2000

Comparison of techniques for estimating overstory canopy cover

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A Comparison of Techniques for Estimating Overstory Canopy Cover

by

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B.S. Pennsylvania State University, 1998

presented in partial fulfillment of the requirements for the degree of

Master of Science

The University of Montana

2000

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5-13-2000
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Applegate, Jason R., M.S., May 2000 Forestry

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Title: A Comparison of Techniques for Estimating Overstory Canopy Cover

Abstract:

Overstory canopy cover is an important ecological attribute that is becoming incorporated into forest planning. Current methods to measure canopy cover are problematic due to the necessary sampling intensity, bias of instruments, inconsistencies between observers, and the desire for future projections. The Northern Idaho (NI) variant of the Forest Vegetation Simulator (FVS v.6.2) is capable of predicting canopy cover and has great potential for use in forest management. Research was conducted to determine the degree of accuracy between FVS and two field instruments considered accurate in measuring canopy cover (moosehorn and GRS densitometer) for two criterion of canopy cover (live crown and convex polygon).

Mean canopy cover estimates for 107 plots in 25 stands were compared to FVS predictions, both with and without accounting for crown overlap. FVS (without accounting for crown overlap) was found to underpredict canopy cover across a range of stand densities and covertypes when compared to the moosehorn and GRS densitometer. For the live crown definition of canopy cover, at the plot level, mean estimates of canopy cover between the moosehorn and densitometer were not significantly different for four of the five covertypes examined. For the fifth covertype, significant differences were found but the mean difference was less than 5%. For the convex polygon definition of canopy cover, mean estimates of canopy cover between the moosehorn and densitometer were not significantly different for two of the 5 covertypes. When significant differences were found in three of the covertypes, the mean difference was less than 5%. The difference in mean estimates of canopy cover between the live crown and convex polygon definitions of canopy cover was 10%. Stand level analyses were less conclusive due largely to a small sampling size and a large number of contrasts. FVS underpredicted canopy cover regardless of whether or not adjustments for crown overlap were made.

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Acknowledgements

I wish to thank Dr. Tara Barrett, chair of my committee, for her encouragement in my academic and research efforts, for her immortal patience, and for her assistance and advice in all stages of this project. I would like to thank Dr. Hans Zuuring for his assistance with the statistical analysis and Dr. Kelsey Milner for his insight into modeling and vegetation sampling. I would like to thank Nicholas Crookston for donating his time and efforts in being part of this project and in sharing his expertise of FVS with me. I would also like to thank the foresters who helped make this research possible. Specifically, I thank Joe Yates and Jerry Sass for their efforts in securing me study sites on the Flathead National Forest.

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Chapter I.

Introduction

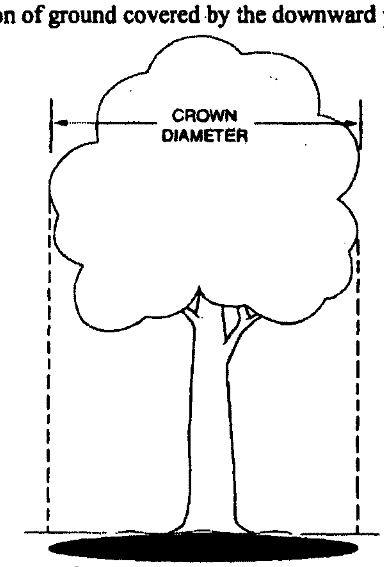
Justification

The paradigm of ecosystem management requires consideration of all management activities within the ecological framework of a given area. Canopy cover has become recognized as a critical factor of that ecological framework. Overstory canopy cover affects understory diversity and development (Skovlin and Harris 1974; Bennett and others 1987; Mitchell and Bartling 1991; Nemati and Goetz 1995; Klinka and others 1996), forest regeneration (Busing 1994; McLaren and Janke 1996; Rebertus and Burns 1997; Caccia and Ballare 1998), forest hydrology (Ingebo 1955), rates of photosynthesis and transpiration (Eastham and Rose 1988; Mackey and Band 1997), and stand thermodynamics (Reifsnyder and Lull 1965). Additionally, canopy cover has been recognized as a significant component of wildlife habitat (Nelson and Buech 1996; Cade 1997). Despite its recognized importance, canopy cover has only recently become incorporated into forest planning.

Forest planning on public lands is increasingly being done for larger spatial areas. Both the United States Forest Service (USFS) and the Bureau of Land Management (BLM) have used canopy cover in regional assessments, such as the Columbia River Basin Assessment (ICRBEIS 1996) and the Sierra Nevada Ecosystem Project (SNEP 1996), and in local assessments and watershed analysis (TEA 1996). Additionally, canopy cover is used in habitat conservation plans (HCP) to protect native fisheries in the Inland West (Plum Creek 1999a). However, before canopy cover can be incorporated into forest planning, it must first be quantified.

Canopy cover has generally been defined as the percent of ground covered by the downward projection of the tree crown, with 100% being the maximum possible value (Gysel and Lyon 1980; Barbour and others 1987; Helms 1998) (Figure 1). If within crown gaps and dead biomass are excluded, then a better definition may be the percent of ground covered only by the *living* crown of a tree (Figure 2). This definition would include live foliage and branches, but would exclude dead material and the bole of the tree. Canopy cover may also be defined as the area of photosynthetically active tissue divided by the ground area (leaf area index) (Barbour and others 1987) (Figure 3). The measure of percent cover may be substantially different between these definitions depending on stand structure, vigor, and species composition. This discrepancy can be problematic in states such as Oregon, Washington, Idaho, and California where canopy cover retention along riparian areas is required by state regulations (Belt and others 1992). Accurate means of measuring and predicting canopy need to be compared and, where lacking, standardized.

Figure 1. The proportion of ground covered by the downward projection of tree crown



(Modified from Avery and Burkhart 1994)

Figure 2. The proportion of ground covered by the live tree crown

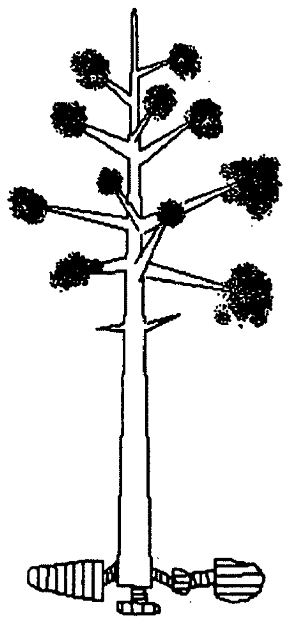
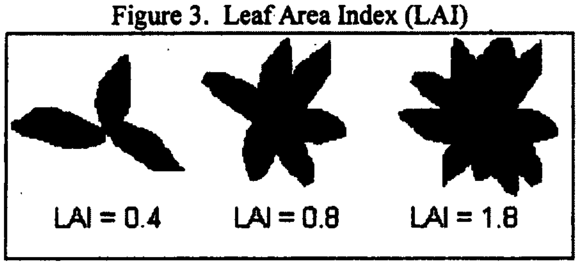


Figure 3. Leaf Area Index (LAI)



(Taken from http://www.gardenwithinsight.com)

Quantifying canopy cover

Techniques to measure canopy cover from the ground regardless of definition are diverse. The moosehorn (Bonner 1967), spherical densiometers (convex and concave) (Lemmon 1956), vertical tube (Johansson 1985), densitometer (Stumpf 1998), canopy camera (Johnson and Vogel 1968), light meters (Jackson and Harper 1955), ceptometers (Ingebo 1955), the crown gap (C) ratio (Whelan and others 1988), basal area correlation (Cade 1997), density scales (Belanger and Anderson 1992), gimbal sight (Walters and

Soos 1962), vertical projection methods (Daubenmire 1959; Vales and Bunnell 1988), and ocular estimates (Ganey 1994), have been, and continue to be, used in the field. The moosehorn, spherical densiometers, point estimates (vertical tube or densitometer), and ocular estimates are commonly utilized because they are relatively quick, and do not require additional manipulation once the data is acquired. However, the moosehorn, and point estimates of canopy cover (vertical tube or densitometer) are considered to be the most accurate since they sample a relatively small area directly above the observer (Bunnell and Vales 1990).

Efforts have been made to predict canopy cover using a variety of different computer based models. The Forest Vegetation Simulator (FVS), also known as the Prognosis model for stand development, is an individual tree, distance independent growth and yield simulator developed by the USFS (Stage 1978). It is capable of predicting overstory and understory canopy development (Moeur 1985). This model is of potential benefit to foresters and land managers because it predicts canopy development over time, and there is no cost to obtain this software since it is in the public domain. Since it has such potential, this study was conducted to ground-truth the model and develop correction factors to calibrate it. Canopy cover was defined and measured as (i) the percent of ground covered by the downward projection of the tree crown (including within crown gaps and dead biomass) in the shape of a convex polygon, and (ii) as the percent of ground covered only by the *living* crown of a tree, excluding within crown gaps and dead biomass. The moosehorn and the densitometer were used to assess the model under both definitions.

Objectives

1. To compare the mean percent canopy cover measured with a moosehorn and densitometer for each definition of canopy cover (live crown, convex polygon).

2. To compare the percent canopy cover measured by the moosehorn and densitometer with that obtained from FVS projections for each two definitions of canopy cover (live crown, convex polygon).

3. To compare the mean percent canopy cover measured by the moosehorn and densitometer with that obtained from aerial photograph interpretation.

4. To compare the mean percent canopy cover obtained from aerial photographs with that estimated from the FVS projections.

5. To compare the mean percent canopy cover estimated from FVS (v.6.2) which accounts for crown overlap with those estimated from an earlier version FVS which does not account for crown overlap.

6. If FVS (v.6.2) is unreliable in predicting percent canopy cover, develop a series of regression equations to calibrate the model (based on covertype).

The specific hypotheses used to meet these objectives are:

1. H_0: the population mean percent cover (moosehorn) = the population mean percent cover (densitometer)*
   H_1: the population mean percent cover (moosehorn) ≠ the population mean percent cover (densitometer)*

2. H_0: the population mean percent cover (moosehorn & densitometer) = the population mean percent cover (air photo)*
   H_1: the population mean percent cover (moosehorn & densitometer) ≠ the population mean percent cover (air photo)*

3. H_0: the population mean percent cover (moosehorn & densitometer) = FVS canopy cover predictions*
   H_1: the population mean percent cover (moosehorn & densitometer) ≠ FVS canopy cover predictions*

* for both definitions of canopy cover

4. H_0: the population mean percent cover (aerial photos) = FVS canopy cover predictions
   H_1: the population mean percent cover (aerial photos) ≠ FVS canopy cover predictions

Literature Review

Instruments

The moosehorn was developed in Canada to aid in correlating actual cubic timber volume on measured plots with estimated volume from aerial photographs (Garrison 1949; Bonner 1967). The moosehorn is a handheld, optical instrument, which uses a mirror to vertically project the image of a dot grid onto the canopy above (operating like a periscope). The number of dots that fall onto the canopy out of the total possible number of dots (n = 25) yields the percent cover (Bonner 1967). Only the central dot is projected upwards (vertically), while the remaining dots are projected at angles ranging from 1.8 to 5.1 degrees. Bunnell and Vales (1990) concluded that altering the angle of the projection (through the center unbiased dot) beyond 7.2 degrees resulted in statistically significant bias. When used properly, the widest angle attainable by the moosehorn is 5.1 degrees, thereby making the moosehorn a relatively unbiased instrument to measure canopy cover (Bonner 1967, Bunnell and Vales 1990).

The densitometer is a handheld, optical instrument, which uses a mirror to vertically project the image of a single dot onto the above canopy. A major limitation with a single point estimate is that a number of observations must be taken to obtain accurate estimates of percent cover. Johansson (1985, 1996) recommends 50-200 points per 0.1 ha, while Laymon (1988, as cited in Ganey and Block 1994) recommend at least 20 points per

0.1 ha. The accuracy of any instrument using a single point estimate depends on the skill of the observer, the overall structure of the stand, and the number of points per unit area (Johansson 1985, Bunnell and Vales 1990). Neither the moosehorn nor the densitometer is recommended for estimating canopy cover in multistory stands due to problems associated with delineating canopy strata and obstructive understory vegetation (Bonner 1967; Bunnell and Vales 1990; Coates 1995).

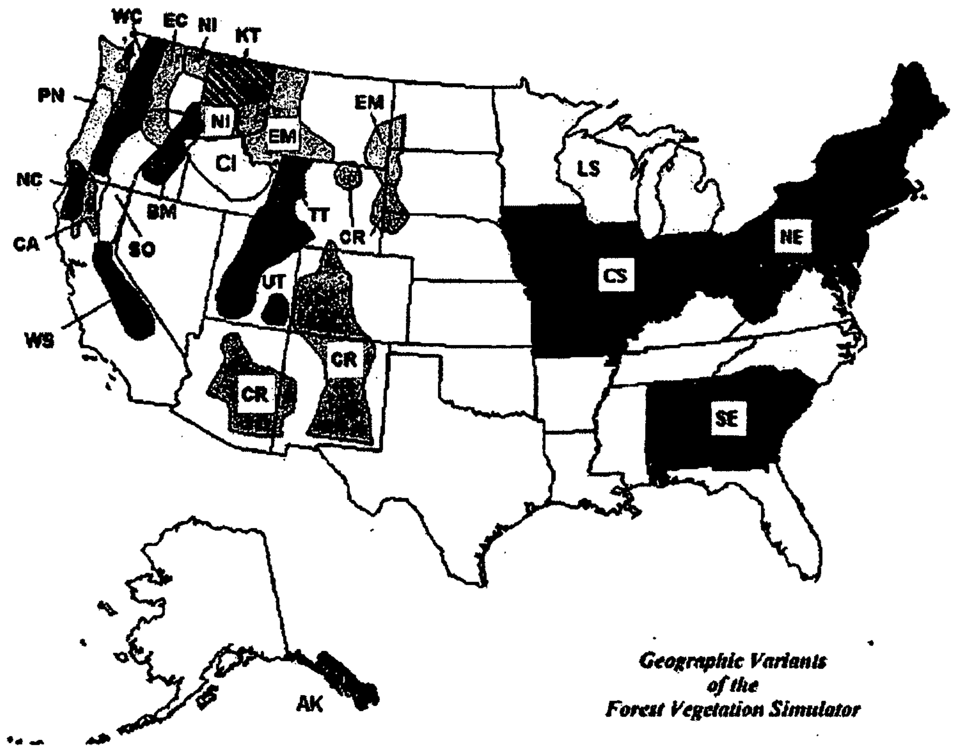
Aerial photographs have been valuable tools in estimating canopy cover over large areas ever since their inception during the 1950's (Hanks and Thomson 1964; Moessner 1964; Wert and Wickman 1970). However, cover estimates from aerial photos are only useful at the resolution at which the photos are taken, and thus, canopy gaps within individual tree crown may be missed (Avery and Burkhart 1994). Additionally, meteorological conditions and phenology may impede the acquisition of photos (Avery and Burkhart 1994). Once obtained, there are a number of techniques available to determine percent canopy cover for a given area which include developing localized density scales, dot grids, and a comparative technique based on the Bitterlich principle (Winterberger and Larson 1988).

Canopy cover for stands with multiple canopy layers may be difficult to determine by aerial estimates if only the dominant and codominant trees are visible. Early studies examining the correlation between ground and aerial observations by Bonner (1968) concluded that the degree of correspondence between the moosehorn and aerial photo estimates of percent cover depends on the resolution of the aerial photo and the skill of the interpreter. Wert and Wickman (1970) concluded that there were no significant differences between aerial and ground estimates of canopy cover. Although aerial photographs typically cover more extensive land areas in less time than ground estimates, fine scale details are lost.

The Forest Vegetation Simulator

The Forest Vegetation Simulator (FVS) is a distance-independent, individual tree growth and yield model developed by the USFS (Stage 1973). The Prognosis model for stand development was the original model that evolved into the Forest Vegetation Simulator. Stage developed Prognosis for use in the Inland Empire area of Idaho and Montana. In the early 1980s, the National Forest Timber Management Staff selected the individual-tree, distance-independent model form as the nationally supported framework for growth and yield modeling. The Timber Staff incorporated the Prognosis modular structure and capabilities into the national model framework. This model framework is the Forest Vegetation Simulator, or FVS. The Forest Vegetation Simulator (FVS) has several components working together to simulate forest growth under various management actions. There are three main growth components of the FVS: a large tree model, a small-tree model, and an establishment model. FVS treats a stand as the population unit, using forest inventory or stand examination data to project the stand (http://www.fs.fed.us/fmsc, April 2000). FVS is also capable of modeling a number of ecologically significant stand attributes, such as the effects of forest fires, percent canopy cover, spruce budworm damage, and the effects of dwarf mistletoe, on stand development. There are currently 20 geographic variants of FVS for the United States (Figure 4) with all of them capable of modeling overstory canopy cover. Only the NI variant currently models understory development through the use of the COVER and SHRUBS extension model (Moeur 1985).

