, 50%, 75%, and 100% basal area removal), always removing the smallest remaining trees. This minimized spatial clumping and ensured removal proceeded from the understory to overstory. Care was taken to protect standing trees and branches, especially saplings, during cutting. Trees outside the plot boundaries, but within one tree height of the plot edge, were also cut at each sampling stage using the same criteria for removal. These trees were not sampled for crown characteristics; however, they were limbed and the branches were scattered so that none of the cut tree was visible to the indirect instruments.

Before each tree was cut, a complete inventory of all dead and live branches was taken at 1 m height intervals by climbing and pruning each tree branch. Then, 10% of the cut branches were systematically sampled to estimate the wet mass of the following crown fuel components: (1) dead and live branchwood in the diameter classes of 0–3, 3–6, 6–10, 10–25, 25–50, and >50 mm; (2) live and dead foliage; (3) cones; and (4) lichen and moss. This time-intensive task involved stripping all dead and live foliage from the subsample branch by hand and weighing the foliage on a portable scale. Lichens, mosses, and cones were also separated from the branch and weighed. Branchwood was cut into the size classes by sliding a fixed-width gauge up a branch segment and then cutting the branch when a threshold diameter class was reached. A small subsample from each crown fuel component pile was collected and placed in an oven at 80 °C for 2 days to determine moisture content. Green mass for all

**Table 2.** General description of the study areas included in this study.

| Study area | Cover type[a] | Land management agency | Elevation (m) | Aspect[b] | Basal area ($m^2 \cdot ha^{-1}$) | Overstory density ($trees \cdot ha^{-1}$)[c] | Understory density ($trees \cdot ha^{-1}$) | Avg. overstory height (m) | Plot size (ha) |
|---|---|---|---|---|---|---|---|---|---|
| Ninemile | Ponderosa pine / Douglas-fir | Lolo National Forest, Montana | 1050 | NNE | 30.5 | 481 | 2514 | 22 | 0.07 |
| Salmon | Douglas-fir / lodgepole pine | Salmon-Challis National Forest, Idaho | 2300 | SE | 37.7 | 1178 | 1033 | 17 | 0.03 |
| Tenderfoot | Lodgepole pine | Lewis and Clark National Forest, Montana | 2290 | NE | 42.7 | 1145 | 2300 | 19 | 0.03 |
| Flagstaff | Ponderosa pine | Coconino National Forest, Central Arizona | 2308 | S | 69 | 2067 | 633 | 15 | 0.03 |
| Blodgett | Sierra Nevada mixed conifer | Blodgett Forest Research Station, California | 1300 | NNE | 46.8 | 382 | 142 | 34 | 0.07 |

[a]Cover-type species: ponderosa pine (*Pinus ponderosa* var. *ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta* var. *contorta*).
[b]N, north; S, south; E, east; W, west.
[c]Overstory are those trees with diameter at breast height >10 cm.

crown fuel components was converted to dry mass using the moisture content for that sample (Deusen and Baldwin 1993).

Several branches from each species of tree on the site were taken back to the laboratory for computation of specific leaf area (SLA). Branches were clamped onto a stand, and a digital photograph was taken directly down against a neutral background. This image was imported into software to compute the projected area of the branch including needles and branchwood. The needles were then stripped off the branch by hand, weighed, counted, and then mounted on white paper. Each paper was scanned using a scanner and associated software to compute projected needle area and needle length. One needle from each paper was cut in half, and the long and short axes of the cross-section were measured. Total needle area was then computed for each needle from the length, width, and height using the cross-sectional shape geometry of a half-sphere, rectangle, or triangle, depending on the species. The branch projected leaf area, needle projected leaf area, and total needle area was divided by the needle mass to calculate three measures of SLA.

Biomass estimates (kg) by crown fuel component were computed for each branch using regression equations developed from the subsampled branches by tree species (Alemdag 1980; Monserud and Marshall 1999). The dry mass of each crown fuel component was predicted from measured branch characteristics (e.g., length, width, foliar ratio, mass) on the subsampled branches. Regression equations were applied to the unsampled branches to compute crown biomass by fuel component.

These crown fuel data were summarized to bulk density measures by 1-m intervals for the entire stand profile, and they were used as dependent variables in the indirect measurement evaluation. Gap fractions estimated from the six techniques were related to measured CBD using regression analysis. Detailed descriptions of crown fuel sampling methods and developed crown biomass equations are presented in Scott and Reinhardt (2002), so only indirect measurement techniques and their analyses are presented here.

### Indirect measurements

A 5 × 5 grid of 25 points was established inside plot boundaries with each point 5 m apart. The grid was oriented up and down the slope, and if the slope was flat, it was oriented north and south. Each point was marked with a 15-cm nail attached to yellow flagging. A crew of four extensively trained technicians took measurements for each of the six indirect instrument techniques at each point at waist level (1 m above ground).

The LAI2000 wand was positioned directly over the sampling point and above the undergrowth. Most measurements were taken at dawn or dusk or if the sky was heavily overcast. One calibration reading was taken in the open outside the stand before and after the 25 inside-stand measurements. All readings for the 25 points were stored in the instrument and downloaded to a computer for postprocessing analysis that included eliminating spurious readings (transmittance > 1.0 for all zenith angles).

Radiation flux was measured with the ceptometer at each sample point as an average of four measurements taken by pointing the level wand in the four cardinal directions. Each measurement was taken as an average of PAR flux density ($W \cdot m^{-1}$) across all sensors on the wand. All four measurements for each point, taken as close to solar noon as possible, were stored in the instrument and downloaded at day's end. Four calibration readings outside the stand in an opening were taken directly before and after the 25 below-canopy readings.

A high-resolution digital image was taken at each of the 25 sample points with the CIDpci and hemispherical photography (hemiphoto) and stored on a laptop computer. The CIDpci wand was pointed downslope or north if the slope was flat. CIDpci images were analyzed with the accompanying CID software. Hemispherical photographs were taken with a Nikon 990/995 digital camera with a Coolpix 900 fish-eye lens mounted on a self-leveling tripod positioned about 1 m directly above the sample point. Exposure and f-stop settings depended on light conditions and were selected by the camera. High-resolution digital photographs (1024 × 1024 pixels) were imported into the Hemiview software (Delta T devices, Inc., Cambridge, UK; http://www.delta-t.co.uk) for computation of gap fraction.

The densiometer and point sampling tube were held level by hand directly above each sample point. The number of points in the densiometer grid that contained clear sky (i.e., no canopy material) was counted on the concave mirror. The point sample was taken by holding the sampling tube directly vertical and sighting through the tube and recording if the cross-hairs did not intercept canopy material. Both estimates were recorded on a plot form.

### Data analysis

We used three canopy metrics and four aggregations of crown biomass components to evaluate the performance of the indirect techniques across diverse representations of the forest canopy (Table 3). The canopy metrics are (1) canopy loading (CL), canopy biomass per unit area ($kg \cdot m^{-2}$); (2) average CBD (CBDave), computed as an average of CBD across all 1-m canopy layers ($kg \cdot m^{-3}$); and (3) maximum CBD (CBDmax), the maximum CBD value ($kg \cdot m^{-3}$) across all canopy layers.

These metrics were selected to represent different expressions of canopy characteristics that might be useful to fire modeling and land management and that might be detected using the indirect techniques. Each canopy metric was computed using four different aggregations of canopy biomass based on groupings of the crown components (Table 3): (1) foliage only, (2) foliage, moss and lichen, and all branchwood less than 3 mm diameter (this is the material assumed to be available to a crown fire); (3) all foliage and branchwood excluding tree stems greater than 75 mm diameter; and (4) all canopy material: foliage, branchwood, and stems.

The canopy metrics were computed by summing the appropriate crown biomass components for canopy biomass aggregation across all trees for each 1 m height layer, and then dividing by plot area. This yields 12 unique canopy measures. Large stems and branches are not considered canopy fuel because they are rarely consumed in a crown fire, but they were included in this analysis because they were detected by all indirect techniques and their presence cannot be removed from most of the indirect measurements.

