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Forest Ecology and Management 232 (2006) 188–197

Forest Ecology and Management

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Comparison of five canopy cover estimation techniques in the western Oregon Cascades

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Received 27 April 2005; received in revised form 23 May 2006; accepted 24 May 2006

Abstract

Estimates of forest canopy cover are widely used in forest research and management, yet methods used to quantify canopy cover and the estimates they provide vary greatly. Four commonly used ground-based techniques for estimating overstory cover – line-intercept, spherical densiometer, moosehorn, and hemispherical photography – and cover estimates generated from crown radii parameters of the western Cascades variant of the Forest Vegetation Simulator (FVS) were compared in five Douglas-fir/western hemlock structure types in western Oregon. Differences in cover estimates among the ground-based methods were not related to stand-structure type ($p = 0.33$). As expected, estimates of cover increased and stand-level variability decreased with increasing angle of view among techniques. However, the moosehorn provided the most conservative estimates of vertical-projection overstory cover. Regression equations are provided to permit conversion among canopy cover estimates made with the four ground-based techniques. These equations also provide a means for integrating cover data from studies that use different techniques, thus aiding in the ability to conduct synthetic research. Ground-based measures are recommended for specific objectives. Because the FVS-estimated cover levels were consistently lower and more variable than most of the ground-based estimates (by up to 44, 17% on average), ground-based measures of canopy cover may be preferable when accuracy is an important objective.

Keywords: Oregon Cascades; Canopy cover; Line intercept; Densiometer; Moosehorn; Hemispherical photography; FVS

1. Introduction

Estimates of canopy cover are widely used in forest research and management, including in the Pacific Northwest Region of the USA (PNW). Regulations for certain regional wildlife species require maintenance of certain levels of canopy cover (e.g., Weiss et al., 1991; Verner et al., 1992). Canopy cover is often used as a criterion for classifying stand structure (e.g., Wisdom et al., 2000; Azuma and Hanson, 2002), and as a surrogate for shade when monitoring stream temperatures (e.g., OWEB, 1999). In addition, cover estimates are used to estimate penetration of light to the understory (e.g., Canham et al., 1990; Lieffers et al., 1999; Englund et al., 2000).

Despite the importance of quantitative estimates of canopy cover, there is no standard measurement method. Instead, estimates are derived with a wide variety of ground-based techniques. Commonly used ground-based methods include ocular estimates, the moosehorn (Robinson, 1947), spherical densiometers (concave and convex; Lemmon, 1956), the densitometer (Stumpf, 1993), hemispherical photography (Evans and Coombe, 1959), point counts, and the line-intercept method (Canfield, 1941; O'Brien, 1989). Less commonly cited ground-based methods include stem and crown mapping, the vertical tube (Johansson, 1985), and the gimbal sight (Walters and Soos, 1962). Additionally, predictive relationships between tree size and canopy cover derived from empirical measures are used in stand or tree growth models to estimate vertically projected canopy cover, such as Forest Vegetation Simulator (FVS; Donnelly and Johnson, 1997), ORGANON (Hann, 2003), and certain forest-gap models (e.g., Garman et al., 2003). Where direct measures of canopy cover cannot be

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0378-1127/$ – see front matter © 2006 Published by Elsevier B.V.
doi:10.1016/j.foreco.2006.05.069

acquired, estimates of cover can be derived by applying these predictive relationships to ground-based measures of tree sizes.

Estimates of percent cover vary among ground-based methods, primarily due to differences in the angle of view from zenith captured (e.g., Bunnell and Vales, 1990; Applegate, 2000). Larger angles of view result in greater estimates of canopy cover because canopy gaps visually ''close'' as the angle of view is lowered from directly overhead towards the horizon (Kirchoff and Schoen, 1987; Bunnell and Vales, 1990). For a given amount of vertical canopy cover, we would expect that estimates from narrow- and wide-angle techniques would be more similar in single-layer stands than in multi-layer stands.

Conceptually, ''canopy cover'' is the vertical projection of plant foliage onto a horizontal surface. In practice, measurements of ''canopy cover'' assess either foliage, foliage plus stems, or canopy perimeters, and may do so with instruments with a variety of angles of view. While a few researchers have distinguished between vertically projected cover and cover measured with wider angles of view (e.g., crown completeness, Bunnell et al., 1985; angular cover, Nuttle, 1997), there is a general tendency for overstory cover measured with different angles of view to be referred to as ''canopy cover''. As a result, different techniques with different angles of view are estimating cover values for different meanings of canopy cover. In our comparison of techniques, we refer to ''canopy cover'' in this broader sense that encompasses different angles of view, and distinguish it from the term ''vertical canopy cover''. Only as the angle of view of canopy reduces to zero, only measuring the area directly overhead, does angular canopy cover become equivalent to vertical canopy cover. The line-intercept method, with a theoretical zero width, is therefore expected to provide the least-biased, most accurate estimates of vertical canopy cover. It is also the most directly comparable measure to line-intercepts used to estimate cover from remote sensing imagery (O'Brien, 1989).

Predictive models of canopy cover are constrained by several factors. The range of conditions in which parameterization data are sampled limits model applications to similar conditions. Of greater importance is the influence of the type of method used to collect the ground-based measures for model development. Given the variability in measures with different canopy-cover estimation methods, predictive models are generally no better than the ground-based methods, having the same error and limitations as the methods used to generate the model-parameterization data.