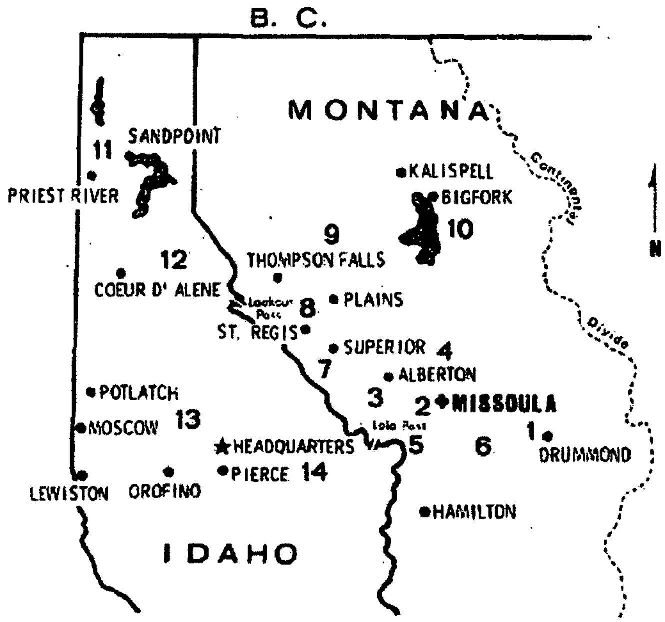
Figure 4. Geographic variants of the Forest Vegetation Simulator.



(Taken from http://www.fs.fed.us/fmsc/fvs_variants, April 2000)

In 1978, tree crown widths of more than 800 trees were measured at 14 sites in northern Idaho and northwestern Montana (Figure 5) to develop equations to predict crown weight and crown bulk density (Brown 1978) for the NI variant of FVS. One measurement taken in the field was individual tree crown width. The live crown of each sample tree was visually divided up into 2 or 3 separate sections depending on branch width. Tree crown width was taken for each section (average of two perpendicular measurements taken at the bottom of a crown section). In 1985, 370 trees from that data set were selected to develop logarithmic regression equations to predict crown width, to ultimately estimate canopy cover, for 11 conifer species of the Inland west (Table 1)(Moeur 1981, 1985). For each sub-sampled tree, a crown width was determined by averaging all of the crown widths for each section. FVS defines canopy cover as the percent of ground covered by the downward projection of the tree crown (Moeur 1985).

Figure 5. Geographic distribution of original cover measurements



(Taken from Brown 1978)

Table 1. Species recognized in the NI variant of FVS

Common name	Scientific name	code
Douglas-fir	Pseudotsuga menziesii	DF
Engelmann Spruce	Picea engelmannii	ES
Grand fir	Abies grandis	GF
Lodgepole pine	Pinus contorta	LP
Ponderosa pine	Pinus ponderosa	PP
Subalpine fir	Abies lasiocarpa	AF
Western larch	Larix occidentalis	WL
Western hemlock	Tsuga heterophylla	WH
Western redcedar	Thuja plicata	WC
Western white pine	Pinus monticola	WP
Whitebark pine	Pinus albicaulis	BP

(Modified from Moeur 1981)

For trees < 3.5" in diameter at breast height, tree height, crown length and stand basal area were used as independent variables in the regression equation (Eq. 1) for each species. For trees ≥ 3.5" dbh, species, height, diameter, and crown length were used as independent variables in the regression equation for each species (Eq. 2) (Moeur 1985).

Eq. (1): For trees < 3.5" dbh:

$$(\ln)\text{crown width} = b_0 + b_1\ln(\text{height}) + b_2\ln(\text{crown length}) + b_3\ln(\text{BA})$$

Eq. (2): For trees ≥ 3.5" dbh:

$$(\ln)\text{crown width} = b_0 + b_1\ln(\text{diameter}) + b_2\ln(\text{height}) + b_3\ln(\text{crown length})$$

Individual tree crown area is computed as the area of a circle with diameter equal to predicted crown width (Figure 6). The regression parameters for the intercept and height are species specific (Moeur 1985).

Figure 6. Downward projection of a tree crown as calculated by FVS

$\text{Area} = 3.1416*r^2$

where r is estimated using species specific logarithmic linear regression equations

Stand canopy closure is computed as:

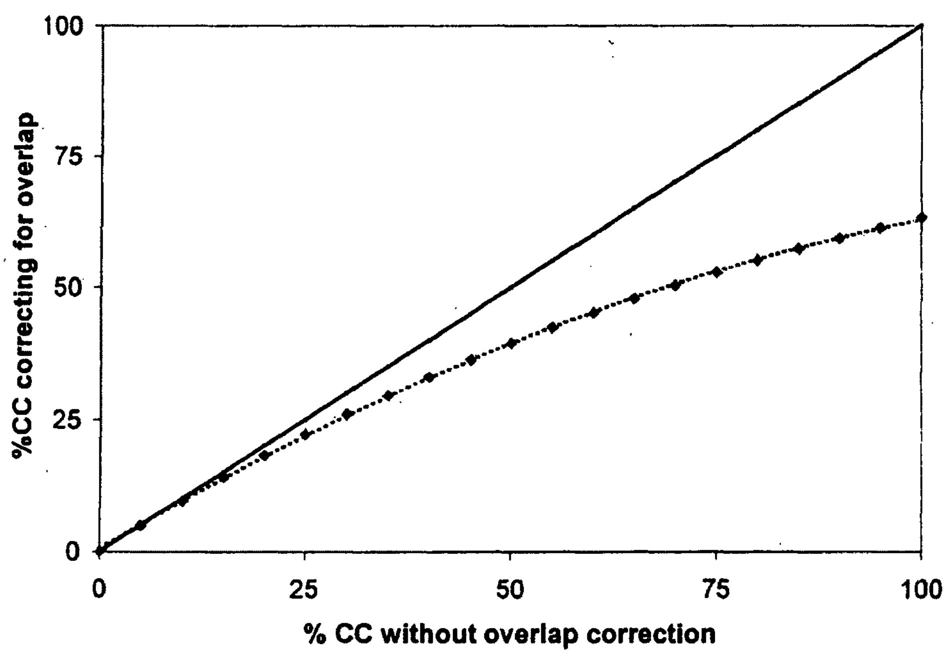
$$\text{Eq. (3): Canopy closure} = \frac{\Sigma \text{ of tree crown areas ft}^2}{43{,}560 \text{ ft}^2/\text{acre}} \times 100 \text{ percent}$$

(Moeur 1985). It is possible to get values greater than 100% when using the above formula. To account for overlapping crowns, Crookston and Stage (Crookston and Stage 1999) developed a correction factor to account for crown overlap. The correction is based on the theory of geometric probability for randomly located figures on a plane (Crookston and Stage 1999). The corrected canopy cover is calculated as:

$$\text{Eq. (4): Corrected canopy cover} = 100[1 - \exp(-.01C')]$$

Where C' is the uncorrected canopy cover from Eq. (3). This correction is greatest at higher levels of canopy cover (Figure 7).

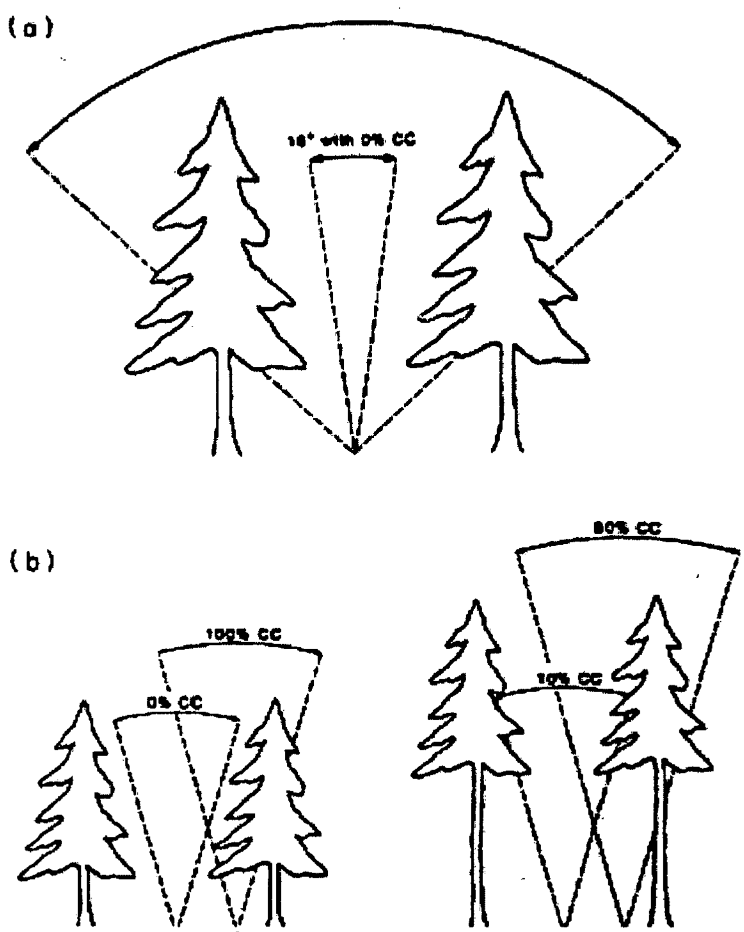
Figure 7. Relationship between FVS versions by accounting for crown overlap (dotted)



Previous comparisons of canopy cover measurements

The spherical densiometer, patterned after one proposed by Robinson (Lemmon 1956), is a handheld instrument that uses a convex or concave 2.5" mirror to estimate canopy cover. The area that is sampled depends on the angle of view, the height to the base of the live crown, and the height from which the angle is projected (Bunnell and Vales 1990) (Figure 8, Table 2).

Figure 8. Angle of view for a spherical densiometer



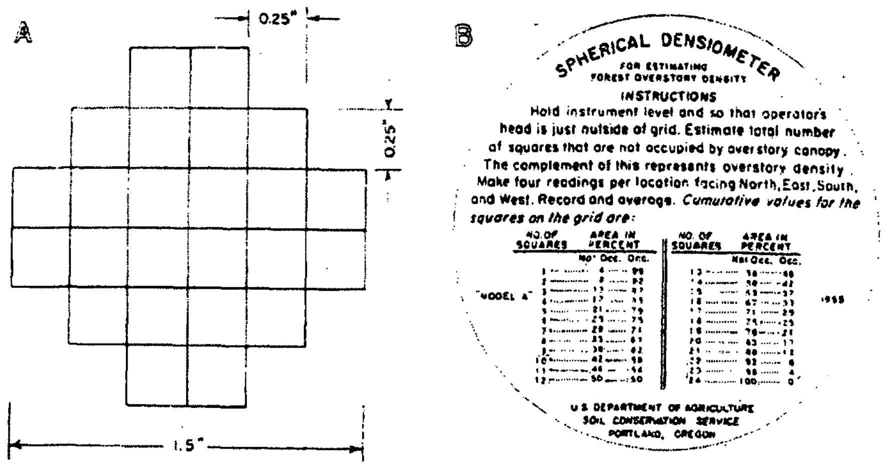
(Taken from Bunnell and Vales 1990)

Table 2. Diameter of sampled canopy area for different views and canopy layers

angle	canopy height	diameter of area projected (ft)	angle	canopy height	diameter of area projected (ft)
6	40	4.19	60	40	46.19
	50	5.24		50	57.74
	60	6.29		60	69.28
	70	7.34		70	80.83
	80	8.39		80	92.38
	90	9.43		90	103.92
	100	10.48		100	115.47
	120	12.58		120	138.56
	130	13.63		130	150.11

The convex densiometer has an angle of projection of approximately 60 degrees (Bunnell and Vales 1990) and uses an etched grid of twenty-four squares, each 0.25 $in.^2$, to estimate canopy cover (Lemmon 1956, 1957). One may calculate canopy cover one of three ways: i) count the number of intersecting grid corners upon which there is canopy coverage, divide that number by 37 (the total number of intersecting points) then multiply it by 100; ii) estimate the total number of squares not occupied by canopy cover, then look at the table of canopy cover values associated with the densiometer, or iii) the observer may visualize four equally spaced dots within each box, then count the number of dots that are covered by the canopy (each dot would represent 1.042%) (Lemmon 1956, 1957) (Figure 9). Coates (1995) observed that there were no significant differences between using the intersecting points or in visualizing four equally spaced dots.

Figure 9. Schematic and directions for using a densiometer

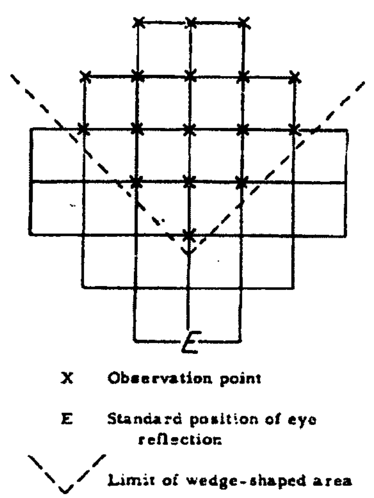


(Taken from Lemmon 1957)

Typically, four measurements are taken per plot, one in each of the cardinal directions from either the same point (Lemmon 1956; Coates 1995) or from a set distance from plot center (Strickler 1959). Strickler (1959) and Griffing (as cited in Cook and others 1995) recommend using a tripod to further reduce bias. The concave densiometer estimates canopy cover essentially the same way; however, the area sampled is substantially less than the convex densiometer because the angle is approximately 30 degrees, and the image is inverted (Cook and others 1995). Lemmon (1956, 1957) reported no statistical significance between observers (with both types of densiometers) and states that for stands with a density of over 60%, the densiometer is accurate to +/- 5%; alpha = .01 (Lemmon 1956, 1957). In contrast, Vales and Bunnell (1988) showed significant differences between observers, concluding that training and experience are necessary for use of the densiometer. Studies have also shown significant differences between the two densiometers across different stand densities (Cook and others 1995).

Two problems are encountered when using the spherical densiometers to estimate canopy cover. The first problem occurs because four densiometer readings are taken per plot; one in each of the cardinal directions. The area of the canopy that is reflected in the mirror depends on the distance between the densiometer and the lower bound of the canopy layer (Figure 8). At low canopy heights, and keeping the location of readings constant, the projected areas overlap, whereby double counting of points occurs. Strickler (1959) proposed a modification to the densiometer to counter this problem. Using only 17 intersecting points of the upper portion of the sphere (in a wedge-shape) eliminates this multiple counting of points (Figure 10). Though acknowledged in a number of studies, this modification has not frequently been used in field measurements (Bunnell and Vales 1990; Coates 1995).

Figure 10. Adjustment offered by Strickler for use with the spherical densiometer



(Taken from Strickler 1959)

The second problem in using densiometers that occurs is from using oblique angles to estimate canopy cover. Viewing the canopy as a layer, trigonometry elucidates that the distance through the canopy that the image is projected is greatest at the periphery of the mirror, and least at the center. Bunnell and Vales (1990) observed that viewing angles less than 30 degrees resulted in relatively unbiased results. The convex and concave densiometers have viewing angles of 60 degrees and 30 degrees respectively. With Strickler's modification, the angles increase to 80 degrees and 120 degrees, respectively (Cook and others 1995). Therefore, the modification proposed by Strickler still resulted in densiometer bias (Cook and others 1995).

Use of the convex densiometer as put forth by Lemmon and Strickler results in overestimation of 30-40% (Cook and others 1995). An understory comprised of high brush or many small trees further limits the use of the densiometer by partially or completely obscuring the above canopy image (Vales and Bunnell 1990; Coates 1995). Consensus among observers indicates that there is some bias associated with the densiometer. Further comparative analysis between cover estimates is difficult because some observers may count any foliage or branch as canopy regardless of size or vigor, while others may be selective with their definition of canopy (Ganey and Block 1994). Spherical densiometers have been shown to result in higher estimates of canopy cover than the moosehorn (Vales and Bunnell 1990; Cook and others 1995) and vertical tube (Ganey and Block 1994).

Vora (1988) showed that the densiometer and ocular estimates of canopy cover did not differ significantly. At higher levels of canopy density, the densiometer was found to yield differing results than both the vertical tube and moosehorn (Vales and Bunnell 1990; Coates 1995). This may be a result of the bias inherent at the periphery of the mirror. Neither the moosehorn nor the densiometer is recommended for estimating canopy cover in multistory stands (Bonner 1967; Bunnell and Vales 1990; Coates 1995).

Ocular estimates of canopy cover entail an observer looking up and estimating what percentage of the overstory above that point is covered by canopy. No instrumentation is used but training is required to obtain accurate estimates (Vales and Bunnell 1988).

A large degree of inter-observer variation has been shown to exist for the spherical densiometers, the moosehorn (Vales and Bunnell 1988; Cook and others 1996) and the vertical tube (Ganey and Block 1994). Perhaps this can be attributed in some part to the sampling methods researchers have used in the past. In contrast, Lemmon (1956) found no inter-observer variation for the spherical densiometers, and Vora (1988) found no inter-observer variation for the densiometer and ocular estimates of canopy cover.

A comparison of research techniques follows and is summarized in table three. Lemmon (1956, 1957) and Bonner (1967) did not publish enough information on their study areas to offer meaningful comparisons between their studies. Garrison (1949) sampled a 173-acre ponderosa pine stand with ten, 0.25-acre plots, taking fifteen moosehorn readings per plot. Strickler (1959) used seven clusters of four plots in ponderosa pine/Douglas-fir stands taking one reading in each cardinal direction per plot. Johansson (1985) used eight, 0.1 ha. rectangular, plots representing two thinning treatments, and estimated cover with 50, 100, and 200 points per plot. Vora (1988) established 330 (~0.05acre) plots along 33 transects through a ponderosa pine forest type in the Blacks Mountain Experimental forest, California. Ocular estimates of cover were made on each plot followed by estimates made using the spherical densiometer 1-year later without using Strickler's method.