Gap fractions estimated from the six indirect techniques at each of the four stand conditions (uncut, 25% removal, 50%

**Table 3.** Factors employed in the evaluation of indirect techniques to estimate canopy characteristics.

| Variable | Description |
|---|---|
| **Canopy metrics** | |
| CL | Canopy loading ($kg \cdot m^{-2}$) |
| CBDave | Average canopy bulk density over all canopy layers ($kg \cdot m^{-3}$) |
| CBDmax[a] | Canopy bulk density of canopy layer with greatest bulk density ($kg \cdot m^{-3}$) |
| **Canopy biomass aggregations** | |
| 1 | Canopy biomass is represented by only dead and live foliage |
| 2[a] | Canopy biomass is defined as dead and live foliage plus live branchwood less than 3 mm in diameter and dead branchwood less than 6 mm in diameter; this was considered the best representation of combustible canopy fuel for this study |
| 3 | Canopy biomass is all branch and foliage biomass but no stems |
| 4 | Canopy biomass includes all foliage, branches, and stems |
| **Indirect techniques** | |
| LAI2000 | LI-COR LAI-2000 leaf canopy analyzer |
| Hemiphoto | Hemispherical photography |
| CIDpci | CID digital plant canopy imager |
| Ceptometer | AccuPAR ceptometer |
| Densiometer | Spherical densiometer |
| Point | Vertical point sampling technique |
| **Indirect analysis schemes** | |
| A | Average gap fraction across all five zenith angles |
| B | Average gap fraction across top three zenith angles |
| C | Gap fraction for top zenith angle (0°–15°) |
| D | Average gap fraction across five zenith angles using a transformation of eq. 3: $CBD = \sum -(\ln T_i) \sin \theta_i \cos \theta_i / 2$ |
| E | Average gap fraction across top three zenith angles using a transformation of eq. 3: $CBD = \sum -(\ln T_i) \sin \theta_i \cos \theta_i / 2$ |

**Note:** Canopy metrics and biomass aggregations represent the 12 canopy characteristic expressions (represented by canopy metric plus definition suffix; for example, CL1 is canopy loading computed from only foliage) used to evaluate indirect technique performance. Indirect measurement techniques and analysis schemes represent the 19 indirect measurement methods employed in this study (indirect schemes were not used with ceptometer, densiometer, point, and allometric methods; that is, LAI2000A is gap fraction averaged across five zenith angles for LI-COR LAI-2000 instrument).

[a]Indicates the canopy biomass aggregation selected to best represent canopy fuels for fire modeling in the regression analysis.

removal, 75% removal) on each plot were related to the 12 canopy measures using correlation and regression techniques. For the LAI2000, CIDpci, and hemiphoto methods, gap fractions were computed using five schemes that used different sets of zenith angles and averaging procedures (Table 3). First, gap fraction was averaged across all five zenith angle ranges (7°, 23°, 38°, 53°, and 68° from vertical for LAI2000 and 9°, 27°, 45°, 63°, and 81° for hemiphoto and CIDpci), then across the top three angles, and lastly, from only the topmost zenith angle. In addition, gap fraction was computed as a weighted average across the five and three zenith angles using a transformation from eq. 3 where the weight ($w$) is

$$[5] \qquad w = \frac{\sum -(\ln T) \sin \theta \cos \theta}{2}$$

where $\theta$ is the midpoint of the range of zenith angles and $T$ is gap fraction (Table 3). For the ceptometer, the average of the four below-canopy ceptometer measurements for each sample point was divided by the calibration or outside-canopy measurements to compute gap fraction. Gap fraction for the densiometer was approximated by the number of clear-sky points divided by the total number of points (94) on the concave mirror averaged across all sample points. For the point technique, gap fraction was computed for the entire stand as the number of clear-sky sample points divided by 25 (total number sample grid points).

To evaluate indirect method performance, we conducted an extensive correlation analysis where the Pearson's correlation coefficient ($r$) was used to evaluate the ability of each indirect technique to consistently estimate the canopy representations across the five study sites and four or five sample stages. We performed a second correlation analysis on the LAI2000, hemiphoto, and CIDpci measurements to evaluate the five schemes of computing gap fraction for predicting the canopy characteristics (see Table 3).

A mixed-effects linear model was used to develop the best predictive equations for each indirect technique once it was determined that the data fit the assumptions for parametric statistics. Study site was included as a random effect in the model, and the $R^2$ and PRESS statistic were calculated using the fixed-effects equation. Residual analysis was performed to check model assumptions. To reduce the total number of possible equations, we selected only one canopy metric, CBDmax (maximum CBD across all 1-m canopy layers, Table 3), because it best represented the CBD needed to model crown fire behavior (Scott and Reinhardt 2001, 2002; van Wagner 1977). We also chose to compute CBDmax using only one canopy biomass aggregation: sum of all foliage and live branchwood less than 3 mm and dead branchwood less than 6 mm (CBDmax2, Table 3). This biomass aggregation best represented the fuels that would be consumed in most crown fires and includes the fuels used in most fire behavior models (Sando and Wick 1972; Scott and Reinhardt 2002). Other stand characteristic variables (stand height, basal area, and measured SLA) were included in the regression equation if they significantly ($p < 0.05$) improved the model. We also developed CBD regression equations using measured LAI from the LAI2000, hemiphoto, and CIDpci to CBDmax, because this LAI is an easily obtained measurement for these instruments.

## Results

Profiles of canopy bulk density were computed from the developed biomass equations for each study site for each of the canopy biomass aggregations (Fig. 2). Maximum CBDs and stand heights vary across each site because of differences in stand height, species composition, and site productivity. Tree stems and large branches account for the majority of CBD estimates, especially at lower levels in the canopy. This presents a dilemma because foliage and small branches are considered the primary fuels for crown fires, but the gap fraction estimated by all the indirect techniques includes all canopy materials. The highest canopy bulk densities of combustible biomass are found in the mid-canopy; however, if all crown components are summed, the highest bulk densities are at the canopy base, where tree stems are found (Fig. 2). The greatest amount of combustible canopy biomass, and as a result, the densest combustible canopy layers, are contained in the overstory canopy layers occupied by the largest trees. The removal of smaller trees in the initial harvest treatments did little to reduce CBD in these overstory layers (Scott and Reinhardt 2002).

### Indirect method evaluation

Results of the correlation analysis for all combinations of canopy metrics and biomass aggregations with indirect measurements of gap fraction are summarized in Fig. 3. In general, correlation coefficients were above 0.50 and significant, but it was difficult to determine the best indirect technique across the canopy representations because of great variation in measurements and the low number of observations ($n = 23$). The ceptometer, densiometer, and point sampling techniques (most correlation coefficients < 0.6) did not perform as well as the LAI2000, hemiphoto, and CIDpci (correlation coefficients > 0.6). The LAI2000, hemiphoto, and CIDpci consistently perform well across all canopy biomass aggregations and for all canopy metrics of CBD. The CIDpci appeared to perform the best with the exception of foliage only (Fig. 3*a*) and all crown material (Fig. 3*d*) biomass aggregations. The correlation coefficients for canopy loading (CL) were relatively weak with all indirect techniques except hemispherical photography, because the CL measurement does not incorporate the vertical distribution of canopy material across the stand profile. The ceptometer, densiometer, and point techniques seemed best able to predict CL, especially when foliage and all branchwood biomass components are aggregated (Fig. 3*c*).

As expected, canopy biomass aggregations that include most crown components — foliage and all branches (Fig. 3*c*) and all canopy components including stems (Fig. 3*d*) — correlated best with almost all indirect techniques. This is

**Fig. 2.** Vertical profiles of measured canopy bulk density (CBD, kg·m$^{-3}$) for each canopy biomass aggregation (see Table 3 for details) for each study site: (*a*) Ninemile, (*b*) Salmon, (*c*) Flagstaff, (*d*) Blodgett, and (*e*) Tenderfoot. Note the height scales are different for Ninemile and Blodgett to fully portray CBD height distributions.