Previous studies comparing field and/or modeling methods for estimating canopy cover have demonstrated important differences among methods (e.g., Bunnell and Vales, 1990; Ganey and Block, 1994; Cook et al., 1995; Applegate, 2000; Englund et al., 2000). However, we are unaware of previous studies comparing the line-intercept method with other methods in multiple structure types. Given that the line-intercept method is commonly used (e.g., Azuma and Hanson, 2002; Fiala, 2003), and is expected to offer the most reliable estimates of vertical canopy cover, further study is warranted to determine the relationship of other commonly used cover techniques relative to the line-intercept method among stand-structure types. With the lack of standardized methods, a means for comparing cover measures recorded among techniques is also desired for integration of multiple datasets. This is especially important given that different techniques are measuring alternative definitions of canopy cover that are inaccurately used interchangeably. Recognizing the large amounts of time that are often required to collect detailed canopy cover data, it is increasingly common for managers to rely solely on modeled estimates of canopy cover. However, the relation of these estimates to what is observed on the ground has not been well explored. Therefore, it is also of interest to compare modeled cover with ground-based estimates.

The objectives of this study were to: (1) compare estimates of canopy cover among the ground-based line-intercept, hemispherical photography, moosehorn, and convex spherical densiometer methods; (2) compare the variability in cover estimates obtained by these techniques; (3) create regression equations to facilitate comparisons of estimates made among these methods; and (4) compare ground-based estimates with canopy cover estimates generated by the FVS equations. The FVS was chosen for evaluation in this study because of the availability of tree attributes in our data, the diversity of stand-structure types in our study, and the prevalence of FVS and its extensions in use in current forest research and management (e.g., Christensen et al., 2002; Hummel et al., 2002). The methods were compared in five *Pseudotsuga menziesii* (Mirb.) Franco/*Tsuga heterophylla* (Raf.) Sarg. (Douglas-fir/western hemlock) structure types in the western Oregon Cascade Range.

2. Methods

2.1. Study sites

The study was conducted in 52 forested stands located in the Mt. Hood and Willamette National Forests of the Oregon Western Cascades during June–September, 2001 (Fig. 1). Plots were located in the *Tsuga heterophylla* forest zone (Franklin and Dyrness, 1988) and spanned a range of Douglas-fir/western hemlock structure types. Stand-structure types included: unthinned, lightly thinned, and heavily thinned young stands (38–52 years old); mature stands (120–180 years); and old-growth forests (>250 years). All structure types were dominated by Douglas-fir, western hemlock, and western redcedar (*Thuja plicata* Donn ex. D. Don), which made up 95% or more of the stand basal area.

There were eight replicates within each of the three young structure types (Table 1). Half of these stands were from the Young Stand Thinning and Diversity Study sites harvested between 1994 and 1996 (CCEM, 1996), and the other half were from the Uneven-Aged Management Project stands harvested from 1999 to 2000 (CCEM, 1999). Within each stand, tree data were collected on multiple 0.1 ha subplots located along transects spaced 20-m apart. We randomly selected five of these subplots from each of the stands for use in this study.

There were 14 replicates each for the mature and old-growth structure types (Table 1). The stands were comprised of USDA

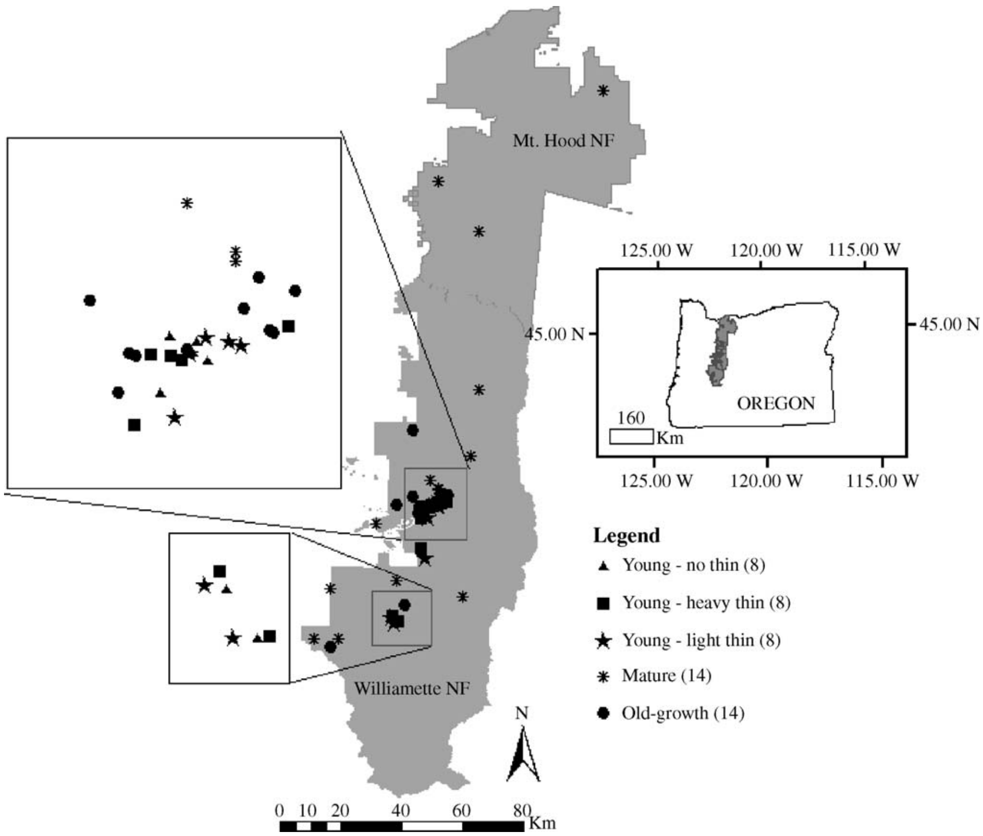

Fig. 1. Locations of the 52 stands by structure type, located in the Willamette and Mt. Hood National Forests, used in this study.