Vales and Bunnell (1988, 1990) established twenty-three, 2 x 10m plots (along slope contours) to encompass a range of canopy cover values. Cover measurements were taken at 1-meter intervals along each edge and along a centerline (n = 23). Photographs using 50mm and 100mm lenses were taken at each corner and at the 3-meter and 7-meter mark on each side (n = 8), and hemispherical photographs were taken along the centerline of each plot at the 3-meter and 7-meter marks (n = 2). They too did not use the Strickler correction.

Ganey and Block (1994) used sixty, 0.1 ha plots in a ponderosa pine stand in Arizona. A plot was established, a transect run through it, and measurements were made along this transect at five points for the densiometer (Dealy 1960) and 36 points for the vertical tube. The Strickler modification was not used. Coates (1995) used 70 variable radius plots representing 11 stands in northeastern Washington State. Canopy estimates were made with the moosehorn and the spherical densiometer, one reading per plot. The Strickler modification was not used.

Cook and others (1996) used six, 150m x 150m treatment areas of varying canopy density (3 harvested and 3 unharvested) with 9 macroplots established per treatment area. An additional three macroplots were established in a low tree density area. For each macroplot, one reading of the convex spherical densiometer was taken using Strickler's modification. Sixteen moosehorn readings were taken per plot, and four concave spherical densiometer readings were taken per plot using Strickler's modification. Though Strickler's modification was used, the recommended four readings per plot with a convex densiometer (one in each cardinal direction) were not taken. This may have possibly contributed to the biased estimates observed in this study. Johansson (1996) used eight, 0.1 ha plots with 200 points/plot to test for vertical tube accuracy (Table 3).

Despite the abundance of techniques to estimate current canopy cover, predicting future canopy conditions is required for landscape level management. Natural resource managers are increasingly depending upon growth simulators and derived models to assist in the management of a number of stochastic ecological characteristics, including canopy cover (Nelson and Buech 1996; Mitchell and Popovich 1997). The dependent variables used in these models are typically stand attributes that show up in inventory data. The stand attribute that is most strongly correlated with canopy cover is basal area/acre (Cade 1997; Mitchell and Popovich 1997). Mitchell and Popovich (1997) showed a quadratic relationship between basal area and canopy cover up to a canopy density of 60%. The increasing demand for management over large geographic areas has led to the creation of a number of computer models to predict stand conditions (Biging and Wensel 1990; Macguire and others 1991; Teck and others 1996). Given the extreme degree of environmental, spatial and genetic variation inherent in the landscape, it is imperative that the growth predictions correspond to the conditions that currently exist.

Coates (1995) compared ground estimates of canopy cover with those predicted by an unknown variant of FVS. FVS predictions were significantly different from estimates obtained from the convex densiometer but not for the moosehorn. It should be realized however, that the model did not account for canopy overlap. FVS has recently been adjusted to account for canopy overlap. Given the potential extent to which FVS can be used in the management of forest ecosystems, research needs to be done to ascertain the validity of the output and the degree of correlation among other canopy cover estimation techniques.

Table 3. Summary of previous canopy cover comparisons

Researcher	**Year**	**Covertype**	**Plot size**	**Instruments**	**# of obs/plot**	**n (plots)**
Garrison	1949	Ponderosa pine	0.25-acre	moosehorn	15	10
Lemmon	1956	Ponderosa pine	*	concave & convex densiometers	4	28
Lemmon	1957	*	*	concave & convex densiometers	1	*
Strickler	1959	Ponderosa pine/ Douglas-fir	*	concave & convex densiometers	4	28
Dealy	1960	Mt. mahogany/ w. juniper	transects	convex densiometer	20	8
Bonner	1967	various	0.23-acre	moosehorn /projected dot	80/1000	12
Bonner	1968	various	*	moosehorn /air photos	*	36
Johannson	1985	Spruce	0.1ha	vertical tube	50,100,200	*
Vora	1988	Ponderosa pine	~0.05-acre	convex densiometer / ocular	1	330
Vales and Bunnell	1988	Hemlock/ Douglas-fir	2mx10m	moosehorn /gimbel sight / convex densiometer /ocular / photos	33 each 2/8 for photos	23
Bunnell and Vales	1990	Hemlock/ Douglas-fir	2mx10m	moosehorn/ gimbel sight / convex densiometer / ocular / photos	33 each 2/8 for photos	23
Ganey and Block	1994	Ponderosa pine	.25-acre	Vertical tube / Densiometer	36/5	60
Cook et. al.	1995	various	0.1-acre	concave & convex densiometers/moosehorn	4 / 1/ 16	39
Coates	1995	various	variable	convex densiometer / moosehorn / ceptometer/FVS	4 / 1 / 16	71
Johannson	1996	Birch	0.1-ha	vertical tube	200	8

Chapter II.

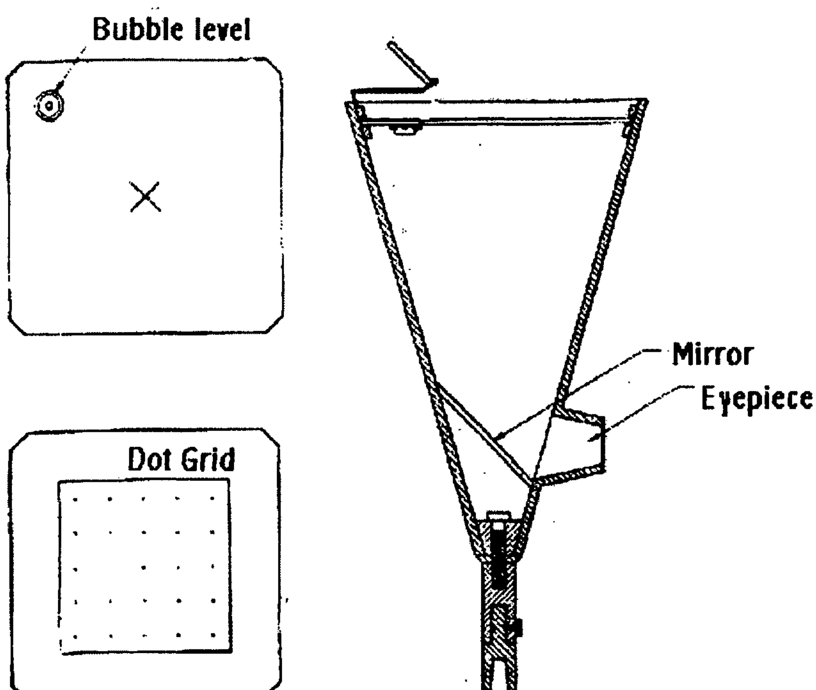
Instruments and Methods

Field Instruments:

Moosehorn

The moosehorn is a handheld optical instrument that uses a 45-degree mirror to reflect the image of the canopy through a dot grid. The observer looks through an eyepiece and then counts the number of dots, out of 25, that fall onto the above canopy. The grid is composed of 25 equally spaced dots with lines connecting the points resulting in a 4x4 grid, each square 0.25". There is a small bubble level to keep the observer looking at a perfect 90-degree angle (Figure 11). The instrument used in this study is constructed out of PVC pipe and is approximately 8" in length by 2" in width.

Figure 11. Moosehorn schematic



(Modified from Garrison 1949)

Densitometer

The densitometer is a handheld optical instrument that uses a 45-degree mirror to reflect the image of the canopy through a single point. The observer looks through an eyepiece and then determines if the point hits the canopy. The densitometer has two internal bubble levels to keep the observer looking at 90-degree angles. The densitometer is essentially a vertical tube but with internal levels.

Methods:

Study sites:

Two study sites were chosen, one on Flathead National Forest in northwestern Montana, and one on Lubrecht Experimental Forest (LEF), Montana. Stands were selected on the Flathead National Forest due to the willingness of federal forestry personnel to establish plots for this research. Stands on the LEF were selected because they contained permanent research plots that had been recently remeasured, and represented a variety of covertypes and stand densities.

(1) Flathead National Forest, Montana:

The Flathead National Forest is located in northwestern Montana (Figure 12). The location of the study site is Township 25 North, Range 18 West, sections 24 and 25 (Figure 13). The study site is primarily a Douglas-fir (*Pseudotsuga menziesii*) and western larch (*Larix occidentalis*) (DF-WL) covertype but also present are: lodgepole pine (*Pinus contorta*), grand fir (*Abies grandis*), Engelmann spruce (*Picea engelmannii*), paper birch (*Betula papyrifera*), and aspen (*Populus tremuloides*). The understory is composed mostly of Rocky Mt. maple (*Acer glabrum*) and paper birch.

The stands are even-aged, 82 years old, are on gently rolling terrain, and all naturally regenerated following a stand replacement wildfire in 1918. These stands can be characterized as having single strata of canopy cover in the overstory and a single stratum of canopy cover in the understory. The three stands were all thinned to target trees per acre (109 or 222) in the late 1970's. The study site totals 138-acres and surrounds privately owned land (Figure 13). The Bond Creek trail runs through one of the stands. An inventory was conducted in June 1999 using 41 variable-radius plots (BAF 20). Data collected on each individual tree included: species, diameter at breast height (dbh), tree height and crown ratio (subsampled based on diameter class). Aerial photographs taken in 1997 (at a scale of 1:24000) were obtained and USFS personnel ocularly determined percent cover within 10% cover classes for each stand. Canopy cover was measured in mid-October 1999.

Figure 12. Flathead National Forest, MT.

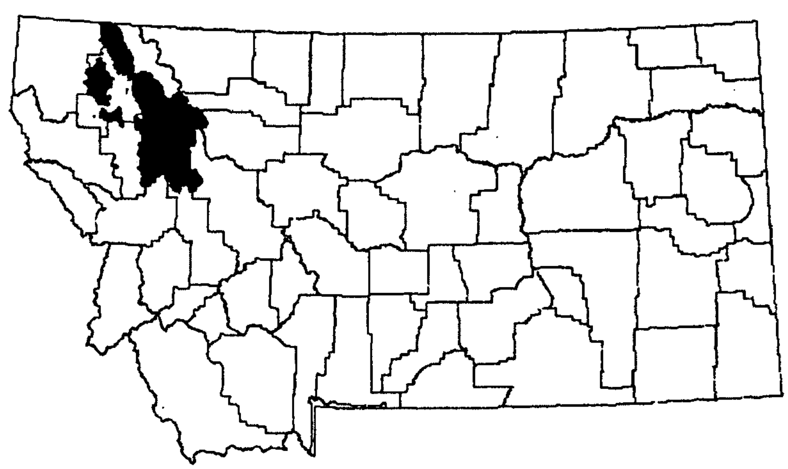
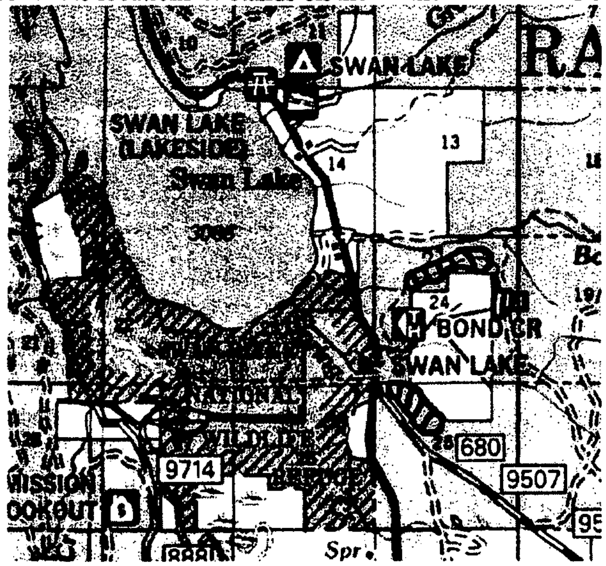


Figure 13. Approximate locations of stands on the Flathead National Forest (hatched)



2. *Lubrecht Experimental Forest, Montana*

The Lubrecht Experimental Forest is a 28,000-acre research facility owned and operated by the School of Forestry, University of Montana. It is located approximately 30 miles northeast of Missoula, MT (Figure 14). In the early 1980's, several levels of growing stock (LGS) units were established to (i) demonstrate different thinning treatments and (ii) serves as a basis for studying stand response to the thinning treatments. Each stand (of homogenous, second growth, unmanaged timber) was subdivided into 4 units of equal size, each of which were thinned to a different mean trees per acre (TPA) target. One stand was treated as a control (no thinning), one stand was thinned to 435 TPA (10'x10' spacing), one stand was thinned to 220 TPA (14'x14' spacing), and one stand was thinned to 110 TPA (20'x20' spacing). In units where a 10'x10' spacing was not possible, due to poor quality of trees or a patchy stand, a "desired marked leave tree" treatment was used. In that instance, crop trees were selected to remain in the stand (Figure 15)(MFCES 1986).

Figure 14. Approximate location of Lubrecht Experimental Forest (LEF), MT (inset).

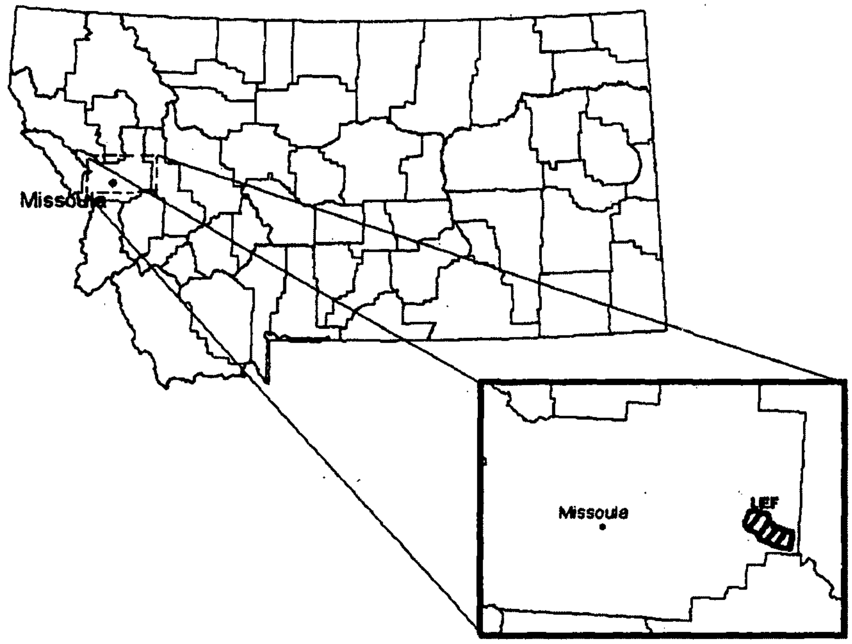
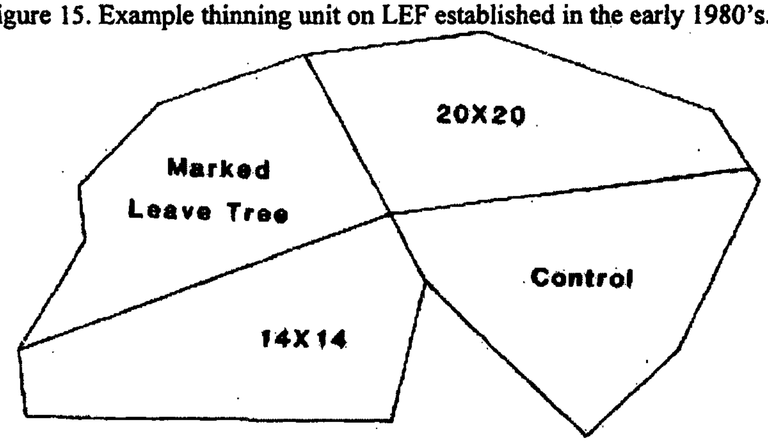


Figure 15. Example thinning unit on LEF established in the early 1980's.

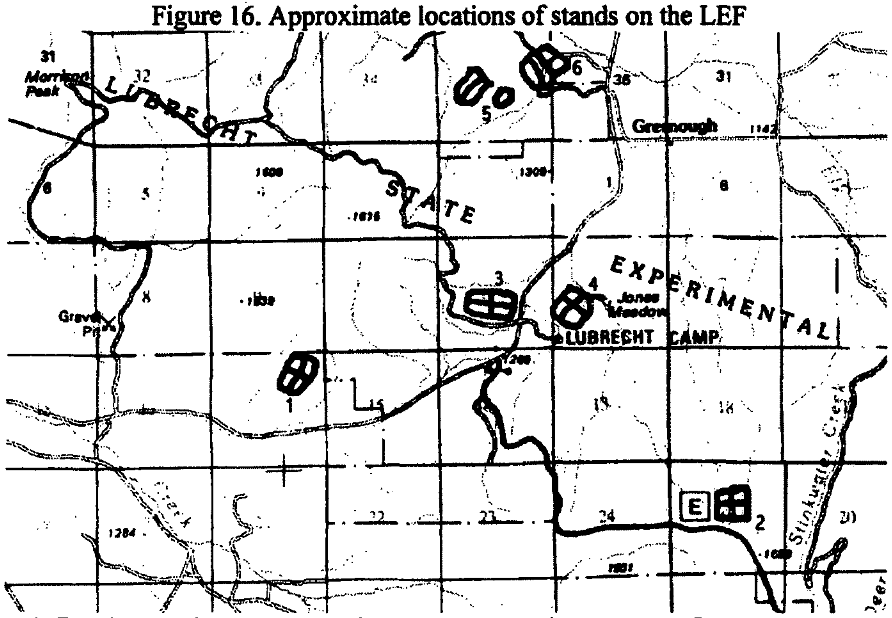


(Taken from MFCES 1986)

Several demonstration units were established on LEF in various timber types representative of western Montana (western larch, ponderosa pine, lodgepole pine, and Douglas-fir/ponderosa pine). In each stand of each unit, a minimum of three 0.1-acre permanent plots were established and inventoried on a regular basis. The stands used in this research project are part of the thinning demonstration project. One stand each of (i) lodgepole pine (LP), (ii) western larch (WL), and (iii) ponderosa pine (PP) covertypes were selected, and 3 stands of a ponderosa pine/Douglas-fir (PP-DF) covertype were selected. This design allowed such variables as site (soils, elevation) and species composition to be held relatively constant while changing only stand density. All of the stands are second-growth timber and naturally regenerated following logging and wildfire in the 1930's.