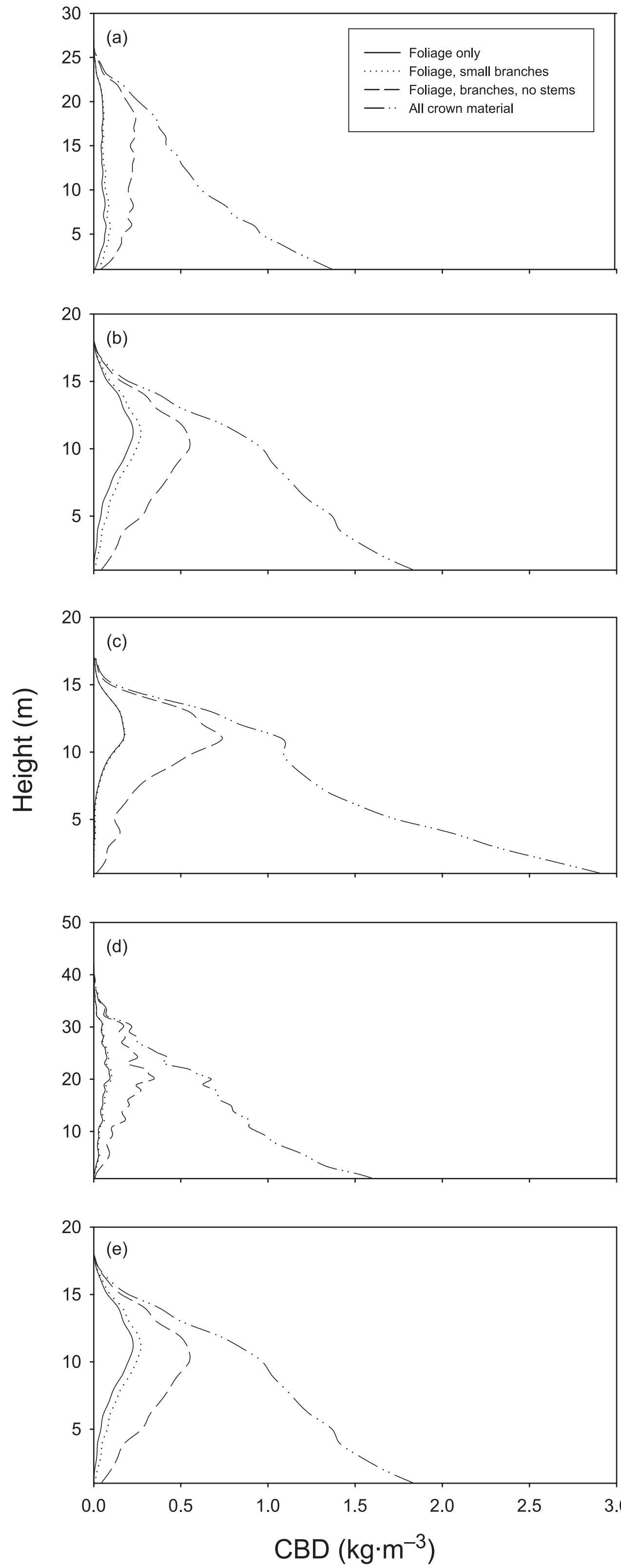
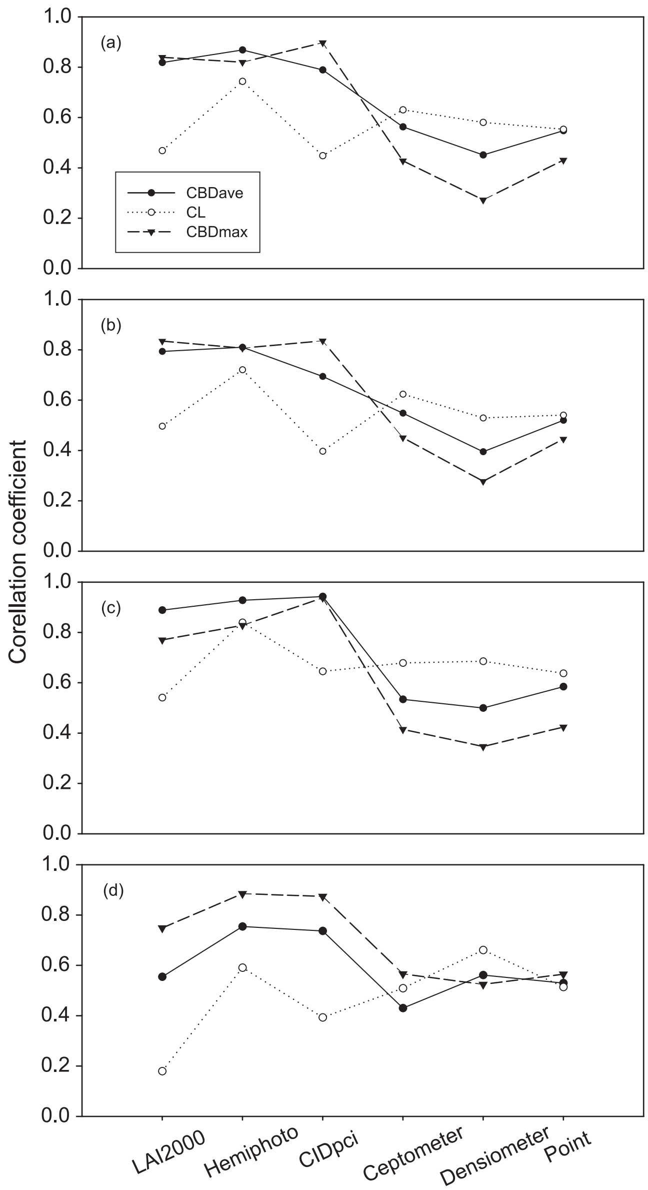


**Fig. 3.** Absolute values of correlation coefficients for gap fractions measured from the six indirect techniques with the three canopy metrics (CL, CBDave, and CBDmax; see Table 3 for definitions). Each graph represents a different aggregation of the canopy biomass components used to compute the canopy measures: (*a*) foliage only, (*b*) foliage and combustible branchwood, (*c*) foliage and all branchwood, and (*d*) all crown fuels (foliage, branchwood, and stems). Gap fractions for LAI2000, hemiphoto, and CIDpci were calculated as a weighted average of the top three zenith angles. Line graphs were used to best portray the differences between canopy metrics and do not signify a continuous relationship between techniques.




because readings from the indirect instruments include all crown material in the computation of gap fraction, including stems and large branches. However, it was interesting that the differences between biomass aggregations were relatively small across all canopy metrics except for canopy loading (CL) (Fig. 3). This might indicate that the projection of foliage can cover most supportive tissue and even some large stems (Fassnacht et al. 1994; Stenberg et al. 1994). Most indirect techniques had the best correlation coefficients when CBDmax was used for foliage and small branches, except for hemiphoto, which seemed to correlate best with CBDave for all but the total biomass aggregation.

The best indirect analysis schemes for estimating canopy characteristics (CL, CBDave, CBDmax) for the hemiphoto, LAI2000, and CIDpci techniques appear to be the schemes that use only the top zenith angle and the ones that correct gap fraction by light-beam length across the three or five zenith angle categories (schemes C, E in Table 3) (Fig. 4). Correlations for the top zenith angle are high for most techniques because there are a large number of grid measurements ($n$ = 25) within the small study site plot. Canopy fuels defined by only foliage and branchwood and by all crown material (shown in Figs. 3*c*, 3*d*) appear to have the highest correlation with all three instruments and all schemes. Again, canopy loading, CL, has the poorest performance, especially for the LAI2000 and CIDpci, because the measure cannot distinguish canopy depth. The CBDmax is the canopy metric that consistently correlates best with the LAI2000 for all five schemes. It also happens that the weighted average of the top three or five zenith angles correlates best with most canopy biomass fuel representations (Fig. 4). Correlations between canopy biomass aggregations across all schemes were quite high (most $r > 0.9$), meaning canopy fuel aggregations have little influence on the scheme used to compute gap fraction for the three indirect methods.

We found that the indirect methods had a slightly better relationship to the CBDmax canopy metric than to the CBDave and CL (Fig. 3) and it best characterizes canopy fuel available for crown fires. This supports our selection of CBDmax as the only canopy measure to use in the regression analysis. Because there are few differences between correlation coefficients across all canopy biomass aggregations, there are few negative consequences in the selection of only the foliage and small branch aggregation for computing CBDmax across all indirect techniques.