Forest Service Current Vegetation Survey inventory plots (CVS; Max et al., 1996; USDA Forest Service, 2001) and permanent sample plots (PSP; Acker et al., 1998). CVS plots were circular 1.0 ha fixed-area plots systematically located on a 1.7-mile grid (3.4 miles in designated wilderness areas), with five systematically located 0.1 ha subplots in each plot. Subplots were located in the four major cardinal directions at a distance of 40.8 m from a center subplot. PSP plots were 1 ha rectangular stem-mapped plots. The PSP plots were subjectively located in the region around the HJ Andrews Experimental Forest (44.2°N, 122.2°W) to represent different community types of mature and old-growth forests. The mature stands in this study were randomly selected from 35 PSP and CVS plots that were between the ages of 120–180 years. The old-growth stands were randomly selected from 73 CVS and PSP stands that were >250 years. We used the systematic five 0.1 ha subplot arrangement established by the CVS program for all the PSP and CVS plots used in this study, establishing 0.1 ha circular subplots and recording tag numbers for selected trees within the 1 ha stem-mapped plot at each PSP site.

2.2. Cover measurements

We based sample sizes for each technique on recommendations from the literature. Previous use of hemispherical photography suggested a minimum sample of 6–10 photographs per stand (e.g., Canham et al., 1990; Easter and Spies, 1994). We took photos at 20 points per stand. Recommendations for the moosehorn ranged from 10 to 100 per plot (e.g., Garrison, 1949; Bonnor, 1967). We collected 65 moosehorn

Table 1
Attributes of the sampled stands used in this study, by structure type

Range of stand conditions						
Stand-structure type	Stands (n)	Age (years)	Stand area (ha)	Stem density[a] (tph)/relative density[b]	Elevation (m)	Basal area (m^2/ha)
Young unthinned	8	38–51	8–52.6	888–2597	577–911	50–82
Young light thin	8	41–52	10.4–37.2	397–873/30	524–902	33–59
Young heavy thin	8	39–51	12.8–34.8	198–629/20	610–905	19–45
Mature	14	121–177	1	138–857	366–1097	39–133
Old-growth	14	331–525	1	130–1002	427–1190	50–174

[a] Stem densities are provided for Young Stand Thinning and Diversity Study sites and mature and old-growth sites.
[b] Relative density (Husch et al., 1972) is provided for the Unevenaged Management Project sites.

measurements per stand. Previous studies using the densiometer ranged from 4 measures per subplot to 30 measures per stand (e.g., Lemmon, 1956; Cook et al., 1995; Vales and Bunnell, 1988; Englund et al., 2000). We obtained 35 densiometer measurements per stand. We followed the protocols of the USDA Forest Service Forest Inventory and Analysis (FIA) program, using 15 17-m line transects to collect line-intercept canopy data (Azuma and Hanson, 2002).

In each of the five 0.1-ha circular subplots per stand, canopy measurements were recorded along three 17-m slope-corrected line transects radiating out from the center of each subplot (azimuth 0°, 120°, and 240°). The locations of canopy measurements differed for the four methods being compared, with replicate measures for the same technique located to minimize overlap. Densiometer measurements were recorded at the center of a subplot, and at distances of 8.5 and 17 m along each transect. Moosehorn measurements were recorded at the center of the subplot, and at 4.25-m intervals along each of the three transects. Hemispherical photo-points were located at the center of each subplot and every 11.3 m along each transect.

Two observers collected measurements. To ensure consistency, observers practiced recording cover estimates using the line-intercept, densiometer, and moosehorn techniques prior to actual field measurements. When recording field measures, observers took turns measuring cover with the various methods to minimize observer bias.

The line-intercept method measures canopy cover by recording horizontal distances covered by live crown along a line-transect (Canfield, 1941; O'Brien, 1989). It includes the entire length within the outline of a crown as cover. Canopy cover data were collected for individual tree species in a maximum of three vertical canopy layers. In each stand, trees were assigned to one of three canopy layers, with discrete layers differing by a minimum of 5 m in mean height. Actual heights varied among stands, as canopy layers were relative to conditions within a stand. Canopy cover was measured for each species of live tree and shrub $\geq$1.4 m tall along horizontal transects. Shrubs were included because the other three methods could not distinguish between taller shrub and overstory tree cover. For every species and canopy layer, the distance along each transect line where the crown first intercepted the line to the point where the crown (or multiple contiguous crowns of the same species) last intercepted the line was recorded (to the nearest dm), using a clinometer to verify crown interception directly overhead. Projection of individual cover elements by species and layer was done using transect distance measurements to estimate total crown distance over each transect. The proportion of transect lengths that were intercepted by crowns was the ground-estimated canopy cover, and ranged from 0 to 100%.