For the LEF plots (n = 66), electronic copies of 1995 inventory data were obtained. Data collected on each individual tree included: species, diameter at breast height (dbh), tree height and crown ratio (tree height and crown ratios were sub-sampled based on diameter class). Canopy measurements were taken from June through August 1999. Aerial photographs of the study sites, taken in 1996, were obtained and LEF personnel determined percent cover within 10% cover classes in August 1999.

Figure 16. Approximate locations of stands on the LEF



1=Ponderosa pine; 2=W. Larch; 3=Ponderosa pine/Douglas-fir; 4=Lodgepole pine; 5, 6= Ponderosa pine/Douglas-fir

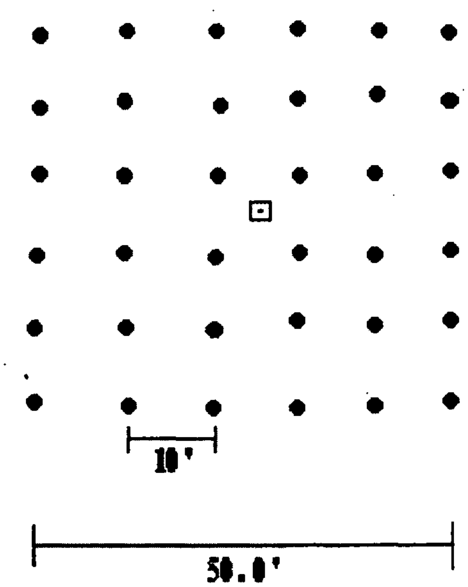
Study Design:

Canopy cover was defined as (i) the percent of ground covered by the "live crown" (green foliage, live branches) of a tree (Figure 2) and (ii) the percent of ground covered by the downward projection of the tree crown. In this research, the downward projection of the tree crown was represented by the shape of a "convex polygon" (the connecting points being the outermost branch tips) not a circle (Figure 17). The rationale for this was that it would be easier to visualize a line connecting two points of a tree crown rather than the arc of a circle, and that tree crowns rarely form a perfect circle.

Canopy cover of dominant and codominant trees (≥ 4.6"dbh) was measured at thirty-six points for each plot (Figure 18), using the moosehorn and densitometer for each definition of canopy cover. Inventory data were then processed through the NI variant of FVS (v. 6.2) to determine percent canopy cover (accounting for crown overlap). FVS projections without accounting for canopy overlap were then calculated to be included in this analysis.

Figure 17. Canopy cover for an individual tree visualizing a convex polygon

Figure 18. Sampling locations per plot



Analysis:

There is an inherent discrepancy between the moosehorn and densitometer in how they estimate mean percent canopy cover. For each of the 36 sample points per plot, the moosehorn obtains a percent value. Therefore, the mean percent canopy cover per plot is the average of these 36 values. However, the densitometer obtains either a "hit" or a "miss" for each of the 36 points, and obtains one mean estimate of percent cover per plot. It is appropriate to used normal-based testing procedures when comparing these instruments if a statistical rule of thumb is applied.

For large n, and π not too near 0 or 1, the distribution of the random variable "y" (% canopy cover) may be approximated by a normal distribution with mean (μ), equal to $n\pi$, and standard deviation (σ) equal to the square root of the quantity $[n\pi(1-\pi)]$. This approximation should only be used when $n\pi \geq 5$ and $n(1-\pi) \geq 5$

(Ott 1993), where n is the number of sample points per plot and π is the percent canopy cover per plot (as a proportion). For this study, based on a sample size of 36 points, it is appropriate to compare the mean percent canopy cover values of these instruments as long as the percent canopy cover per plot is between 14-86%.

Analyses were performed at two spatial scales to determine if there were statistically significant differences in mean canopy cover between all methods. At the plot level, a series of regression equations were developed, with one method of estimating canopy cover used as a dependent variable (y) and another method of estimating canopy cover used as an independent variable (x). For the null hypothesis of no difference to be rejected the intercept, β_0, and slope, β_1, must be significantly different from 0 and 1, respectively. This test was performed using a simultaneous test of significance as described in Draper and Smith (1981). Specifically, the hypothesis is:

$$H_0: (\beta_0, \beta_1) = (0,1)$$
vs.
$$H_1: (\beta_0, \beta_1) \neq (0,1)$$

and is tested by comparing a computed test statistic, Q, to a modified F statistic (which this researcher designates as F'). To reject the null hypothesis, $Q \geq F'$. The test statistic Q, is equal to: $(\beta_0 - b)'\ X'X\ (\beta_1 - b)$, where β_0 is the estimated intercept from the regression, and β_1 is the estimated slope from the regression. The specific matrices are:

$$[\beta_0\text{-b}, \beta_1\text{-b}] \quad \begin{bmatrix} n & \Sigma x \\ \Sigma x & \Sigma x^2 \end{bmatrix} \quad [\beta_0\text{-b}, \beta_1\text{-b}]$$

The test statistic F' is equal to: $ps^2F_{(p,v,1-\alpha)}$, where:

β = hypothesized population parameter
p = the number of regression parameters
s^2 = variance (MSE of regression)
n = number of plots
v = (n - p)
b = regression parameter
α = significance level of test (Bojang 1983)

At the stand level, a One-way ANOVA was performed to determine if there were significant differences in mean canopy cover between methods for each covertype (Table 4). If so, Tukey's Honestly Significantly Difference (HSD) multiple comparisons procedure was used to determine which methods were significantly different from each other. Confusion matrices were developed for agreement assessment between methods based on 20% cover classes.

Table 4. Example ANOVA for stand level analysis (DF-WL covertype)

	Sums of Squares	**df**	**Mean square**	**F**	**p**
CC Method	4469.81	6	744.97	15.76	< .0005
Error	662.00	14	47.29		
Total	5131.81	20			

Chapter III.

Results

Without stratifying by covertype, FVS underpredicted canopy on all plots on both study sites regardless of how canopy cover was defined (Figures 19-30). Mean cover estimates for plots ranged from 30% (FVS v.6.2) to 67.45% (densitometer "polygon") on the LEF, and from 30.1% (FVS v. 6.2) to 71.9% (densitometer "polygon") on the Flathead NF (Table 5).

Figure 19. Canopy cover (live crown) for all plots on the Lubrecht Experimental Forest (n = 66) (PP-DF, LP, PP, WL covertypes)

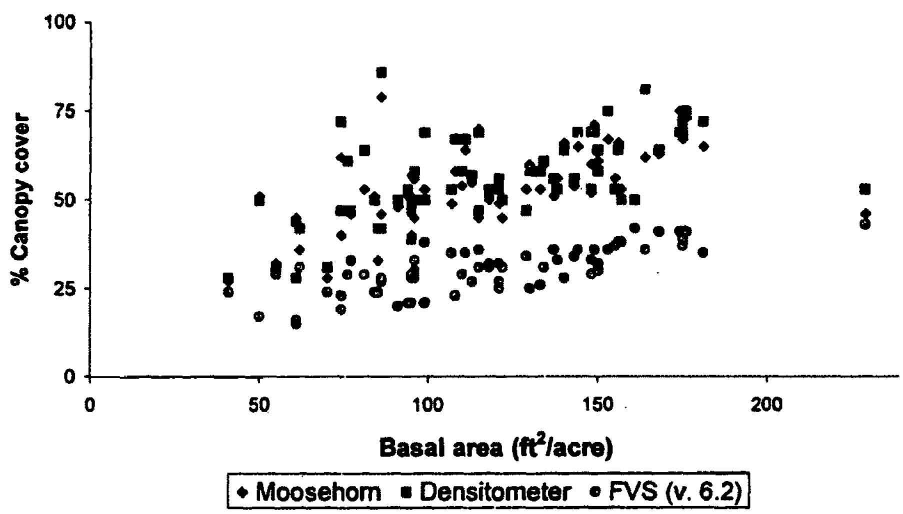


Table 5. Mean percent cover by instrument and study site

Study Site	Method	Mean % Cover	Std. error
LEF (n=66)	Moosehorn (live crown)	54.27	1.41
	Densitometer (live crown)	56.21	1.49
	Moosehorn (polygon)	65.64	1.51
	Densitometer (polygon)	67.45	1.60
	FVS (v 6.2)	30.33	.81
	FVS (v 5.0)	36.59	1.17
Flathead NF (n=41)	Moosehorn (live crown)	59.39	1.80
	Densitometer (live crown)	62.83	1.93
	Moosehorn (polygon)	67.76	1.78
	Densitometer (polygon)	71.93	1.87
	FVS (v 6.2)	30.10	1.20
	FVS (v 5.0)	36.44	1.76

Figure 20. Canopy cover (live crown) of all plots on the Flathead National Forest (n = 41)
(DF-WL covertypes)

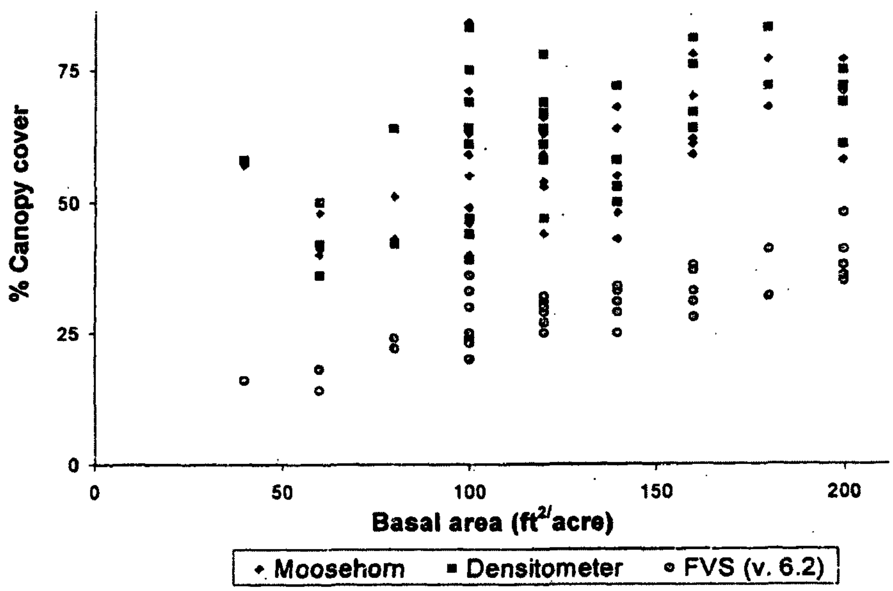


Figure 21. Canopy cover (polygon) for all plots on the Lubrecht Experimental Forest (n = 66)
(PP-DF, LP, PP, WL covertypes)

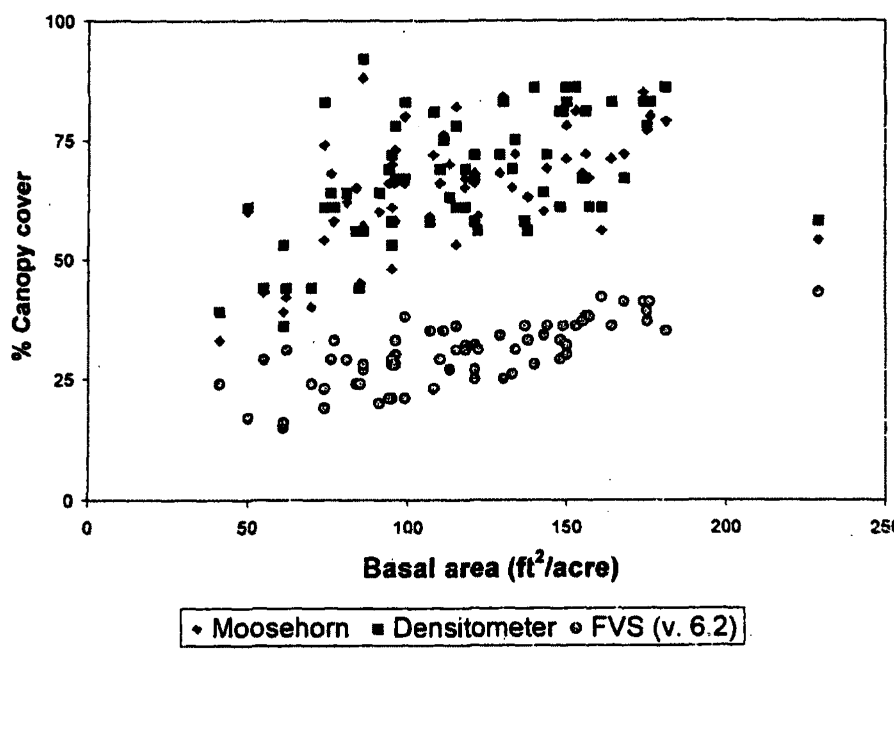


Figure 22. Canopy cover (polygon) of all plots on the Flathead National Forest (n = 41) (DF-WL covertype)

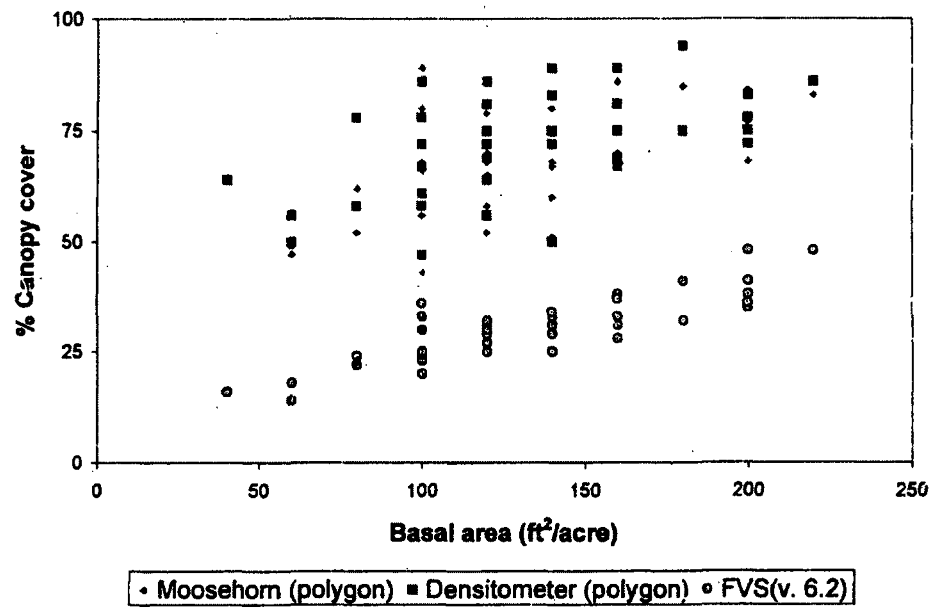


Figure 23. Relationship between the moosehorn (live crown) and FVS (corrected) cover estimates (n=107)