Increasing the number of sample grid points did not improve the estimate of canopy bulk density (CBDmax2) using the LAI2000, hemiphoto, and CIDpci indirect techniques (Fig. 5). The highest correlations were achieved when all 25 grid points were used to compute average gap fraction. Correlation coefficients did not significantly change when only nine points were used, but they were highly variable and inconsistent when only the center grid point was used.

## Predictive CBD equations

Regression equations for predicting CBD (CBDmax2) from gap fraction and stand variables performed well for the LAI2000, CIDpci, and hemiphoto ($R^2 > 0.60$) and poorly for the ceptometer, densiometer, and point ($R^2 < 0.50$) (Table 4). Two or three regression equations are shown for each indirect technique; one equation uses the gap fraction estimated by the indirect equipment to estimate CBD, while the other equations includes any gap fraction transformation and stand variable that may improve the relationship. The relationship of the CBDmax2 to gap fraction measured from the six indirect techniques over all five study sites is graphed in Fig. 6. These equations can be used to compute CBD from gap fraction measurements from any of the indirect techniques in the field.

**Fig. 4.** Absolute values of correlation coefficients for gap fractions measured from the LAI2000, hemiphoto, and CIDpci methods for all canopy metrics (CL, CBDave, and CBDmax; see Table 3) but for only one definition of canopy fuels (foliage and small branches). Each graph represents a different indirect scheme to estimate gap fraction: (*a*) average of five zenith angle ranges, (*b*) average of three zenith angles, (*c*) top zenith angle, (*d*) weighted average of top five zenith angles, and (*e*) weighted average of top three zenith angle ranges (see Table 3 for more information). Line graphs were used to best portray the differences between canopy metrics and do not signify a continuous relationship between techniques.

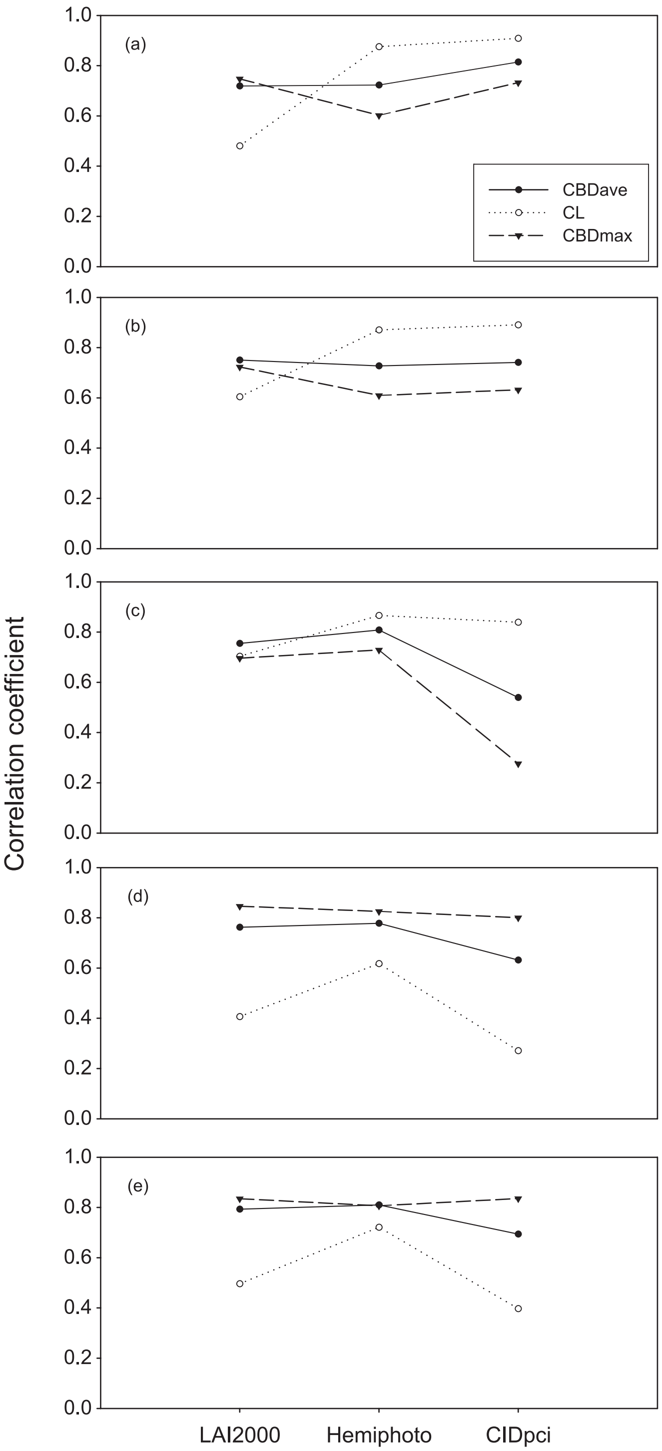
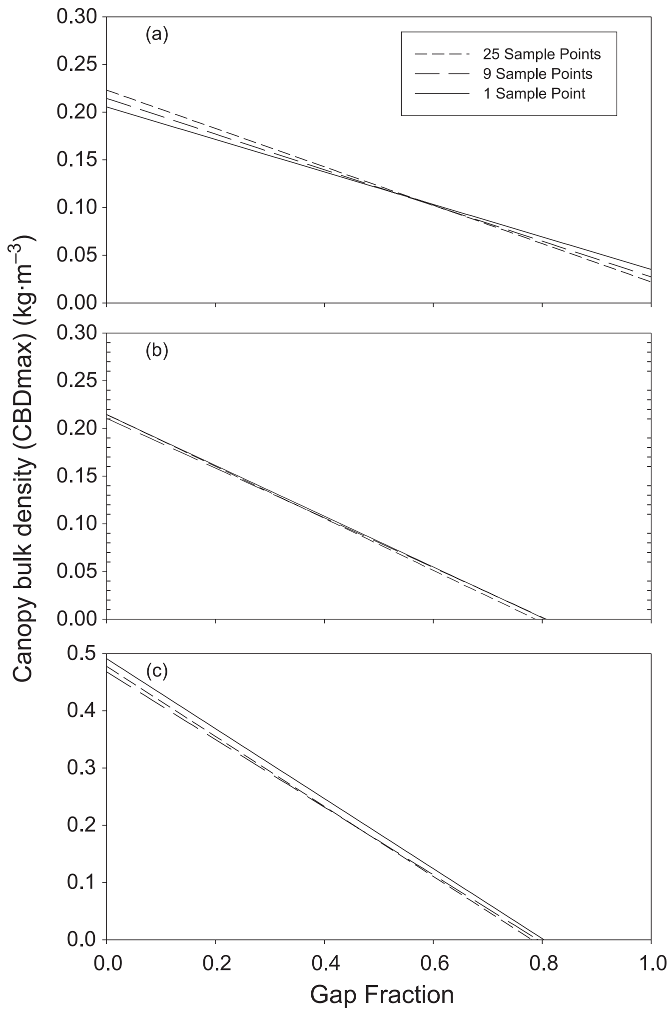



**Fig. 5.** Relationship of canopy bulk density with gap fraction. CBD was computed as a maximum across all 1-m canopy layers using the foliage and small branchwood biomass aggregation (CBDmax2) with gap fraction measured from the six indirect methods: (*a*) LAI2000, (*b*) hemiphoto, and (*c*) CIDpci, using results from the top three zenith angles (see Table 3 for more information).




Gap fraction seems to be linearly related to CBDmax2 (Fig. 6), and the inclusion of stand variables in the regression equations improved the performance across all indirect techniques (Table 4). Predictions of CBDmax2 from the indirect LAI estimate computed from the LAI2000, CIDpci, and hemiphoto did surprisingly well ($R^2 > 0.60$, Table 4). Interestingly, regression equations with stand variables only also did well for predicting CBDmax2 (Table 4), and the variables SLA (specific leaf area) and SBA (stand basal area) significantly improved the regressions for the hemispherical photography and densiometer. Stand height (HEIGHT) improved predictions for the CIDpci (Table 4).