The convex spherical densiometer is a convex spherical-shaped mirror engraved with a graticule (Lemmon, 1956). Four measurements in the cardinal directions were taken at each sample point, assessing a 90° wedge of the densiometer's surface to avoid overlap among measurements (Strickler, 1959). The wedge was oriented such that the angle of sight bisected the 90° angle. This resulted in an angle of view of approximately 60° from the vertical (120° total). The densiometer was leveled on a tripod at approximately 1.4 m above the forest floor. Canopy cover was calculated as the proportion of the 68 points that was intersected by cover.

The moosehorn employs a square grid similar to the spherical densiometer. With the aid of an angled mirror at 45°, vertical canopy cover is reflected through an aperture in the side of the instrument through which the observer records the number of cross-hairs intersected by cover (Robinson, 1947; Bonnor, 1967). We used a self-leveling moosehorn that viewed an angle of 6.3° from the vertical (12.6° total). The proportion of 36 points intersected by cover provided an estimate of canopy cover.

Hemispherical photography provides a wide-angle view of the forest canopy from a given site, using a 180° lens. We used an AE-1 Canon camera with a Canon hemispheric lens (7.5 mm focal length) to estimate canopy cover. Hemispherical photographs were taken approximately 1.4 m above the forest floor, with the camera leveled on a tripod. Because access to many field sites was difficult, many photos were taken under less than ideal conditions (e.g., bright mid-day sun). Nevertheless, these were representative of conditions that may be encountered when working at remote field sites. Canopy photographs were analyzed using the CANOPY (Rich, 1989) software program. Data were summarized using the indirect site factor (ISF), which is the proportion of indirect radiation (assuming uniform cloudy sky) received under a plant canopy compared to an open site (Evans and Coombe, 1959; Rich, 1989). Calculation of ISF assumes that foliage absolutely blocks incoming radiation whereas canopy openings allow unimpeded passage of light. ISF is the variable that estimates canopy completeness or closure that many people use as an estimate of "cover" (e.g., Thomas et al., 1999; Kelley and Krueger, 2005). Therefore, ISF was subtracted from 100 to estimate canopy cover. To assure consistent analysis of images among plots, we re-calibrated ISF estimates with several previously analyzed photos each time we analyzed new hemispherical photos.

The Forest Vegetation Simulator (Donnelly and Johnson, 1997) is an individual tree, distance-independent growth and yield model, commonly used by the USDA Forest Service to evaluate forest-management treatments. Canopy cover is estimated by summing individual tree crown areas, using species-specific crown radii formulae developed from regional inventory plots. The estimated canopy cover is then corrected for crown overlap by assuming a random distribution of canopy elements (Crookston and Stage, 1999). The overlap-corrected measures were used, as they were commensurate with those of other methods where cover could not exceed 100%. We calculated overlap-corrected cover using previously collected tree dbh and height data for live trees on the sampled subplots in each stand using the FVS Region 6 crown radii parameters for the PNW variant of the model. In the PSP stands, however, trees between 5 and 15 cm diameter at breast height (dbh) were only measured on a subset of the plot area. Therefore, only trees >15-cm dbh were included when calculating FVS-based cover for the PSP stands.

2.3. Analyses

This study used a split-plot design with stand-structure type as the plot-level treatment and the technique for estimating cover as the subplot treatment. A two-way ANOVA (PROC MIXED, SAS Institute, 1999) was used to examine the effects of measurement technique, stand-structure type, and the interaction among technique and structure type. We expected percent cover to differ among stand-structure types and techniques, and we examined these factors to document their significance. A non-significant interaction between technique and structure type was of interest and motivated examining differences only among methods. Analysis of residuals and normal probability plots revealed non-constant variance and lack of normality for all measures (Shapiro–Wilk $W = 0.992$, $p = 0.37$), so logit transformations of percent canopy cover were used.

Paired contrasts were used to discern differences among canopy cover methods for significant ($\alpha = 0.05$) effects. Contrasts were performed using the Scheffé correction for family-wise comparisons, and using Bonferroni multipliers when only specific sets of individual pair-wise comparisons were conducted. Simple linear regressions were constructed for each pair of methods, with one method arbitrarily selected as the explanatory variable and the other as the response.

The stand-level standard deviations for each of the cover-estimating methods were calculated to assess the variability of the cover estimates made by each of the ground-based methods. The differences in standard deviations were visually compared among individual stands for the ground-based cover-estimating methods, and among the stand-structure types.

3. Results

There was no significant interaction between ground-based canopy-cover estimation method and stand-structure type ($F_{12,188} = 1.14$, $p = 0.33$). Mean percent cover values differed among stand-structure types ($F_{4,188} = 62.55$, $p < 0.0001$) and among methods ($F_{3,188} = 35.78$, $p < 0.0001$).

Pair-wise comparisons of means between ground-based methods generally were significantly different (Table 2; Fig. 2). Only the cover estimates of the densiometer and hemispherical photography, and of the hemispherical photography and line-intercept methods were similar ($p > 0.05$). However, hemispherical photography estimates of cover tended to be greater than line-intercept values at low percent cover levels. The moosehorn generally provided the lowest estimates of cover, while the densiometer and hemispherical photography generally had the highest cover estimates. Linear regression coefficients and equations described the differences among the methods (Table 3).