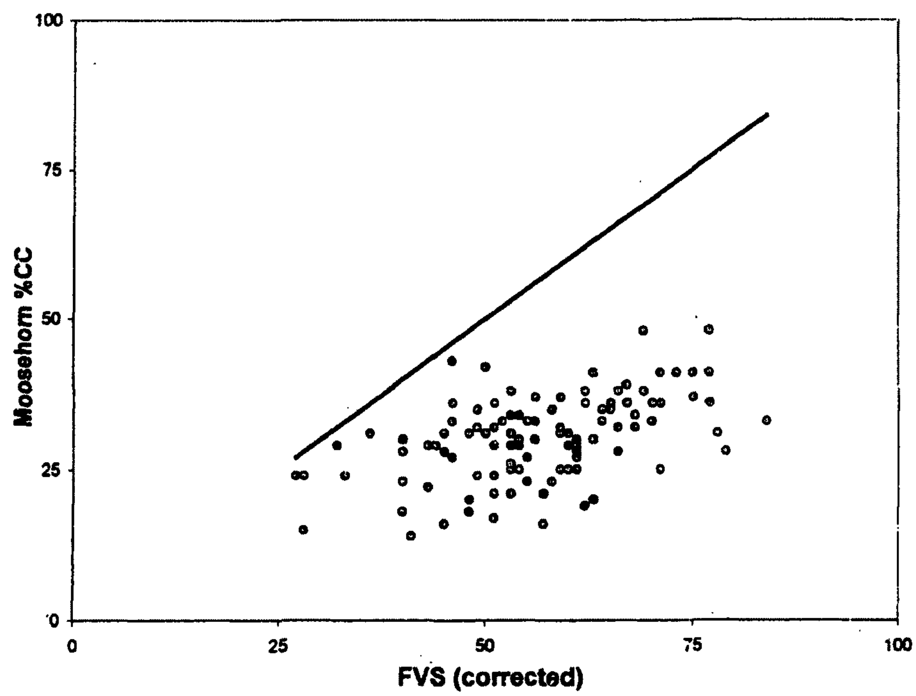
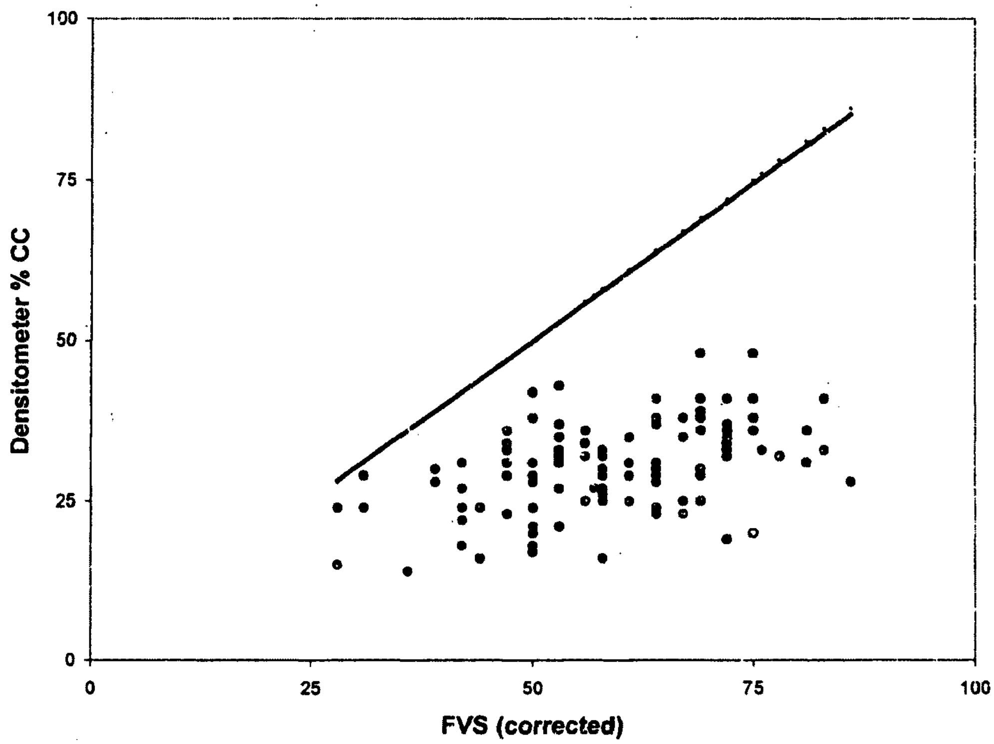


Figure 24. Relationship between the densitometer (live crown) and FVS (corrected) cover estimates



(n=107)

Figure 25. Relationship between the moosehorn (polygon) and FVS (corrected) cover estimates (n=107)

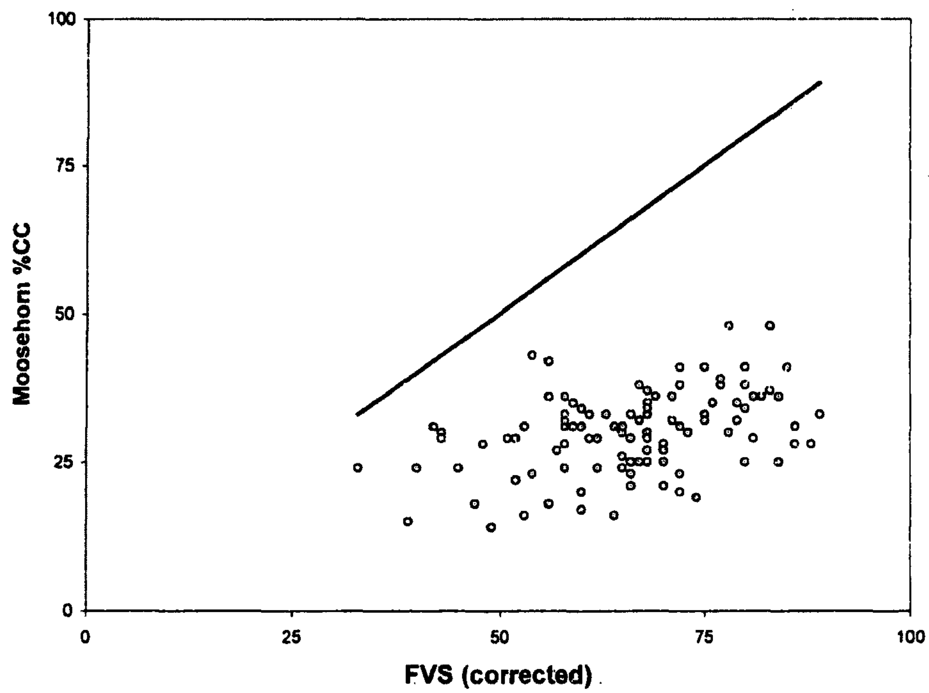


Figure 26. Relationship between the densitometer (polygon) and FVS (corrected) cover estimates (n=107)

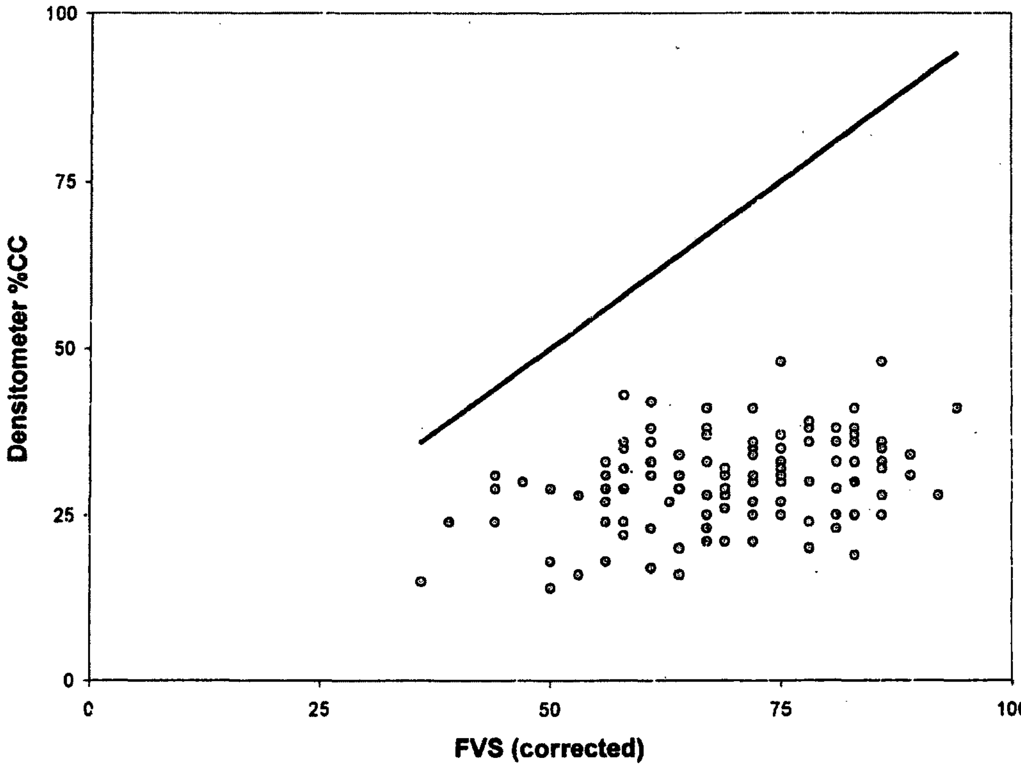


Figure 27. Relationship between the moosehorn and densitometer (live crown) estimates (n=107)

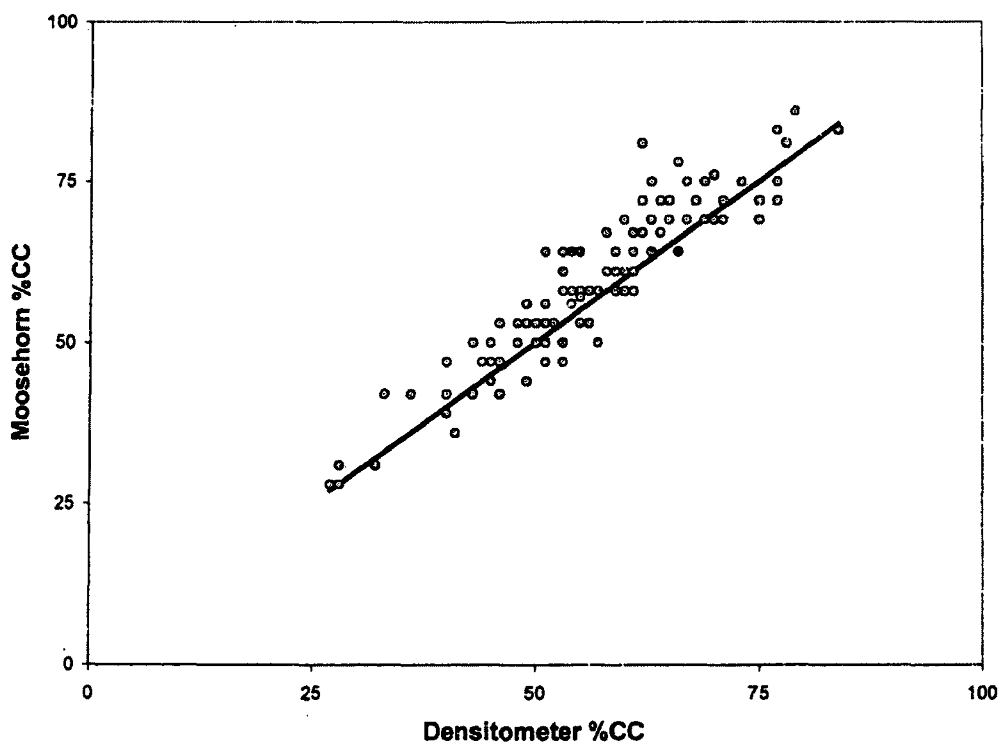
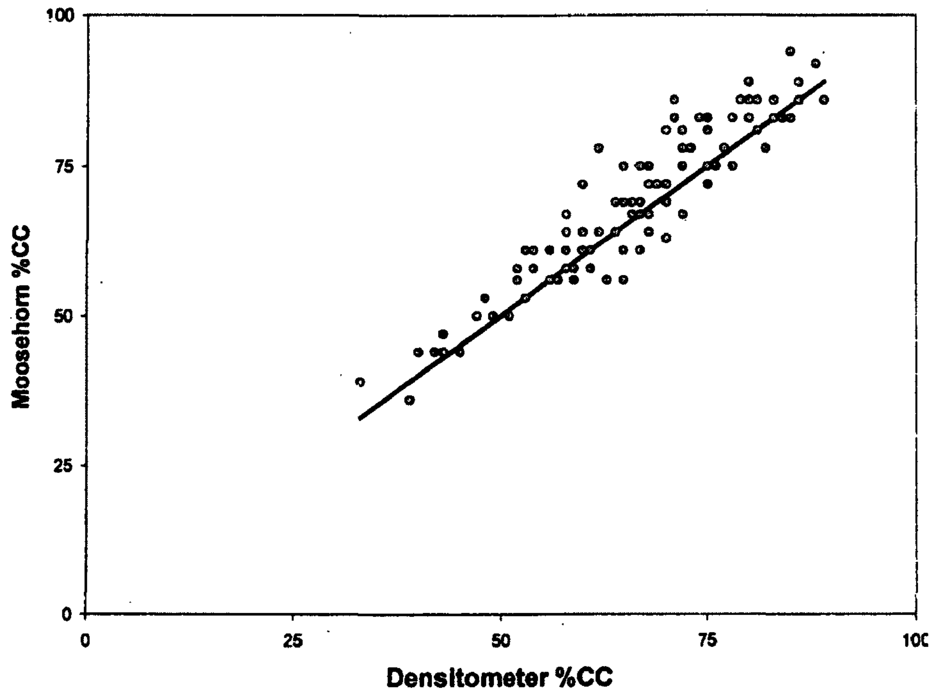


Figure 28. Relationship between the moosehorn and densitometer (polygon) cover estimates (n=107)



The convex polygon definition resulted in higher measures of canopy cover, relative to the live crown definition, on 107 and 103 plots using the moosehorn and densitometer, respectively (Figures 29, 30). The remaining 4 plots had the same values of canopy cover using the densitometer. The differences in mean canopy cover for the moosehorn *between* definitions of canopy cover ranged from 8.36% (DF-WL covertype) to 14.58% (LP covertype), and from 7.83% (WL covertype) to 14.99% (LP covertype) for the densitometer. The differences in mean canopy cover between definitions of canopy cover by covertype group, regardless of instrument used, ranged from 10.58% (WL covertype) to 16.67% (LP covertype).

Figure 29. Canopy cover by definition for the moosehorn (n = 107)

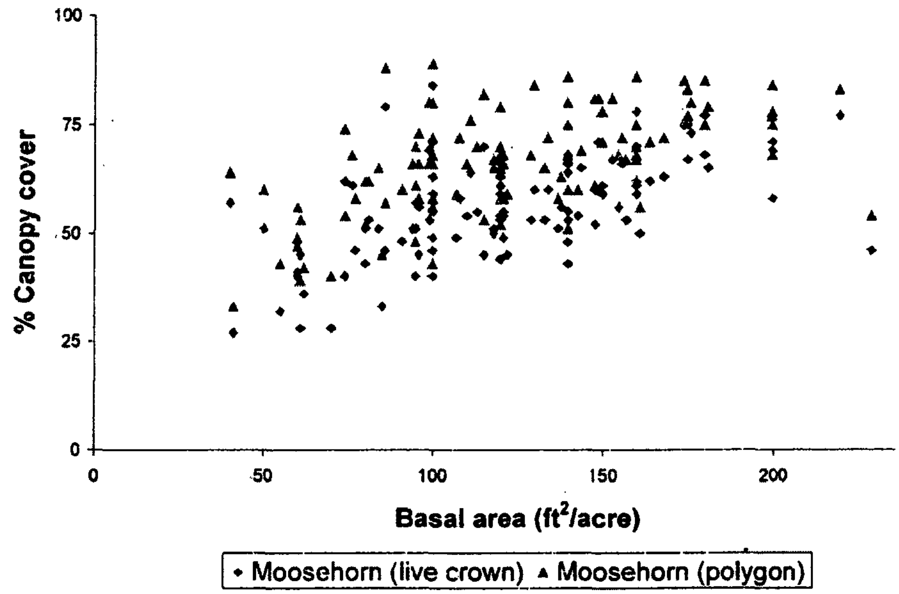
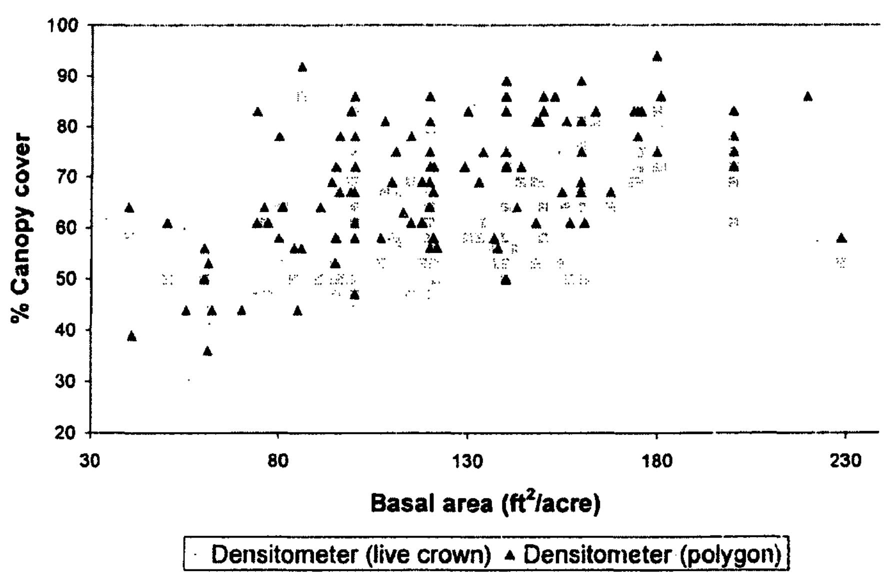


Figure 30. Canopy cover by definition for the densitometer (n = 107)



Confusion matrices:

The typical approach to incorporating canopy cover into forest management is by using 3, 4, or 5 cover classes. Confusion matrices were developed to determine the level of agreement between the various methods within 20% cover classes (Tables 6 –12).