## Discussion

The relationship of gap fraction to CBD is greatly influenced by vegetation and site conditions on the study plot, presumably because of the differences in species and stand morphological characteristics. These compositional and structural differences are responsible for the high variation shown

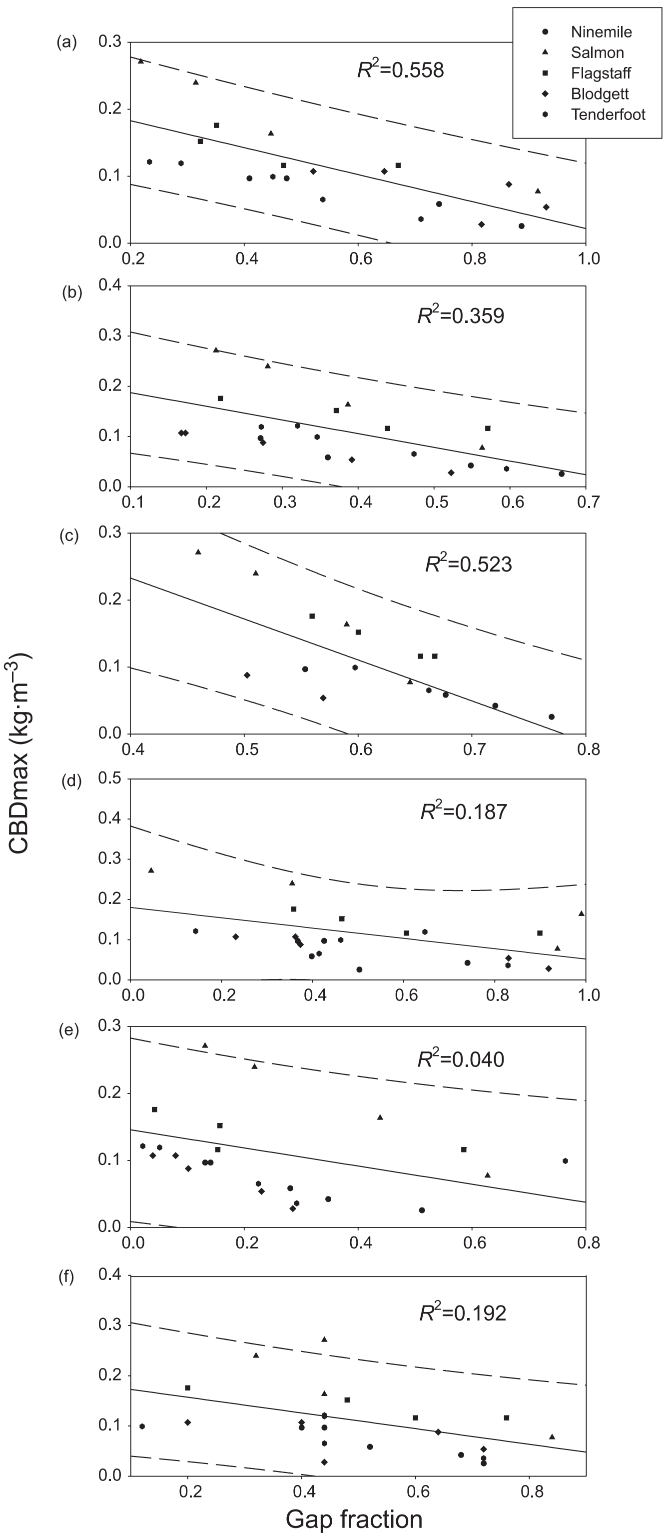
**Table 4.** Results of regression analysis to predict the maximum canopy bulk density (CBDmax2) of the foliage and small branchwood biomass aggregation for all indirect techniques.

| Equation | Regression coefficients (SE) | $p$ value | $R^2$ | PRESS |
|---|---|---|---|---|
| **LI-COR LAI-2000 (LAI2000)** | | | | |
| ŷ = 0.2231 – 0.2012 LAI2000A | Intercept: 0.2231 (0.0226) | <0.0001 | 0.558 | 0.0387 |
| | LAI2000A: –0.2012 (.0245) | <0.0001 | | |
| ŷ = 0.0402 + 7.6293 LAI2000E | Intercept: 0.0402 (0.0167) | 0.0286 | 0.696 | 0.0269 |
| | LAI2000E: 7.6293 (0.7713) | <0.0001 | | |
| **Hemispherical photography (Hemiphoto)** | | | | |
| ŷ = 0.2147 – 0.2726 HemiphotoA | Intercept: 0.2147 (0.0272) | <0.0001 | 0.359 | 0.0579 |
| | HemiphotoA: –0.2726 (0.0375) | <0.0001 | | |
| ŷ = 0.028 + 2.257 HemiphotoE | Intercept: 0.028 (0.0197) | 0.1704 | 0.629 | 0.0373 |
| | HemiphotoE: 2.257 (0.2988) | <0.0001 | | |
| ŷ = 0.299 + 1.166 HemiphotoE – 0.022 SLA – 0.003 SBA + 0.00028 SLA×SBA | Intercept: 0.299 (0.081) | 0.0027 | 0.687 | 0.0162 |
| | HemiphotoE: 1.166 (0.6530) | 0.0976 | | |
| | SLA: –0.022 (0.0065) | 0.0044 | | |
| | SBA: –0.003 (0.0005) | <0.0001 | | |
| | SLA×SBA: 0.00028 (0.00005) | <0.0001 | | |
| **CID plant canopy imager (CIDpci)** | | | | |
| ŷ = 0.4777 – 0.6119 CIDpciA | Intercept: 0.4777 (0.0655) | <0.0001 | 0.515 | 0.0385 |
| | CIDpciA: –0.6119 (0.1018) | 0.0001 | | |
| ŷ = 1.5579 – 3.6370 CIDpciA + 2.4666 (CIDpciA)$^2$ – 0.00681 HEIGHT | Intercept: 1.5579 (0.234) | 0.0001 | 0.944 | 0.0071 |
| | CIDpciA: –3.6370 (0.757) | 0.0010 | | |
| | (CIDpciA)$^2$: 2.4666 (0.617) | 0.0031 | | |
| | Height: 0.00681 (0.0074) | 0.0027 | | |
| **AccuPAR ceptometer (ceptometer)** | | | | |
| ŷ = 0.1802 – 0.1284 ceptometer | Intercept: 0.1802 (0.0280) | <0.0001 | 0.187 | 0.0751 |
| | Ceptometer: –0.1284 (0.0228) | <0.0001 | | |
| ŷ = 0.1044 – 0.0730 ceptometer + 0.00036 SBA | Intercept: 0.1044 (0.0372) | 0.0127 | 0.314 | 0.0575 |
| | Ceptometer: –0.0730 (0.0273) | 0.0166 | | |
| | SBA: 0.00036 (0.000125) | 0.0109 | | |
| **Stand densiometer (densiometer)** | | | | |
| ŷ = 0.1457 – 0.1353 densiometer | Intercept: 0.1457 (0.0279) | 0.0001 | 0.043 | 0.0959 |
| | Densiometer: –0.1353 (0.0404) | 0.0038 | | |
| **Point sampling (point)** | | | | |
| ŷ = 0.1884 – 0.1562 point | Intercept: 0.1884 (0.0308) | <0.0001 | 0.192 | 0.0747 |
| | Point: –0.1562 (0.0402) | 0.0012 | | |
| **Stand-related variables only** | | | | |
| ŷ = 0.295 – 0.0219 SLA – 0.00319 SBA + 0.00032 SLA×SBA | Intercept: 0.295 (0.0769) | 0.0016 | 0.633 | 0.0284 |
| | SLA: –0.0219 (0.0061) | 0.0028 | | |
| | SBA: –0.00319 (0.00048) | <0.0001 | | |
| | SBA×SLA: 0.00032 (0.000040) | <0.0001 | | |
| **Indirect measurement of LAI** | | | | |
| ŷ = 0.0424 + 0.06778 $LAI_{LAI2000}$ | Intercept: 0.0424 (0.0178) | 0.0300 | 0.642 | 0.0321 |
| | LAI: 0.06778 (0.0073) | <0.0001 | | |
| ŷ = 0.0396 + 0.0511 $LAI_{Hemiphoto}$ | Intercept: 0.0396 (0.0293) | 0.1945 | 0.616 | 0.0795 |
| | LAI: 0.0511 (0.0094) | 0.0001 | | |
| ŷ = –0.0234 + 0.2056 $LAI_{CIDpci}$ | Intercept: –0.0234 (0.0203) | 0.2772 | 0.784 | 0.0169 |
| | LAI: 0.2056 (0.0236) | <0.0001 | | |