Stand-level cover calculations made using FVS overlap-corrected equations ranged between 42 and 93%. There was a significant interaction between stand-structure type and technique when comparing cover estimates from the ground-based methods with FVS ($F_{16,235} = 2.28$, $p = 0.004$). Therefore, we compared ground-based methods with FVS-modeled cover within each stand-structure type using Bonferroni-adjusted p-values.

Cover estimates made with FVS generally were lower than estimates of the ground-based methods (Table 4; Fig. 3). FVS cover estimates were significantly lower than densiometer estimates among all stand-structure types. Hemispherical photography and FVS estimates were significantly different except in young unthinned stands. Aside from light- and heavy-thin stands, line-intercept cover estimates were significantly higher than FVS estimates. Compared with the moosehorn estimates, FVS cover values did not differ in the young stands, but were significantly lower in mature and old-growth stands.

Stand-level variation of cover estimates generally declined with increasing view angle of method (Fig. 4). With its narrow

Table 2
Differences of least square means for logit-transformed cover estimates among ground-based methods compared in this study

Methods compared	Difference estimate	S.E.	t-Value	Scheffé-adjusted p-value
Densiometer vs. hemispherical photography	0.156	0.110	1.38	0.59
Densiometer vs. line-intercept	0.373	0.110	3.31	0.0135
Densiometer vs. moosehorn	1.077	0.110	9.58	<0.0001
Hemispherical photography vs. line-intercept	0.217	0.110	1.93	0.29
Hemispherical photography vs. moosehorn	0.921	0.110	8.19	<0.0001
Line-intercept vs. moosehorn	0.705	0.110	6.26	<0.0001

Table 3
Equation coefficient estimates (±S.E.) for the simple linear regression models that describe each of the combinations of cover-estimate techniques

Response cover variable	Explanatory cover variable	Intercept	Slope estimate	Adj. R^2	Valid cover range for explanatory variable (%)
Line-intercept	Moosehorn	22.94 (3.34)	0.81 (0.04)	0.87	29–94
Line-intercept	Densiometer	−69.77 (15.89)	1.71 (0.17)	0.65	70–98
Line-intercept	Hemispherical photography	−60.32 (11.10)	1.62 (0.12)	0.77	65–97
Moosehorn	Hemispherical photography	−104.41 (8.78)	2.03 (0.10)	0.89	65–97
Moosehorn	Densiometer	−116.41 (15.31)	2.13 (0.17)	0.76	70–98
Hemispherical photography	Densiometer	−3.58 (6.39)	1.03 (0.07)	0.81	70–98

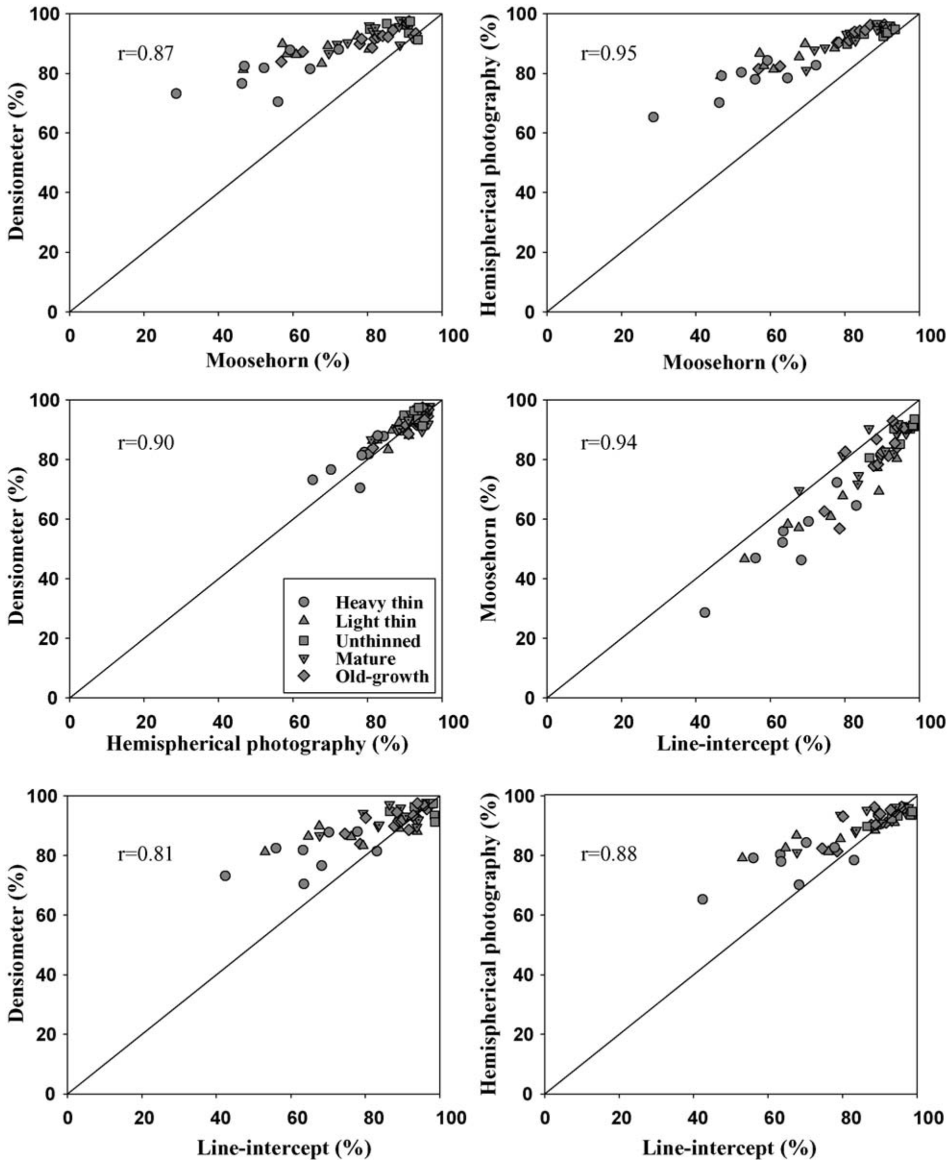

Fig. 2. Comparisons of mean stand-level percent canopy cover for the four ground-based canopy estimation methods in this study. The *r*-values are the Pearson correlation coefficients between each set of two methods.