Table 6. Canopy cover classification for all plots (n = 107)

Moosehorn (crown)		Densitometer (crown)				
% cover	0-20	21-40	41-60	61-80	81-100	Agreement (%)
0-20						
21-40		*6*	3			66.7
41-60		1	*46*	12		77.9
61-80			1	*33*	4	86.8
81-100					*1*	100
Agreement (%)		85.7	92	73.3	20	**80.4%**

Table 7. Canopy cover classification for all plots (n = 107)

Moosehorn (polygon)		Densitometer (polygon)				
% cover	0-20	21-40	41-60	61-80	81-100	Agreement
0-20						
21-40		*2*	1			66.7
41-60			*19*	10	1	66.7
61-80			3	*42*	16	68.9
81-100				1	*12*	92.3
Agreement		100	82.6	73.2	41.4	**70.1%**

Table 8. Canopy cover classification for all plots (n = 107)

FVS (v. 6.2)		FVS (v. 5.0)				
% cover	0-20	21-40	41-60	61-80	81-100	Agreement
0-20	*7*	3				70
21-40		*65*	23			73.9
41-60			*7*	2		77.8
61-80						
81-100						
Agreement	100	94.2	76.7	0		**73.8%**

Table 9. Canopy cover classification for all plots (n = 107)

Moosehorn (live crown)		FVS (v. 6.2)				
% cover	0-20	21-40	41-60	61-80	81-100	Agreement
0-20						
21-40	2	*8*				80
41-60	6	49	*3*			5.2
61-80	2	29	5			0
81-100		1	2			0
Agreement	0	9.2	30			**10.3%**

Table 10. Canopy cover classification for all plots (n = 107)

Densitometer (live crown)		FVS (v. 6.2)				
% cover	0-20	21-40	41-60	61-80	81-100	Agreement
0-20						
21-40	2	*5*				71.4
41-60	6	42	*2*			4.0
61-80	2	37	6			0
81-100		4	1			0
Agreement	0	5.7	22.2			**6.5%**

Table 11. Canopy cover classification for all plots (n = 107)

Moosehorn (polygon)		FVS (v. 6.2)				
% cover	0-20	21-40	41-60	61-80	81-100	Agreement
0-20						
21-40	1	*2*				66.7
41-60	6	23	*2*			6.5
61-80	3	52	5			0
81-100		11	2			0
Agreement	0	2.3	22.2			**3.7%**

Table 12. Canopy cover classification for all plots (n = 107)

Densitometer (polygon)		FVS (v. 6.2)				
% cover	0-20	21-40	41-60	61-80	81-100	Agreement
0-20						
21-40	1	*1*				50
41-60	4	18	*1*			4.3
61-80	4	45	4			0
81-100	1	25	3			0
Agreement	0	1.1	12.5			**1.9%**

Plot level differences by covertype:

Douglas-fir/western larch covertype (Flathead NF):

There were significant ($\alpha = 0.05$) differences in the accuracy of all methods in estimating canopy cover (Table 13, see pg. 50)(Figure 20, 22). Mean estimates of cover ranged from 30.1% (FVS v. 6.2) to 71.9% (densitometer "polygon") (Table 14).

Figure 31. FVS predictions with and without accounting for crown overlap (DF-WL covertype)

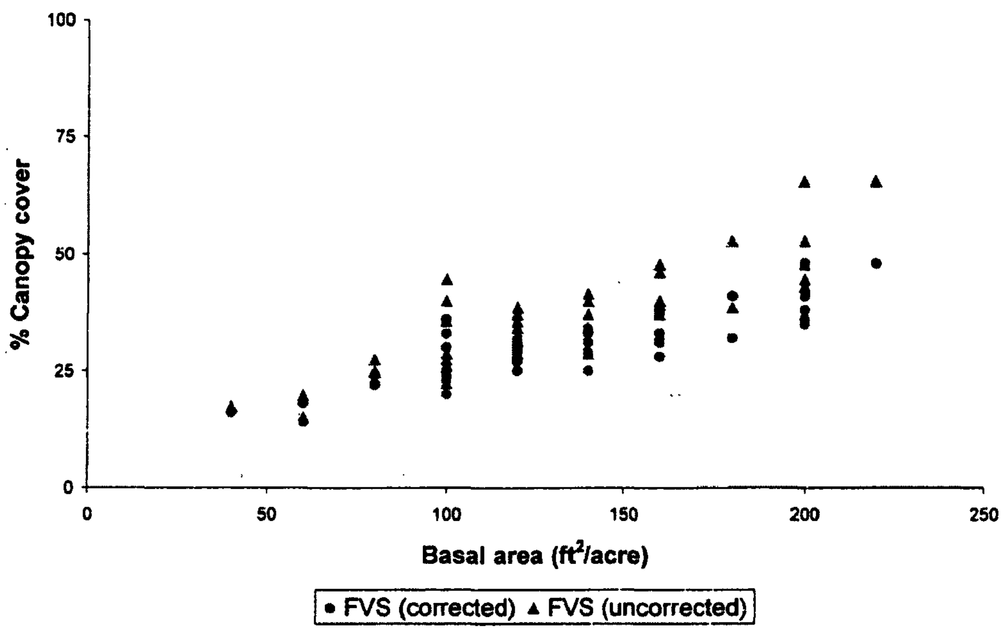


Table 14. Summary statistics by method for the DF-WL covertype

Method	Mean	Standard error
Moosehorn (live crown)	59.39	1.80
Densitometer (live crown)	62.83	1.93
Moosehorn (polygon)	67.76	1.78
Densitometer (polygon)	71.93	1.87
FVS (corrected)	30.10	1.20
FVS (uncorrected)	36.44	1.76

(n=41)

Ponderosa pine/Douglas-fir covertype:

There were no significant ($\alpha = 0.05$) differences in the accuracy between the moosehorn and densitometer for either definition of canopy cover. There were significant differences in the accuracy of all methods in estimating canopy cover (Table 15, see pg. 50, Figures 32, 33, 34). Mean cover estimates ranged from 33.4% (FVS v. 6.2) to 66.3% (densitometer "polygon)(Table 16).

Table 16. Summary statistics by method for PP-DF covertype (n=30)

Method	Mean	Standard error	Standard deviation
Moosehorn (live crown)	54.77	2.00	10.96
Densitometer (live crown)	56.43	2.10	11.50
Moosehorn (polygon)	64.83	1.99	10.92
Densitometer (polygon)	66.27	2.13	11.67
FVS (corrected)	33.40	1.13	6.20
FVS (uncorrected)	41.10	1.68	9.21

Figure 32. Canopy cover (live crown) for the PP-DF covertype

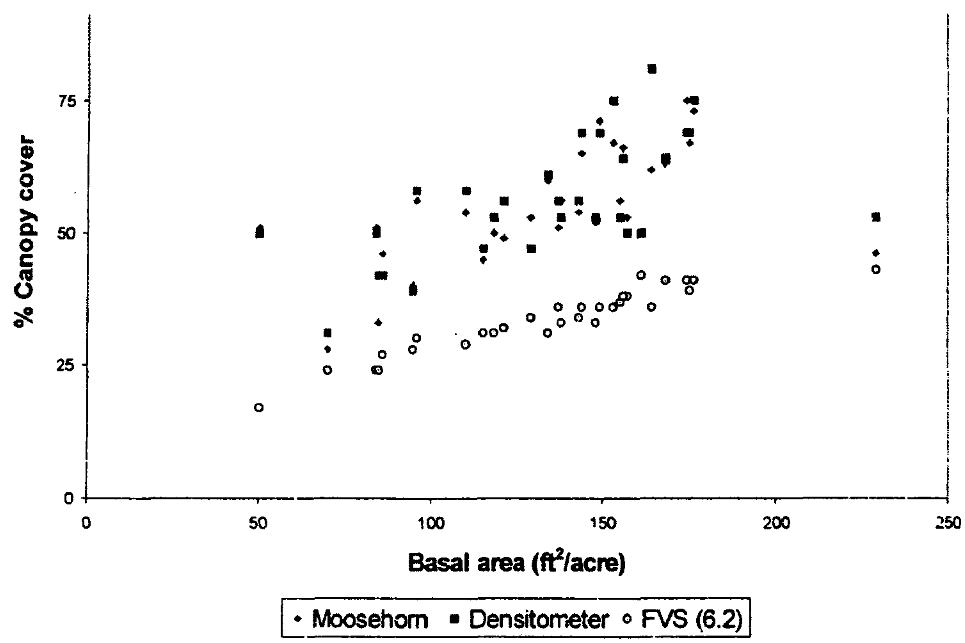


Figure 33. Canopy cover (polygon) for the PP-DF covertype

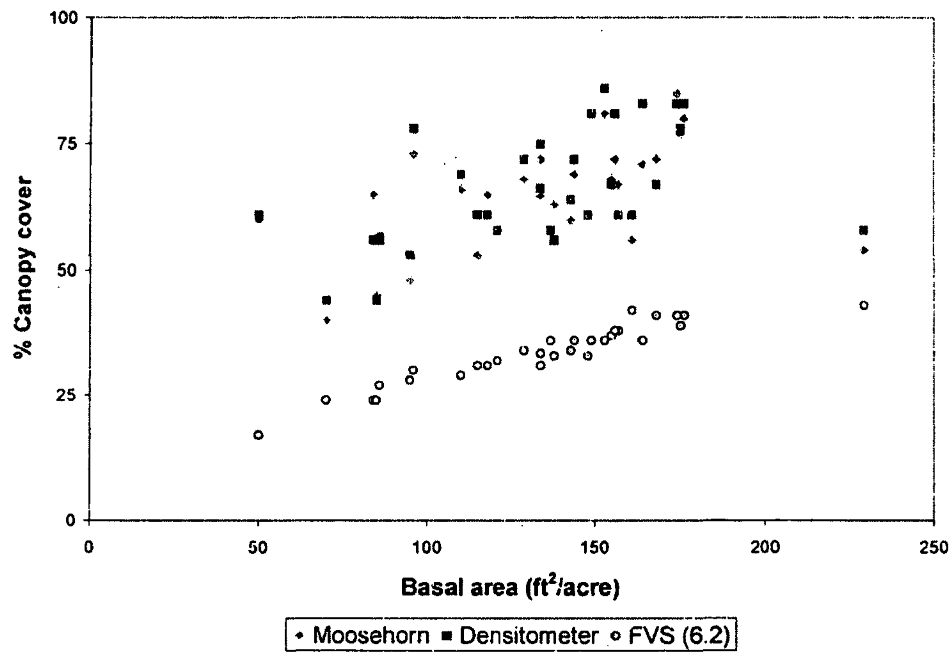
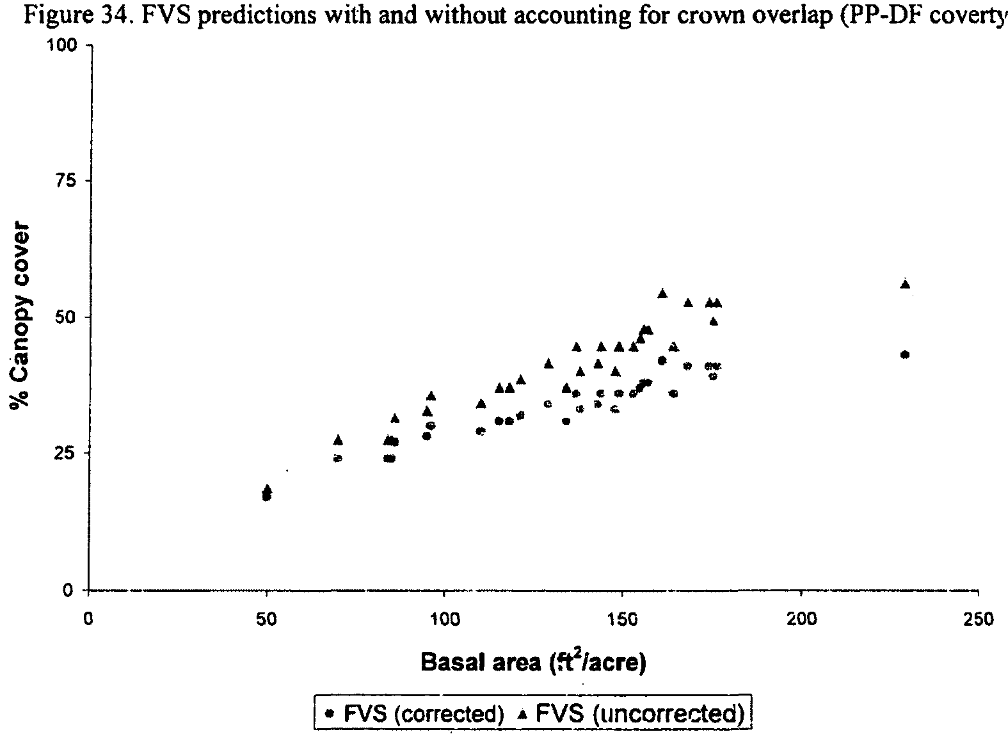


Figure 34. FVS predictions with and without accounting for crown overlap (PP-DF covertype)



Lodgepole pine covertype:

There were no significant (α = 0.05) differences in the accuracy between the moosehorn and densitometer for the "live crown" definition of canopy cover. There were significant differences in the accuracy of all methods in estimating canopy cover (Table 17, see pg. 50, Figures 35, 36, 37). Mean estimates ranged from 21.9% (FVS v. 6.2) to 70.2% (densitometer "convex polygon") (Table 18).

Table 18. Summary statistics by method for LP covertype

Method	Mean	Standard error
Moosehorn (live crown)	53.50	2.89
Densitometer (live crown)	55.08	3.53
Moosehorn (polygon)	68.08	3.84
Densitometer (polygon)	70.17	4.21
FVS (corrected)	21.92	1.25
FVS (uncorrected)	24.92	1.63

(n=12)

Figure 35. Canopy cover (live crown) for the LP covertype

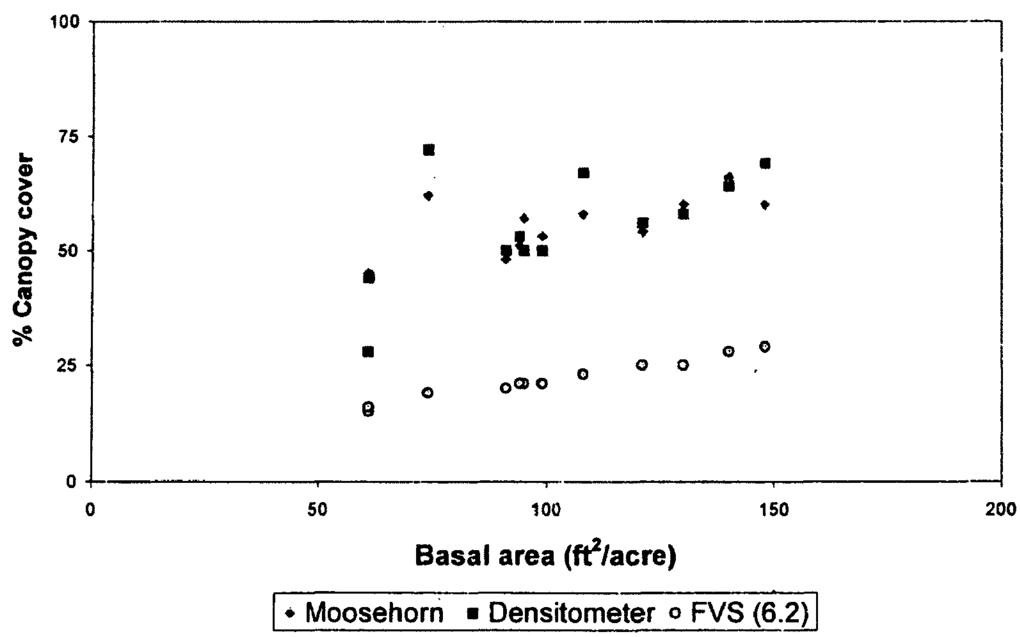


Figure 36. Canopy cover (polygon) for the LP covertype

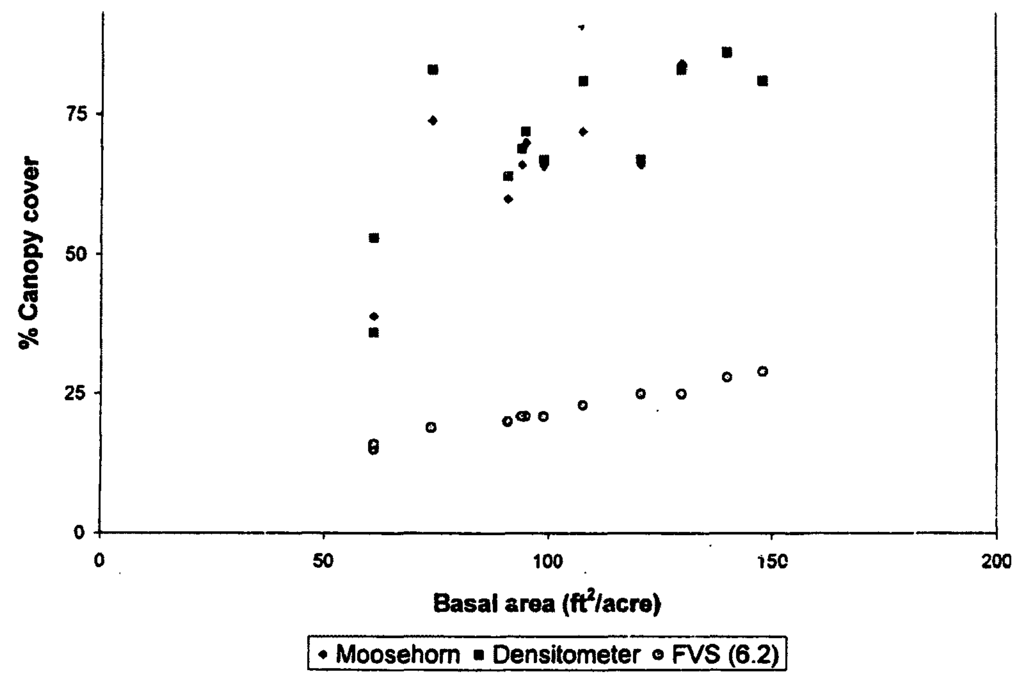
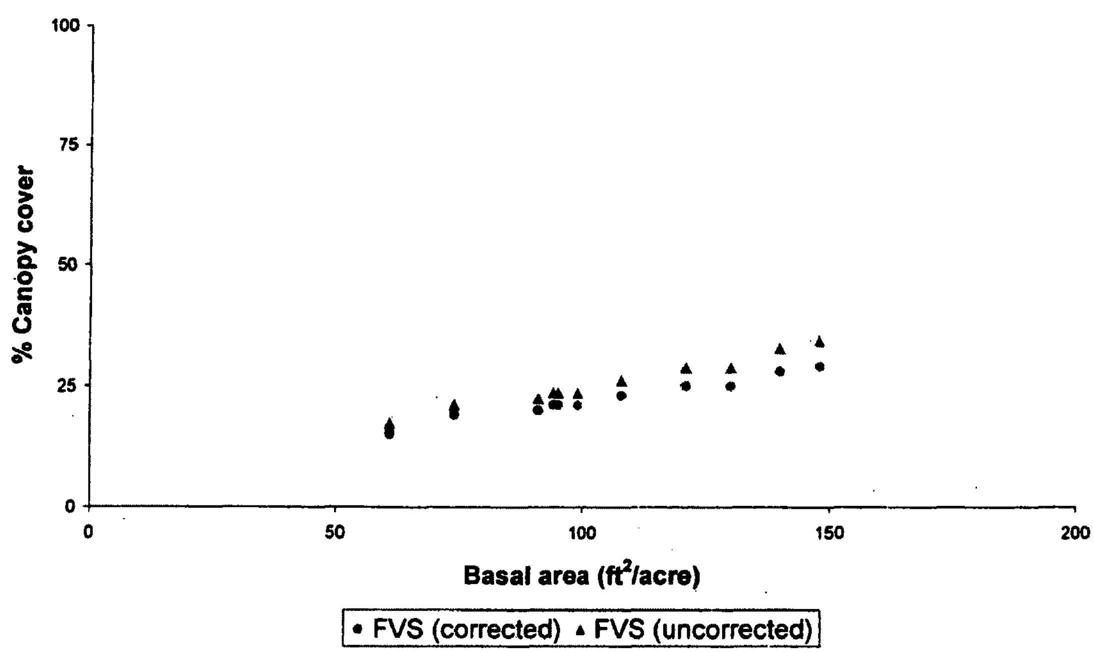


Figure 37. FVS predicted canopy cover with and without correcting for crown overlap (LP covertype)



Ponderosa pine covertype:

There were no significant ($\alpha = 0.05$) differences in the between the moosehorn and densitometer for the "live crown" definition of canopy cover. There were significant differences in the accuracy of all methods in estimating canopy cover between all other methods (Table 19, see pg. 50, Figure 38, 39, 40). Mean estimates ranged from 29.75% (FVS v. 6.2) to 70.08% (densitometer "polygon") (Table 20).