**Note:** The term ŷ denotes CBDmax (kg·m$^{-3}$). The suffix A in each indirect technique label refers to the average gap fraction across all zenith angles, and the suffix E refers to the weighted average gap fraction across all three top angles (Table 3). SLA refers to the average specific leaf area (m$^2$·kg$^{-1}$) of the canopy, SBA refers to stand basal area (m$^2$·ha$^{-1}$), and HEIGHT is the average stand height (m). Also shown are regression equations for predicting CBDmax from stand variables only and from LAI as estimated by the indirect technique.

in Fig. 6. The $R^2$ increases by 0.10–0.20 if stand variables are included in the regression analysis (Table 4), probably because these variables may minimize the subtle differences between study sites. Major stand variables that differ greatly across study sites include stand height, species composition, and stand density. Stand height would dictate the distance that light must travel through the canopy to be detected by the instrument (see eq. 2). This is especially important when

**Fig. 6.** Canopy bulk density computed as a maximum across all 1-m canopy layers using the foliage and small branchwood biomass aggregation (CBDmax2) with gap fraction measured from the six indirect methods: (*a*) LAI2000, (*b*) hemiphoto, (*c*) CIDpci, (*d*) ceptometer, (*e*) densiometer, and (*f*) point, using results from the best analysis scheme (see Table 3 for more information).




light is coming from low zenith angles. Species composition, coarsely represented by SLA in our analysis, dictates foliage morphological characteristics, such as clumping and needle length, which influences the probability that light will hit a foliar particle. Stand density also influences the chance that stems or large branches will intercept light. The most precise CBD regression equations include these stand-related factors.

The performance of most indirect techniques to predict CBD was lowered when combustible canopy biomass (foliage and small branchwood) was used instead of foliage only or all canopy biomass material. Combustible biomass is required by most crown fire models, so regression equations were constructed with this canopy definition, but the precision of the CBD estimate using these biomass components was lower. Fortunately, the best CBD estimates were obtained when CBDmax was used, which is probably the best CBD measure for crown fire modeling (Scott and Reinhardt 2002).

## Evaluation results

The LAI2000, CIDpci, and hemispherical photography were the best techniques for predicting crown fuel characteristics, especially CBDmax. Even though the predictive equations appear inexact ($0.60 < R^2 < 0.95$, Table 4), we feel they are adequate for estimating CBDmax, given the predictive capability of the fire models. However, each instrument has some advantages and disadvantages for field use. The LAI2000 calculates gap fraction from differences in light intensity, and therefore its accuracy is greatly determined by the variability of light conditions outside and below the canopy during sampling. Frequently changing light conditions, such as those experienced on windy or partly cloudy days, can greatly influence the computation of gap fraction; it is best used at dawn or dusk on clear or fully cloudy days (Welles and Norman 1991; LI-COR 1992). Furthermore, the measured light intensity data are for only five static zenith angles, whereas hemispherical photography can produce an image that can be analyzed with any number of zenith angles over a full 360° horizontal view.

The CIDpci performance was quite similar, if not superior, to hemispherical photography because the instruments are essentially the same, except that the CIDpci camera is embedded in an easily used wand, the image resolution is coarser, and the analysis software uses different analysis algorithms. The CIDpci and hemispherical photography performed equivalently (Fig. 3); however, hemispherical photography is less expensive (Table 1). Hemispherical photography can be somewhat difficult to obtain, especially if multiple points are desired to describe variability of stand conditions, because the camera must be leveled on a tripod and the correct exposure and shutter speed must be determined. The LAI2000 measurements may be easier to obtain in the field because the wand can be readily positioned in the appropriate position and a reading taken quickly. Hemiphoto and CIDpci do not require calibration measurements (outside canopy) so they can be used in stands where large calibration openings are distant or rare; however, both are sensitive to the effects of diffuse and direct radiation. Equipment for hemispherical photography costs less than the LAI2000 and CIDpci, and it can be used for many other purposes (Table 1). Additional field crew training may be required for the LAI2000.

The remaining indirect techniques did not perform as well as the LAI2000, hemiphoto, and CIDpci, but they might also have value for measuring CBD under some circumstances. The poor performance of the ceptometer (Fig. 3) is mainly due to the sensors receiving light from all canopy zenith angles, so corrections to light path length are impossible. Dynamic sky conditions also affected ceptometer accuracy. Its high cost (Table 1) and its calibration measurement requirement, coupled with its low performance, make it a poor choice for CBD measurements, but others have found it worked well on sunny days (White et al. 1998). The densiometer and point sampling methods provide a low-cost alternative to CBD measurement, but the low performance coupled with the high number of sample points needed to obtain an accurate estimation of gap fraction probably limits their application.

The allometric approach is a viable alternative to the indirect approaches based on gap fraction presented here, providing there are accurate biomass equations for local applications (Reinhardt and Crookston 2003). The allometric technique requires an extensive inventory of all trees on the plot including seedlings and saplings, where the height, crown base height, and diameter at breast height are measured for each tree. This inventory can take much longer than it takes to measure gap fraction with an optical sensor, but the data can be used for many other forestry applications. Moreover, the abundant forest inventory data previously taken by land management institutions and agencies can be used to compute CBD across large land areas (Keane et al. 2000). It is difficult and somewhat inappropriate to statistically compare CBD estimates from the allometric technique with those measured from these other indirect techniques. The allometric technique depends on accurate biomass equations and general assumptions about crown shape and random tree distribution to determine local crown fuel characteristics.

## Scale analysis

The low variation of indirect measurements across the 25 grid points (Fig. 5) is primarily a scale artifact of our sampling protocol rather than a comprehensive assessment of gap fraction spatial variation. We intensively sampled crown biomass using destructive methods in a small circular 0.3-ha representative portion of the stand instead of sampling the entire stand because crown biomass sampling is costly and time consuming. As a result, our indirect measurements had to be taken on a 5-m grid confined to this small sampling area to ensure the indirect measurements reflected the destructively sampled canopy fuel conditions. The 25 grid sample points are so close together that the indirect instruments often measure the same canopy conditions, because the area scanned by the indirect equipment (field of view) was much greater than the area occupied by the sample plot area. For all study sites, it appears that only three to five measurements were needed to obtain an accurate gap fraction for all indirect techniques to measure the small plot area because of the sensor's large measurement footprint.

It is important that measurement and analysis scales match when estimating CBD from indirect techniques. If CBD estimates are needed at the plot level, then only three to five indirect measurements may be needed, but it can be useful to take additional readings, especially if canopy conditions in plot are highly variable. However, if one CBD estimate is needed for an entire stand or polygon, then the number of indirect sampling points should be sufficient to capture the heterogeneity of canopy conditions across the entire extent of the stand. A good guide might be to use standard sampling designs employed in forestry for tree inventory to determine the number of CBD indirect sample points.

## Limitations of the indirect approach

Although results from this study are promising, there are major limitations in measuring canopy bulk density using indirect techniques. First, all indirect methods are greatly influenced by leaf and branch morphology and geometry (Bolstad and Gower 1990; Stenberg 1996*a*), which is the main reason that the relationship of CBD with gap fraction is different across sites of dissimilar species composition and vertical structures (Fig. 6). All estimations of gap fraction assume a random distribution of material throughout the canopy, which is not the case for most stands. Foliage in pine species, for example, tends to be clustered at the end of the branch, while fir foliage is well distributed along most of the branch length. The specific leaf area (SLA) used in regression analysis was not an important predictive variable (Table 4) because it was calculated by species at the branch level and was not adjusted for branch clumping on the tree (Stenberg 1996*b*). Moreover, SLA can vary throughout the crown profile within a tree species. Measuring specific projected crown area instead of specific leaf area, where needle and branch mass is divided by the area the branch projects on the ground at the tree level, might improve the predictions.