angle of view, the moosehorn generally had the highest within stand variability. The densiometer and hemispherical photography, with their large areas of view, had the lowest stand-level variability. Cover measurements of methods were more variable in stand-structure types with reduced levels of mean percent cover (Fig. 4). For all methods, the unthinned young stands had the highest percent cover concurrent with the lowest amount of variability. The heavy-thin stands were lowest in percent cover but had the highest degree of stand-level variability.

4. Discussion

We expected higher cover estimates with increasing angle of view, based on the findings of Bunnell and Vales (1990). However, estimates of overstory canopy cover using the line-intercept method were higher than estimates with the moosehorn method, even though the line-intercept method had the narrowest angle of view. This likely resulted because the line-intercept method defined the entire distance within each individual crown outline as canopy, while the other techniques did not consider gaps within irregular crowns as canopy. The level of difference between line-intercept and the other ground-based methods may depend on the abundance of trees with open, spreading crowns relative to the abundance of trees with compact crowns. This may be related to understory versus overstory status, but we were unable to evaluate this.

Except for the line-intercept method, the variability of stand-level cover estimates decreased with increasing angle of view. The analysis of individual 17-m line-intercept transects as sample units probably masked the variation captured along each transect, which could be better captured by splitting transect data into multiple points or shorter lengths.

Although the methods differed in their absolute stand-level variability in cover levels, their relative rankings of variability

Table 4
Differences of least square means among the logit-transformed FVS-modeled cover and the four ground-based method cover estimates

Stand-structure type	Methods compared	Difference estimate (mean difference in untransformed % cover)	S.E.	*t*-Value	Bonferroni-adjusted *p*-value
Young unthinned	**FVS vs. densiometer**	−0.967 (−7.12)	0.264	−3.66	**0.0012**
	FVS vs. hemispherical photography	−0.609 (−5.31)	0.264	−2.31	0.0876
	FVS vs. line-intercept	−1.171 (−7.27)	0.264	−4.44	<**0.0001**
	FVS vs. moosehorn	−0.090 (−0.91)	0.264	−0.34	1.0
Young light thin	**FVS vs. densiometer**	−1.229 (−21.26)	0.264	−4.39	<**0.0001**
	FVS vs. hemispherical photography	−1.108 (−19.74)	0.264	−3.96	<**0.0001**
	FVS vs. line-intercept	−0.657 (−10.77)	0.264	−2.35	0.0792
	FVS vs. moosehorn	0.048 (1.15)	0.264	0.17	1.0
Young heavy thin	**FVS vs. densiometer**	−1.336 (−28.14)	0.264	−5.06	<**0.0001**
	FVS vs. hemispherical photography	−1.150 (−25.22)	0.264	−4.36	<**0.0001**
	FVS vs. line-intercept	−0.593 (−13.51)	0.264	−2.24	0.103
	FVS vs. moosehorn	−0.045 (−1.17)	0.264	−0.17	1.0
Mature	**FVS vs. densiometer**	−2.040 (−27.40)	0.20	−10.22	<**0.0001**
	FVS vs. hemispherical photography	−1.877 (−26.31)	0.20	−9.41	<**0.0001**
	FVS vs. line-intercept	−1.601 (−22.22)	0.20	−8.02	<**0.0001**
	FVS vs. moosehorn	−1.001 (−17.50)	0.20	−5.02	<**0.0001**
Old-growth	**FVS vs. densiometer**	−1.586 (−22.03)	0.20	−7.95	<**0.0001**
	FVS vs. hemispherical photography	−1.635 (−22.22)	0.20	−8.20	<**0.0001**
	FVS vs. line-intercept	−1.274 (−18.85)	0.20	−6.38	<**0.0001**
	FVS vs. moosehorn	−0.685 (−11.37)	0.20	−3.43	**0.0028**

Significant differences are highlighted in bold.

among stand-structure types were similar. For all methods, cover estimates were least variable in the unthinned young stands, and most variable in the thinned young stands. The relative height of trees and differentiation in their crowns plays a role in these rankings, especially for techniques capturing wide angles. At a given point, if a tree is taller or has a larger crown then it is more likely to be captured within the angle of view of a technique, compared with a shorter tree or one with a smaller crown. Therefore in stands where there is more vertical differentiation in tree stature and crown form one would expect