Table 20. Summary statistics by method for PP covertype

Method	Mean	Standard error
Moosehorn (live crown)	54.58	2.77
Densitometer (live crown)	56.75	2.51
Moosehorn (polygon)	67.75	2.60
Densitometer (polygon)	71.08	3.16
FVS (corrected)	29.75	1.14
FVS (uncorrected)	35.42	1.66

(n=12)

Figure 38. Canopy cover (live crown) for the PP covertype

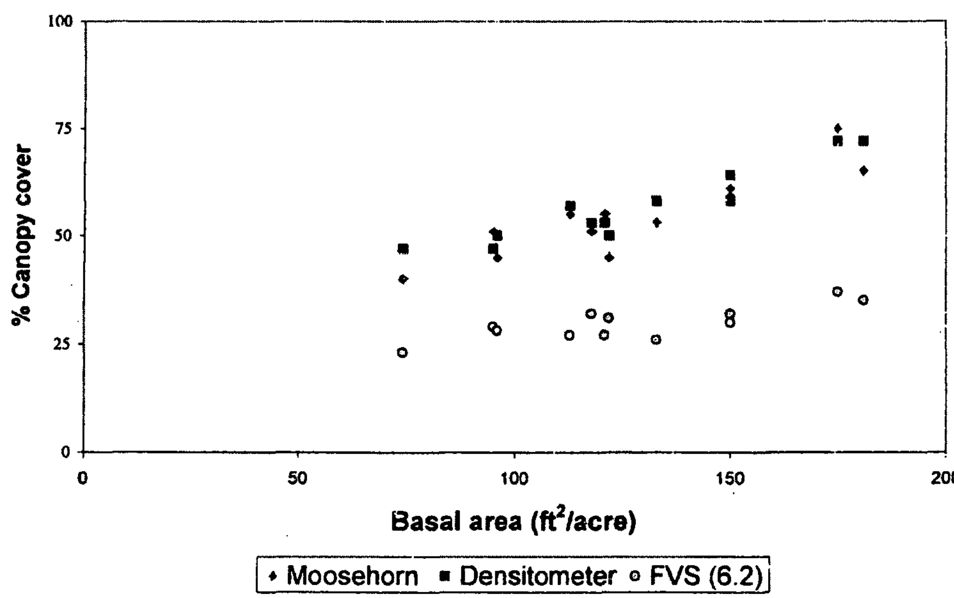


Figure 39. Canopy cover (polygon) for the PP covertype

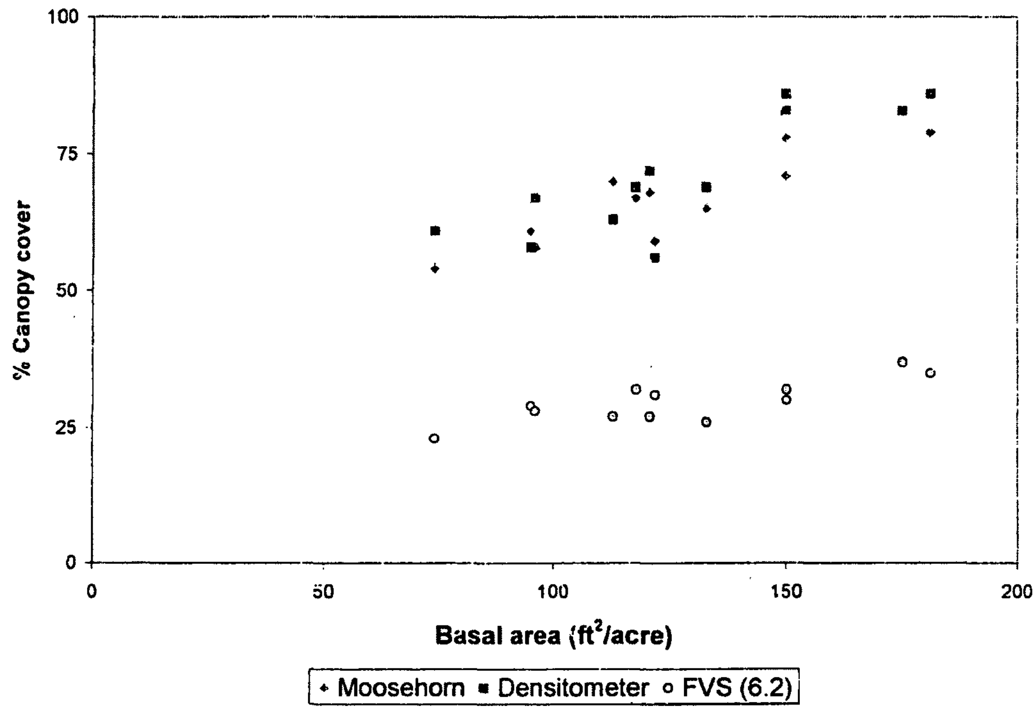
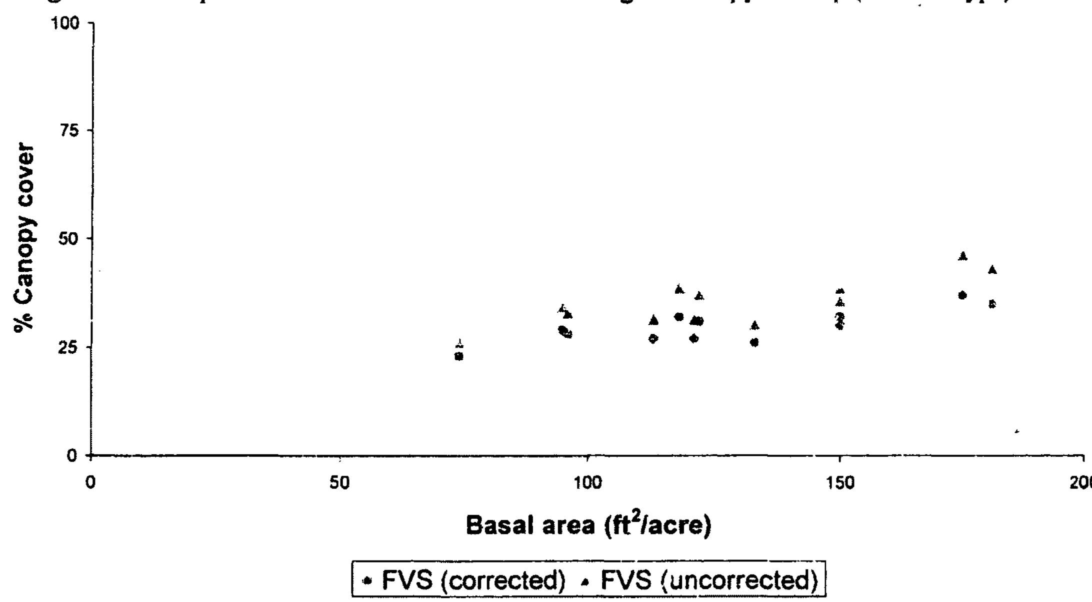


Figure 40. FVS predictions with and without accounting for canopy overlap (PP covertype)



Western Larch:

There were no significant (α = 0.05) differences in between the moosehorn and densitometer for both the "live crown" and "convex polygon" definitions of canopy cover. There were differences in the accuracy of all other methods in estimating canopy cover (Table 21, see pg. 50, Figures 41 - 43). Mean estimates ranged from 31.67% (FVS v. 6.2) to 64.08% (densitometer "polygon") (Table 22).

Table 22. Summary statistics by method for WL covertype

Method	Mean	Standard error
Moosehorn (live crown)	53.50	4.67
Densitometer (live crown)	56.25	4.88
Moosehorn (polygon)	63.08	4.97
Densitometer (polygon)	64.08	4.72
FVS (corrected)	31.67	1.16
FVS (uncorrected)	38.17	1.74

(n=12)

Figure 41. Canopy cover (live crown) for the WL covertype

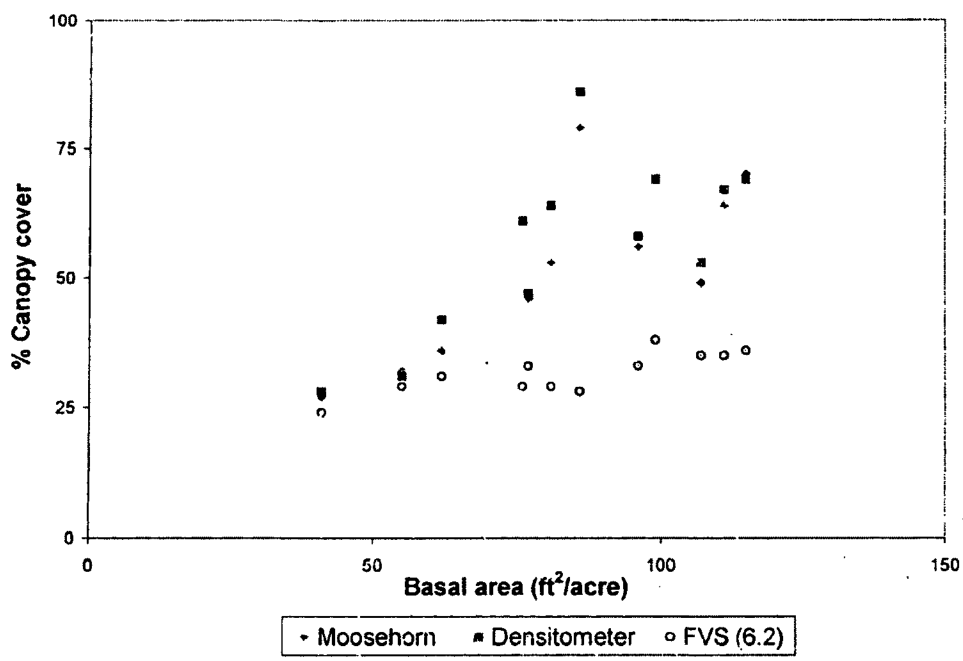


Figure 42. Canopy cover (polygon) for the WL covertype

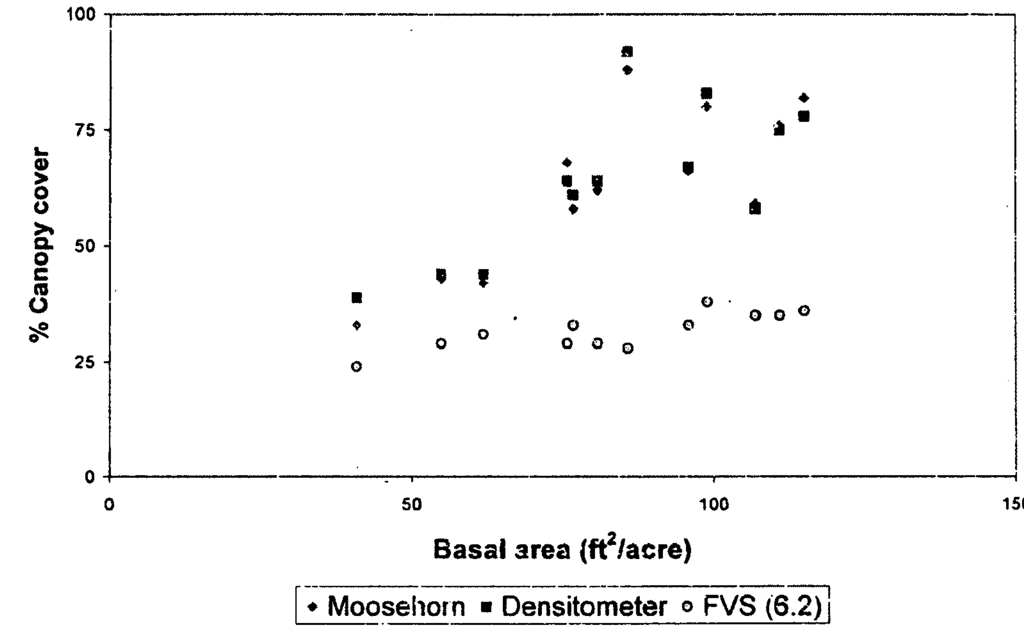


Figure 43. FVS predictions with and without correcting for crown overlap (WL covertype)

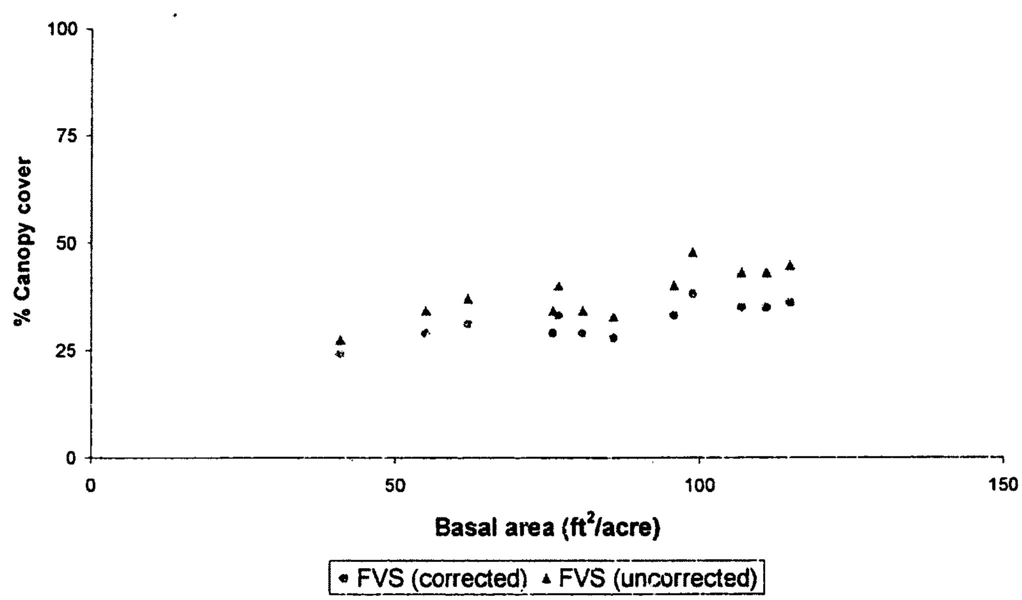


Table 13. Significance tests for the DF-WL covertype

Method (x)	Moosehorn (live crown)				Densitometer (live crown)				Moosehorn (polygon)				Densitometer (polygon)				FVS (corrected)				FVS (uncorrected)			
(y)	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q
Moosehorn (live crown)	*	*	*	*	*4.7*	*0.87*	118.9	567.2	*-7. 5*	*0.99*	44.57	2742.3	*-0.88*	*0.84*	219.6	6438.7	*33.7*	*0.86*	598	35670	*38.2*	*0.58*	598.8	22393
Densitometer (live crown)	*4.7*	*0.87*	118. 9	567. 2	*	*	*	*	*-5.7*	*1.01*	215.1	1343.1	*-4.01*	*0.93*	278.4	3007.8	*37.2*	*0.85*	811	41993	*37.2*	*0.85*	811.4	72733
Moosehorn (polygon)	*-7. 5*	*0.99*	44.57	2742.3	*-5.7*	*1.01*	215.1	1343.1	*	*	*	*	*3.9*	*0.89*	115	729.12	*43.5*	*0.81*	608	76002	*47.9*	*0.56*	609.8	41722
Densitometer (polygon)	*-0.88*	*0.84*	219.6	6438.7	*-4*	*0.93*	278.4	3007.8	*3.9*	*0.89*	115	729.12	*	*	*	*	*49.6*	*0.74*	731	72733	*53.9*	*0.49*	741.6	51161
FVS (corrected)	*33.7*	*0.86*	598.2	35670	*37.2*	*0.85*	811.4	41993	*43.5*	*0.81*	607.9	76002	*49.6*	*0.74*	731.3	72732.6	*	*	*	*	*	*	*	*
FVS(uncorrected)	*38.2*	*0.58*	598.8	22393	*37.2*	*0.85*	811.4	72733	*47.9*	*0.56*	609.8	41722	*53.9*	*0.49*	741.6	51160.7	*	*	*	*	*	*	*	*