Light has a greater chance of being intercepted by canopy material if detected from high zenith angles (not directly above), because it must traverse a greater distance through the canopy. Equation 1 attempts to correct for this by weighting by the sine and cosine function, but this also assumes that the light is passing through a homogeneous medium, which is not always the case in forests. The sample stand might be on a rounded ridge, steep slope, or deep valley, where the light path through the canopy is either reduced or truncated by topography or some other abiotic factor. Alternatively, highly variable crown conditions within the stand due to clumping, shading, sun angle, or dead aerial material (needle drape or lichen) may influence accurate estimation of CBD, depending on the sampling strategy. Because no tested instrument can detect canopy depth, indirect measurements estimate gap fraction across the entire canopy profile, so dense canopy layers cannot be directly measured for CBD.

Canopy fuel characteristics are highly variable in space and time, making it difficult to consistently estimate CBD with the optical indirect techniques presented here. Not only is there a large horizontal variation at small spatial scales due to tree distributions, but the vertical distribution of crown fuels is also highly variable because of diverse distributions of tree sizes and shapes. Sampling of this variability can take numerous measurements over large areas, which may not be feasible for many fuel sampling projects. This limitation is most visible in the regression analysis results in Fig. 6, where most variation is due to across-stand differences in species composition and structure. In fact, gap fraction predictions of CBDmax2 had $R^2 > 0.90$ for many optical methods when the regression analysis was stratified by study site ($n = 4$). Regression equations presented in Table 4 will perform best in stands of similar species composition and structure as those used in this study (Table 2).

Tree, branch, and foliar clumping also contribute to canopy fuel variability, and these factors are responsible for most errors in predicting CBD (Fig. 6). Smith et al. (1993) found that the nonrandom distribution of branches in space caused low LAI2000 LAI measurements, and a clumping factor of 2.63 was used to correct LAI2000 estimates to those predicted from allometric equations. Sampson and Allen (1995) found a weak relationship of LAI measurements from the LAI2000 to allometric equations or litter-trap estimates at very low and high LAIs, which was probably due to crown spatial structure. Strachan and McCaughey (1996) found that 84 LAI2000 measurements are needed to get within 5% of the observed mean for a stand whose crown was highly variable, but only 21 measurements are needed to get to 10% of the mean.

Measurement error can be a major factor in the accuracy of gap fraction measurement. Improper calibration measurements (LAI2000, ceptometer) or camera settings (hemiphoto, CIDpci) can result in inaccurate CBD estimations. The instrument should be positioned to ensure topography, rocks, and people are not in the image frame to achieve the best gap fraction estimates. Measurements for all indirect techniques must be taken when ambient light conditions do not change over short periods. These operator errors are probably the primary explanations for the obvious outliers in Fig. 6 for the Salmon LAI2000 and hemiphoto measurements at low gap fractions.

Our study had only 23 observations to build predictive models for indirect measurement techniques. This is probably is not enough to adequately sample the full range of canopy conditions. Moreover, there were only five study sites with 18 of the total 23 observations created by tree removal, which may contribute to some bias in the sample. Additional measurements across disparate sites and species compositions are needed to build stronger predictive models for indirect techniques. Moreover, the 23 observations are not entirely independent because some trees are present in all replicate measurements. We recommend these procedures be repeated in other conifer and broadleaf stands to develop more robust relationships between canopy characteristics and gap fraction.

The study can be of immediate benefit to managers and researchers by providing a means to estimate canopy bulk density in the field using the regression equations presented here with gap fraction measurements from the indirect techniques. These field measurements can be used to drive classifications of satellite imagery to map CBD across a spatial domain (see Keane et al. 2001) and input this digital map in spatial fire behavior prediction systems such as FARSITE (Finney 1998*b*). Stand-level measurements of CBD can be used in nonspatial models such as NEXUS to calculate crown fire characteristics (Scott 1999). To properly use these regression equations, the intermediate data calculated by the indirect instrument are required to get the gap fraction for the five zenith angle ranges. Then, the estimates of gap fraction are transformed using eq. 3 or Table 3 for the appropriate number of zenith angle ranges.

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## References

Alemdag, I.S. 1980. Manual of data collection and processing for the development of forest biomass relationships. Can. For. Serv. Petawawa Natl. For. Inst. Inf. Rep. PI-X-4.

Alexander, M.E. 1988. Help with making crown fire hazard assessments. *In* Protecting People and Homes from Wildfire in the Interior West: Proceedings of the symposium and workshop. *Edited by* W. Fischer and S.F. Arno. USDA For. Serv. Gen. Tech. Rep. INT-251. pp. 147–153.

Arno, S.F., Parsons, D.J., and Keane, R.E. 2000. Mixed-severity fire regimes in the northern Rocky Mountains: consequences of fire exclusion and options for the future. *In* Wilderness Science in a Time of Change Conference. Vol. 5: Wilderness Ecosystems, Threat, and Management, Missoula, Montana, 23–27 May 1999. USDA For. Serv. RMRS-P-15-VOL-5. pp. 225–232.

Battles, J.J., Dushoff, J.G., and Fahey, T.J. 1996. Line intersect sampling of forest canopy gaps. For. Sci. **42**: 131–140.

Bolstad, P.V., and Gower, S.T. 1990. Estimation of leaf area index in fourteen southern Wisconsin forest stands using a portable radiometer. Tree Physiol. **7**: 115–124.

Brown, J.K. 1978. Weight and density of crowns of Rocky Mountain conifers. USDA For. Serv. Res. Pap. INT-197.

Campbell, G.S., and Norman, J.M. 1989. The description and measurement of plant canopy structure. *In* Plant canopies: their growth, form, and function. *Edited by* P.G. Jarvis. Cambridge University Press, Cambridge, UK. pp. 1–19.

Chason, J.W., Baldocchi, D.D., and Huston, M.A. 1991. A comparison of direct and indirect methods for estimating forest canopy leaf area. Agric. For. Meteorol. **57**: 107–128.

Chen, S.G., Impens, I., Ceulemans, R., and Kockelbergh, F. 1993. Measurement of gap fraction of fractal generated canopies using digitalized image analysis. Agric. For. Meteorol. **65**: 245–259.

Clark, P.E., and Seyfried, M.S. 2001. Point sampling for leaf area index in sagebrush steppe communities. J. Range Manage. **54**: 589–594.

Decagon. 1987. Sunfleck ceptometer user's manual. Decagon Devices, Pullman, Wash.

Deusen, P.C.V., and Baldwin, V.C. 1993. Sampling and predicting tree dry weight. Can. J. For. Res. **23**: 1826–1829.

Dufrene, E., and Breda, N. 1995. Estimation of deciduous forest leaf area index using direct and indirect methods. Oecologia, **104**: 156–162.

Englund, S.R., O'Brien, J.J., and Clark, D.B. 2000. Evaluation of digital and film hemispherical photography and spherical densiometry for measuring forest light environments. Can. J. For. Res. **30**: 1999–2005.

Fassnacht, K.S., Gower, S.T., Norman, J.M., and McMurtie, R.E. 1994. A comparison of optical and direct methods for estimating foliage surface area index in forests. Agric. For. Meteorol. **71**: 183–207.

Ferry, G.W., Clark, R.G., Montgomery, R.E., Mutch, R.W., Leenhouts, W.P., and Zimmerman, G.T. 1995. Altered fire regimes within fire-adapted ecosystems. US Department of the Interior, National Biological Service, Washington, D.C.

Finney, M.A. 1998. FARSITE users guide and technical documentation. USDA For. Serv. Res. Pap. RMRS-RP-4.

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. Can. For. Serv. Pac. For. Cent. Inf. Rep. BC-X-373.

Frazer, G.W., Canham, C.D., and Lertzman, K.P. 2000. Technological tools: Gap Light Analyzer version 2.0. Bull. Ecol. Soc. Am. **12**: 191–197.

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. Agric. For. Meteorol. **109**: 249–263.