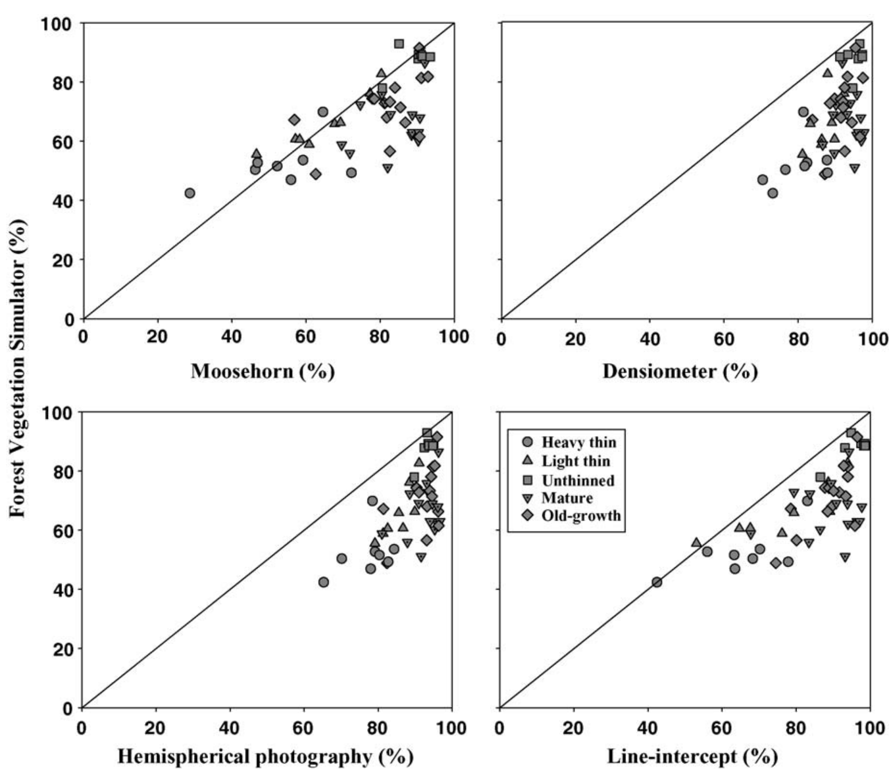

Fig. 3. Comparisons of FVS-modeled cover with canopy estimates from the four ground-based methods measured in this study. Relationships between FVS and the other four methods differed depending on the forest-structure type in which they were measured (see Table 3).

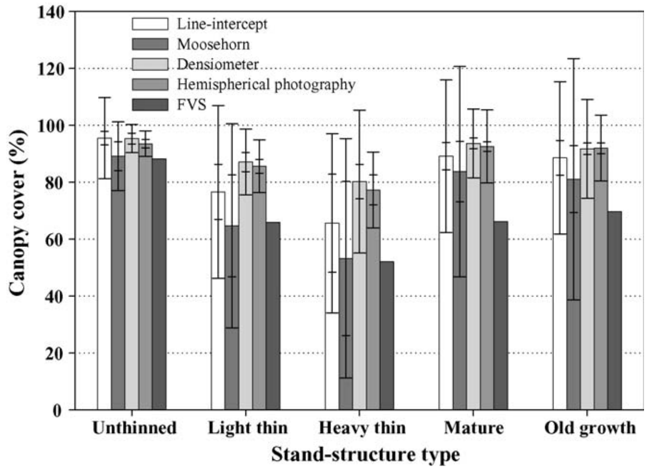

Fig. 4. Mean percent cover estimated by measurement technique for five stand-structure types. The range of stand-level standard deviations within each stand-structure type is provided for the ground-based methods. FVS-estimated cover was a stand-level calculation and therefore did not have a stand-level standard deviation.

more variability in measures of cover. The combination of high cover levels and the lack of vertical differentiation in crowns likely led to the lowest variability among the young unthinned stands. In spite of their short stature, the higher variability in the thinned stands compared to the mature and old-growth stands is consistent with their reduced cover levels, whereby an observer is more likely to sample cover at both locations of very low cover (e.g., in a gap created by overstory removal) and high cover (e.g., where no overstory trees were removed).

With the differences in cover estimates and variability among methods, it was still possible to translate estimates made among them (see Table 3). The lack of interaction between ground-based technique and stand-structure type suggests that these different techniques have consistent relationships to one another, at least for the range of stand densities examined in this study. We recommend the use of our regression equations to translate measurements made with these different techniques in Douglas-fir/western hemlock dominated stands. The use of these equations will permit the comparison of canopy cover estimates recorded with alternative methods at differing locations that could not otherwise be directly compared. The application of our equations is especially relevant given the vast amount of canopy cover data already collected, and the need to integrate existing datasets to examine research questions across a larger spatial scale (i.e., synthetic research). Our recommendation of the use of the equations includes transposing between line-intercept and hemispherical photography measures. While the conservative Scheffé-adjusted p-value did not show significant differences between the line-intercept and hemispherical photograph techniques, biologically the two methods were clearly distinct at low cover levels. However, the linear equations are probably not appropriate for extrapolation to low density stands (e.g., vertically projected cover $<50\%$), where the relationship among methods is likely curvilinear.

The observer's choice of canopy-cover measurement technique depends to a large extent on the forest attribute of interest. Measures with a narrow angle of view will more closely resemble cover estimates made from aerial photography and are directly comparable to the vertical projection cover methods typically used to estimate abundance of understory plants. Conversely, the wide-angle cover estimators should, as Nuttle (1997) suggests, more closely reflect the indirect light levels experienced by a plant, or the perception of cover experienced by an animal. Regardless of the method employed, the researcher should be explicit about the technique that was used to make the estimate, in order to ensure that the angle of view is taken into consideration.