Gary, H.L. 1976. Crown structure and distribution of biomass in a lodgepole pine stand. USDA For. Serv. Res. Pap. RM-165.

Gary, H.L. 1978. The vertical distribution of needles and branchwood in thinned and unthinned 80-year-old lodgepole pine. Northwest Sci. **52**: 303–309.

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

Groeneveld, D.P. 1997. Vertical point quadrat sampling and an extinction factor to calculate leaf area index. J. Arid Environ. **36**: 475–485.

Inouye, D.W. 2000. Gap Light Analyzer version 2.0. Bull. Ecol. Soc. Am. **6**: 191–197.

Johnson, A.F., Woodard, P.M., and Titus, S.J. 1989. Lodgepole pine and white spruce crown fuel weights predicted from height and crown width. Can. J. For. Res. **19**: 527–530.

Jurik, T.W., Briggs, G.M., and Gates, D.M. 1986. A comparison of four methods for determining leaf area index in successional hardwood forests. Can. J. For. Res. **15**: 1154–1158.

Keane, R.E., Garner, J.L., Schmidt, K.M., Long, D.G., Menakis, J.P., and Finney, M.A. 1998. Development of input spatial data layers for the FARSITE fire growth model for the Selway–Bitterroot Wilderness complex, USA. USDA For. Serv. Gen. Tech. Rep. RMRS-GTR-3.

Keane, R.E., Mincemoyer, S.A., Schmidt, K.M., Menakis, J.P., Long, D.G., and Garner, J.L. 2000. Mapping vegetation and fuels for fire management on the Gila National Forest Complex. USDA For. Serv. Gen. Tech. Rep. RMRS-GTR-46-CD.

Keane, R.E., Burgan, R.E., and Wagtendonk, J.V. 2001. Mapping wildland fuels for fire management across multiple scales: integrating remote sensing, GIS, and biophysical modeling. Int. J. Wildland Fire, **10**: 301–319.

Keane, R.E., Veblen, T., Ryan, K.C., Logan, J., Allen, C., and Hawkes, B. 2002. The cascading effects of fire exclusion in the Rocky Mountains. *In* Rocky Mountain futures: an ecological perspective. *Edited by* J.S. Baron. Island Press, Washington, D.C. pp. 133–153.

Kolb, P.F., Adams, D.L., and McDonald, G.I. 1998. Impacts of fire exclusion on forest dynamics and processes in central Idaho. Tall Timbers Fire Ecol. Conf. **20**: 911–923.

Kucharik, C.J., Norman, J.M., and Gower, S.T. 1998. Measurements of leaf orientation, light distribution, and sunlit leaf area in a boreal aspen forest. Agric. For. Meteorol. **91**: 127–148.

LI-COR, Inc. 1992. LAI2000 Plant Canopy Analyzer: operating manual. LI-COR Inc., Lincoln, Nebr.

Linn, R.R. 1997. A transport model for prediction of wildfire behavior. Ph.D. thesis, New Mexico State University, Las Cruces, N.M.

Magnussen, S., and Boudewyn, P. 1998. Derivations of stand heights from airborne laser scanner data with canopy-based quartile estimators. Can. J. For. Res. **28**(7): 1016–1031.

Martens, S.N., Ustin, S.L., and Rousseau, R.A. 1993. Estimation of tree canopy leaf area index by gap fraction analysis. For. Ecol. Manage. **61**: 91–108.

Miller, J.B. 1967. A formula for average foliage density. Aust. J. Bot. **15**: 141–144.

Monserud, R.A., and Marshall, J.D. 1999. Allometric crown relations in three norther Idaho conifer species. For. Sci. **29**: 521–535.

Mutch, R.W. 1994. Fighting fire with fire: a return to ecosystem health. J. For. **92**: 31–33.

Nel, E.M., and Wessman, C.A. 1993. Canopy transmittance models for estimating forest leaf area index. Can. J. For. Res. **23**: 2579–2586.

Neumann, H.H., Hartog, G.D., and Shaw, R.H. 1989. Leaf area measurements based on hemispheric photographs and leaf-litter collection in a deciduous forest during autumn leaf-fall. Agric. For. Meteorol. **45**: 325–345.

Nilson, T. 1999. Inversion of gap frequency data in forest stands. Agric. For. Meteorol. **98–99**: 437–448.

Nilson, T., Anniste, J., Lang, M., and Praks, J. 1999. Determination of needle area indices of coniferous forest canopies in the NOPEX region by ground-based optical measurements and satellite images. Agric. For. Meteorol. **98–99**: 449–462.

Peper, P.J., and McPherson, E.G. 1998. Comparison of five methods for estimating leaf area index of open-grown deciduous trees. J. Arboric. **24**: 98–111.

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

Pierce, L.L., Running, S.W., and Walker, J. 1994. Regional-scale relationships of leaf area index to specific leaf area and leaf nitrogen content. Ecol. Appl. **4**: 313–321.

Reinhardt, E., and Crookston, N.L. (*Editors*). 2003. The fire and fuels extension to the Forest Vegetation Simulator. USDA For. Serv. Gen. Tech. Rep. RMRS-GTR-166.

Roberts, S.D., and Long, J.N. 1992. Production efficiency of *Abies lasiocarpa*: influence of vertical distribution of leaf area. Can. J. For. Res. **22**: 1230–1234.

Sampson, D.A., and Allen, H.L. 1995. Direct and indirect estimates of LAI for lodgepole and loblolly pine stands. Trees (Berl.), **9**: 119–122.

Sando, R.W., and Wick, C.H. 1972. A method of evaluating crown fuels in forest stands. USDA For. Serv. Res. Pap. NC-84.

Scott, J.H. 1999. NEXUS: A system for assessing crown fire hazard. Fire Manage. Notes, **59**: 21–24.

Scott, J.H., and Reinhardt, E.D. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. USDA For. Serv. Res. Pap. RMRS-RP-29.

Scott, J.H., and Reinhardt, E.D. 2002. Estimating canopy fuels in conifer forests. Fire Manage. Today, **62**: 45–50.

Smith, R.W., and Somers, G.L. 1991. SUNSHINE: a light environment simulation system based on hemispherical photographs. USDA For. Serv. Gen. Tech. Rep. SO-267.

Smith, N.J., Chen, J.M., and Black, T.A. 1993. Effects of clumping on estimates of stand vegetation area index using the LI-COR LAI2000. Can. J. For. Res. **23**: 1940–1943.

Smolander, J., and Stenberg, P. 1996. Response of LAI2000 estimates to changes in plant surface area index in a Scots pine stand. Tree Physiol. **16**: 345–349.

Stenberg, P. 1996*a*. Correcting LAI2000 estimates for the clumping of needles in shoots of conifers. Agric. For. Meteorol. **79**: 1–8.

Stenberg, P. 1996*b*. Simulations of the effects of shoot structure and orientation on vertical gradients in intercepted light by conifer canopies. Tree Physiol. **16**: 99–108.

Stenberg, P., Linder, S., Smolander, H., and Flower-Ellis, J. 1994. Performance of the LAI2000 plant canopy analyzer in estimating leaf area index of some Scots pine stands. Tree Physiol. **14**: 981–995.

Strachan, I.B., and McCaughey, J.H. 1996. Spatial and vertical leaf area index of a deciduous forest resolved using the LAI2000 plant canopy analyzer. For. Sci. **42**: 176–181.

van Wagner, C.E. 1977. Conditions for the start and spread of crown fire. Can. J. For. Res. **7**: 23–34.

Walter, J.M.N., and Himmler, G.G. 1996. Spatial heterogeneity of a Scots pine canopy: an assessment by hemispherical photography. Can. J. For. Res. **26**: 1610–1619.

Welles, J.M. 1990. Some indirect methods of estimating canopy structure. Remote Sens. Rev. **5**: 31–43.

Welles, J.M., and Norman, J.M. 1991. Instrument for indirect measurement of canopy architecture. Agron. J. **83**: 818–825.

White, J.D., Running, S.W., Nemani, R., Keane, R.E., and Ryan, K.C. 1998. Measurement and mapping of LAI in Rocky Mountain montane ecosystems. Can. J. For. Res. **27**: 1714–1727.