Efficiency was not directly measured in this study, but it was evident that the line-intercept technique was the most time consuming of the four canopy-measurement methods. This was especially true in stands with many species in all three canopy layers. Looking overhead with the clinometer to ascertain start and end points of cover intercepts and verifying these to the nearest dm on the transect tape was often challenging. The densiometer also was time-intensive because of the challenges to position it properly on sloping ground and then properly position the observer. Hemispherical photography also required considerable care for proper positioning of the camera but this method required fewer measures per stand and thus was faster than the densiometer method. Additionally, hemispherical photography appeared to give consistent results even with mid-day sunny conditions, although uniform overcast sky conditions are preferable to maximize canopy–sky contrast and decrease time spent calculating ISF in the Canopy program. Hemispherical photography also requires substantial time post-field collection to analyze the images. The self-leveling moosehorn was definitely the quickest and easiest instrument to use.

The line-intercept is more time-intensive and less conservative in its cover estimates than the moosehorn, and may not be the best standard for comparison with other cover-estimating methods that exclude small gaps within crowns from their estimates. It may be appropriate to modify the line-intercept method to include gaps of a minimum size within individual crowns, but this could further decrease the efficiency of this method. The moosehorn may be the better method to use in the field for estimating vertically projected overstory cover, particularly in stands with open tree crowns.

However, an obvious benefit of the line-intercept method is that it provides forest managers with additional information lacking among the other methods. In addition to total cover, information on the number of layers of cover, percent cover by species, and vertical canopy structure can be assessed with this method (e.g., Fiala, 2003). Recording percent cover by species, vertical layer, or shade-tolerance is impossible with the densiometer and hemispherical photography. With the moosehorn it may be possible to glean limited information about cover by species or layer, but overlap among layers of cover and tree species, with shorter trees obstructing higher layered trees, can impede the ability of the moosehorn user to identify or differentiate among them. Therefore, if detailed canopy structure information is desired, we recommend the use of the line-intercept method. An example of a potential application of line-intercept is in spotted owl habitat areas where guidelines require greater than 40% of the total canopy in Trees 21″ dbh or more (Verner et al., 1992). For these sites, the line-intercept method could be modified to separate out cover by dbh classes, rather than height layers.

The FVS cover calculations consistently underestimated percent canopy cover compared with the four ground-based methods. A similar result was found in Douglas-fir/western larch (*Larix occidentalis* Nutt.) forests in Montana between moosehorn, densitometer, and the north Idaho variant of FVS (Applegate, 2000). While both line-intercept and FVS are based on vertical projections of crown outlines and would be expected to be most similar, they were not. Instead, moosehorn and FVS estimates were similar in the young stand types, although with greater variation than found in comparisons among ground methods. FVS estimates cover from individual tree dbh measures and uses a random-element assumption to estimate crown overlap. The lower accuracy of the FVS estimates in the older stands might be caused by underestimates of crown area, or overestimates of crown overlap for large trees in this region. The underlying equations relating crown area and dbh are imprecise ($R^2 = 0.4$–0.7, depending on species). Although comparison of effects of simulated treatments on *relative* cover levels is probably not affected, it may not be appropriate to apply the current FVS cover equations to estimate *specific* cover levels in Douglas-fir/western hemlock stands. Observers requiring accurate stand-level estimates of canopy cover may prefer to use ground-based methods.

5. Conclusions

Selection of a ground-based method for measuring canopy cover depends on study objectives. However, our comparisons among methods suggest the following general recommendations. If rapid, efficient estimates of vertically projected canopy cover are desired, we recommend the moosehorn. If information on layering and species is required, then the more labor-intensive line intercept method is appropriate. Hemispherical photography, although related to the other measures, is really an estimate of light penetration, and should be used as a measure of angular canopy openness, rather than canopy cover. Densiometers, with their intermediate angle of view, are a hybrid estimate of cover and light, and may perhaps be appropriate as a cheaper, more efficient alternative to hemispherical photography where wider angle cover is the desired attribute to quantify. Current FVS cover-estimation algorithms may be useful for comparing the effect of different simulated treatments within the model, but appear to underestimate vertically projected canopy cover in Douglas-fir/western hemlock forests, particularly in older forests.

Future research of differences among ground-based methods and cover estimates derived from remotely sensed imagery is warranted. Given the difficulty of modeling cover from tree measurements, and the need to quantify canopy cover efficiently without intensive ground measurements, remotely sensed data may hold promise. Light detection and ranging (LIDAR) remote sensing technology, with the extremely accurate canopy structure attributes it can quantify, is one promising avenue that is becoming increasingly available to researchers (e.g., Lefsky et al., 2001, 2002; Parker et al., 2004). If LIDAR can provide estimates of canopy cover comparable to measures on the ground this would greatly increase efficiency of collection and availability of canopy cover data across the landscape.

Acknowledgements

This project was funded through a joint-venture agreement between the USDA Forest Service Pacific Northwest Research Station and Oregon State University. We thank Manuela Huso for statistical advice, Jason Barker and Gina McIntosh for assistance in data collection, the USDA Forest Service for access to data from the Young Stand Thinning and Diversity and Unevenaged Management Projects, and Bruce McCune for a valuable critique of an earlier draft. We are also grateful to three anonymous reviewers for their valuable comments on the manuscript.

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