Table 15. Significance tests for PP-DFcovertype

Method (x)	Moosehorn (live crown)				Densitometer (live crown)				Moosehorn (polygon)				Densitometer (polygon)				FVS (corrected)				FVS (uncorrected)			
(y)	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q
Moosehorn (live crown)	*	*	*	*	6.4	0.86	158.4	140.9	*-7.6*	*0.96*	69.13	3067.9	*-1.6*	*0.85*	148.7	4077.1	*19.6*	*1.05*	534	13575	*25.1*	*0.72*	523.5	12665
Densitometer (live crown)	6.4	0.86	158.4	140.9	*	*	*	*	*-1.4*	*0.89*	258.5	2210.2	*-0.92*	*0.87*	208.5	2794.1	*21.2*	*1.1*	616	17222	*26.7*	*0.72*	606.5	14959
Moosehorn (polygon)	*-7.5*	*0.96*	69.13	3067.9	*-1.4*	*0.89*	258.5	2210.2	*	*	*	*	8.1	0.86	133.7	119.7	*35.3*	*0.88*	615	29391	*40*	*0.6*	609.7	34650
Densitometer (polygon)	*-1.6*	*0.85*	148.7	4077.1	*-0.9*	*0.87*	208.5	2794.1	8.1	0.86	133.7	119.7	*	*	*	*	*33.8*	*0.97*	689	32233	*39*	*0.66*	681.3	35704
FVS (corrected)	*19.6*	*1.05*	534.1	13575.2	*21.2*	*1.1*	616.4	17222	*35.3*	*0.88*	615.2	29391	*33.8*	*0.97*	688.5	32232.9	*	*	*	*	*	*	*	*
FVS(uncorrected)	*25.1*	0.72	523.5	12665.2	*26.7*	*0.72*	606.5	14959	*40*	*0.6*	608.7	34650	*39*	*0.66*	681.3	35703.5	*	*	*	*	*	*	*	*

Table 17. Significance tests for LP covertype

Method (x)	Moosehorn (live crown)				Densitometer (live crown)				Moosehorn (polygon)				Densitometer (polygon)				FVS (corrected)				FVS (uncorrected)			
(y)	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q
Moosehorn (live crown)	*	*	*	*	12.7	0.74	164.1	143	*4.4*	*0.72*	74.1	2772.2	*6.42*	*0.67*	42.2	2626.3	*14.9*	*1.8*	386	12099	*20.1*	*1.3*	388.8	9829.8
Densitometer (live crown)	12.7	0.74	164.1	143	*	*	*	*	*1.5*	*7.9*	363.7	2051.2	*0.24*	*0.78*	179.9	2884.5	*12.1*	*2*	705	13352	*18.4*	*1.5*	729.7	10986
Moosehorn (polygon)	*4.4*	*0.72*	74.1	2772.2	*1.5*	*7.9*	363.7	2051.2	*	*	*	*	*6.07*	*0.88*	97.83	99.97	*10.5*	*2.6*	438	26218	*18.1*	2	438	22546
Densitometer (polygon)	*6.42*	*0.67*	42.2	2626.3	*0.24*	*0.78*	179.9	2884.5	*6.07*	*0.88*	97.83	99.97	*	*	*	*	*13.6*	*2.6*	798	28369	*21.3*	2	811.9	24862
FVS (corrected)	*14.9*	*1.8*	386.1	12098.6	*12.1*	2	705.1	13352	*10.5*	*2.6*	437.9	26218	13.6	2.6	798	28388.5	*	*	*	*	*	*	*	*
FVS(uncorrected)	*20.1*	*1.3*	388.8	9829.8	*18.4*	*1.5*	729.7	10986	*18.1*	2	438	22546	*21.3*	2	811 9	24861.6	*	*	*	*	*	*	*	*

Table 19. Significance tests for PP covertype

Method (x)	Moosehorn (live crown)				Densitometer (live crown)				Moosehorn (polygon)				Densitometer (polygon)				FVS (corrected)				FVS (uncorrected)			
(y)	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q
Moosehorn (live crown)	*	*	*	*	-2.8	1	134.2	57.24	*-15*	*1*	54.9	2024.9	*4.7*	*0.7*	296.2	3423.6	*-0.6*	*1.9*	349	7622.9	*10*	*1.3*	356.7	4442.8
Densitometer (live crown)	-2.8	1	134.2	57.24	*	*	*	*	*-4.3*	*0.9*	84.7	1488.8	*10*	*0.66*	211.7	2571.8	*9.9*	*1.6*	334	8879.9	*18.5*	*1.1*	333.2	5448.3
Moosehorn (polygon)	*-15*	*1*	54.9	2024.9	*-4.3*	*0.9*	84.7	1488.8	*	*	*	*	*18.9*	*0.69*	221.2	247.2	17.9	1.7	341	17535	*27.3*	1.1	345.6	12510
Densitometer (polygon)	*4.7*	*0.7*	296.2	3423.6	*10*	*0.66*	211.7	2571.8	*18.9*	*0.69*	221.2	247.2	*	*	*	*	*20.4*	1.7	677	25065	*28.7*	1.2	656.4	15354
FVS (corrected)	*-0.59*	*1.9*	348.8	7622.9	*9.9*	*1.6*	334.2	8879.9	*17.9*	*1.7*	341.4	17535	*20.4*	1.7	677.4	25065.1	*	*	*	*	*	*	*	*
FVS(uncorrected)	*10*	*1.3*	356.7	4442.8	*18.5*	*1.1*	333.2	5448.3	*27.3*	*1.1*	345.6	12510	*28.7*	*1.2*	656.4	15354.1	*	*	*	*	*	*	*	*

Table 21. Significance tests for WL covertype

Method (x)	Moosehorn (live crown)				Densitometer (live crown)				Moosehorn (polygon)				Densitometer (polygon)				FVS (corrected)				FVS (uncorrected)			
(y)	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q	B_0	B_1	F'	Q
Moosehorn (live crown)	*	*	*	*	0.93	0.94	110.5	83.5	*-5.4*	*0.93*	33.3	1172.2	*-8.7*	*0.97*	92.2	1356.7	-7.3	*1.9*	1824	5871.6	*3.14*	*1.32*	1791	2869.8
Densitometer (live crown)	0.93	0.94	110.5	83.5	*	*	*	*	*-3.2*	*0.94*	202.5	602.2	*-7.4*	*0.99*	201.3	774.2	2.7	*1.7*	2161	7329.3	*11.9*	*1.2*	2135	3901.2
Moosehorn (polygon)	*-5.4*	*0.93*	33.3	1172.2	*-3.2*	*0.94*	202.5	602.2	*	*	*	*	-3.4	1	80.4	12.7	-10	2.3	1895	17180	2.87	*1.6*	1854	7639.1
Densitometer (polygon)	*-8.7*	*0.97*	92.2	1356.7	*-7.4*	*0.99*	201.3	774.2	*-3.4*	*1*	80.4	12.7	*	*	*	*	*1.5*	2	1839	11754	12	*1.4*	1799	8021.2
FVS (corrected)	-7.3	*1.9*	1824	5871.6	2.7	*1.7*	2161	7329.3	-10	2.3	1894.6	17180	*1.5*	2	1839	11754	*	*	*	*	*	*	*	*
FVS(uncorrected)	*3.14*	*1.32*	1791	2869.8	*11.9*	*1.2*	2135	3901.2	2.87	*1.6*	1853.8	7639.1	12	*1.4*	1799	8021.2	*	*	*	*	*	*	*	*

- numbers in italics indicate significance at the 0.05 level
- reject H_0 if $Q \geq F'$

Stand level:

Canopy cover at the stand level was determined by averaging individual plot means to get an overall stand mean and then averaging all stand means to get a mean for a given covertype. For the LGS units on LEF, each thinning unit was treated as a stand. A One-way ANOVA was used to determine if there were significant differences between these methods at the stand level.

Douglas-fir/western larch covertype:

There were significant differences in mean estimates of percent cover between methods (Table 23).

Table 23. ANOVA for DF-WL covertype

	Sums of Squares	df	Mean square	F	p
CC Method	4469.81	6	744.97	15.76	< .0005
Error	662.00	14	47.29		
Total	5131.81	20			

Mean canopy cover estimates ranged from 33.6% (FVS corrected) to 75% (photo) (Table 24). The primary differences found by Tukey's HSD procedure were between field measurements and FVS projections (Table 25).

Table 24. Summary statistics for DF-WL covertype

Method	Mean	Standard error
Moosehorn (live crown)	60.33	1.86
Densitometer (live crown)	62.67	2.67
Moosehorn (polygon)	68.33	2.03
Densitometer (polygon)	72.33	2.40
Photo	75.00	5.00
FVS (corrected)	33.67	4.41
FVS (uncorrected)	41.33	6.74

(n=3)

Table 25. Tukey's HSD procedure for DF-WL stands (n=3)

		Mean Difference	Std. Error
Moosehorn (live crown)	Densitometer (live crown)	-2.33	5.61
	Moosehorn (polygon)	-8.00	5.61
	Densitometer (polygon)	-12.00	5.61
	Photo	-14.67	5.61
	FVS (corrected)	26.67*	5.61
	FVS (uncorrected)	19.00	5.61
Densitometer (live crown)	Moosehorn	2.33	5.61
	Moosehorn (polygon)	-5.67	5.61
	Densitometer (polygon)	-9.67	5.61
	Photo	-12.33	5.61
	FVS (corrected)	29.00*	5.61
	FVS (uncorrected)	21.33*	5.61
Moosehorn (polygon)	Moosehorn	8.00	5.61
	Densitometer (live crown)	5.67	5.61
	Densitometer (polygon)	-4.00	5.61
	Photo	-6.67	5.61
	FVS (corrected)	34.67*	5.61
	FVS (uncorrected)	27.00*	5.61
Densitometer (polygon)	Moosehorn	12.00	5.61
	Densitometer (live crown)	9.67	5.61
	Moosehorn (polygon)	4.00	5.61
	Photo	-2.67	5.61
	FVS (corrected)	38.67*	5.61
	FVS (uncorrected)	31.00*	5.61
Photo	Moosehorn	14.67	5.61
	Densitometer (live crown)	12.33	5.61
	Moosehorn (polygon)	6.67	5.61
	Densitometer (polygon)	2.67	5.61
	FVS (corrected)	41.33*	5.61
	FVS (uncorrected)	33.67*	5.61
FVS (corrected)	Moosehorn	-26.67*	5.61
	Densitometer (live crown)	-29.00*	5.61
	Moosehorn (polygon)	-34.67*	5.61
	Densitometer (polygon)	-38.67*	5.61
	Photo	-41.33*	5.61
	FVS (uncorrected)	-7.67	5.61
FVS (uncorrected)	Moosehorn	-19.00	5.61
	Densitometer (live crown)	-21.33*	5.61
	Moosehorn (polygon)	-27.00*	5.61
	Densitometer (polygon)	-31.00*	5.61
	Photo	-33.67*	5.61
	FVS (corrected)	7.67	5.61

*. The mean difference is significant at the .05 level.

Ponderosa pine/Douglas-fir covertype:

A One-way ANOVA showed significant differences in mean estimates of percent cover between methods (Table 26).

Table 26. ANOVA for PP-DF covertype

	Sums of Squares	df	Mean square	F	p
CC Method	8395.73	5	1679.15	29.74	<.0005
Error	3049.20	54	56.47		
Total	11444.93	59			

Mean estimates of cover ranged from 33.7% (FVS corrected) to 66.2% (densitometer "polygon") (Table 27). Aerial photo interpretation was not included in this analysis because a Levine's test showed it violated the equal variance assumption for ANOVA ($L = 7.98; p < .0005$). The primary differences were between the ground instruments and FVS projections (Table 28).

Table 27. Summary statistics for PP-DF covertype

Method	Mean	Standard error
Moosehorn (live crown)	54.70	2.73
Densitometer (live crown)	56.40	2.75
Moosehorn (polygon)	64.90	2.40
Densitometer (polygon)	66.20	2.60
FVS (corrected)	33.70	1.40
FVS (uncorrected)	41.30	2.08

(n=10)

Table 28. Tukey's HSD procedure for PP-DF stands (n=10)

		Mean Difference	Std. Error
Moosehorn (live crown)	Densitometer (live crown)	-1.70	3.36
	Moosehorn(polygon)	-10.20*	3.36
	Densitometer(polygon)	-11.50*	3.36
	FVS (corrected)	21.00*	3.36
	FVS (uncorrected)	13.40*	3.36
Densitometer (live crown)	Moosehorn	1.70	3.36
	Moosehorn(polygon)	-8.50	3.36
	Densitometer(polygon)	-9.80	3.36
	FVS (corrected)	22.70*	3.36
	FVS (uncorrected)	15.10*	3.36
Moosehorn (polygon)	Moosehorn	10.20*	3.36
	Densitometer (live crown)	8.50	3.36
	Densitometer(polygon)	-1.30	3.36
	FVS (corrected)	31.20*	3.36
	FVS (uncorrected)	23.60*	3.36
Densitometer (polygon)	Moosehorn	11.50*	3.36
	Densitometer (live crown)	9.80	3.36
	Moosehorn(polygon)	1.30	3.36
	FVS (corrected)	32.50*	3.36
	FVS (uncorrected)	24.90*	3.36
FVS (corrected)	Moosehorn	-21.00*	3.36
	Densitometer (live crown)	-22.70*	3.36
	Moosehorn(polygon)	-31.20*	3.36
	Densitometer(polygon)	-32.50*	3.36
	FVS (uncorrected)	-7.60	3.36
FVS (uncorrected)	Moosehorn	-13.40*	3.36
	Densitometer (live crown)	-15.10*	3.36
	Moosehorn(polygon)	-23.60*	3.36
	Densitometer(polygon)	-24.90*	3.36
	FVS (corrected)	7.60	3.36

*. The mean difference is significant at the .05 level.

Lodgepole pine covertype:

A One-way ANOVA showed significant differences in mean estimates of percent cover between methods (Table 29).

Table 29. ANOVA for LP covertype

	Sums of Squares	df	Mean square	F	p
CC Method	13118.93	6	2186.49	25.01	<.0005
Error	1835.75	21	87.42		
Total	14954.68	27			

Mean cover estimates ranged from 22% (FVS corrected) to 85% (photo) (Table 30).

The primary differences were between ground instruments and FVS (Table 31).

Table 30. Summary statistics for LP covertype (n=4)

Method	Mean	Standard error	Standard deviation
Moosehorn (live crown)	53.50	3.62	7.23
Densitometer (live crown)	55.25	3.59	7.18
Moosehorn (polygon)	68.00	6.07	12.14
Densitometer (polygon)	70.00	5.45	10.89
Photo	85.00	7.07	14.14
FVS (corrected)	22.00	2.08	4.16
FVS (uncorrected)	25.00	2.48	4.97

Table 31. Tukey's procedure for LP stands (n=4)

		Mean Difference	Std. Error
Moosehorn (live crown)	Densitometer (live crown)	-1.75	6.61
	Moosehorn (polygon)	-14.50	6.61
	Densitometer (polygon)	-16.50	6.61
	Photo	-31.50*	6.61
	FVS (corected)	31.50*	6.61
	FVS (uncorrected)	28.50*	6.61
Densitometer (live crown)	Moosehorn	1.75	6.61
	Moosehorn (polygon)	-12.75	6.61
	Densitometer (polygon)	-14.75	6.61
	Photo	-29.75*	6.61
	FVS (corected)	33.25*	6.61
	FVS (uncorrected)	30.25*	6.61
Moosehorn (polygon)	Moosehorn	14.50	6.61
	Densitometer (live crown)	12.75	6.61
	Densitometer (polygon)	-2.00	6.61
	Photo	-17.00	6.61
	FVS (corected)	46.00*	6.61
	FVS (uncorrected)	43.00*	6.61
Densitometer (polygon)	Moosehorn	16.50	6.61
	Densitometer (live crown)	14.75	6.61
	Moosehorn (polygon)	2.00	6.61
	Photo	-15.00	6.61
	FVS (corected)	48.00*	6.61
	FVS (uncorrected)	45.00*	6.61
Photo	Moosehorn	31.50*	6.61
	Densitometer (live crown)	29.75*	6.61
	Moosehorn (polygon)	17.00	6.61
	Densitometer (polygon)	15.00	6.61
	FVS (corected)	63.00*	6.61
	FVS (uncorrected)	60.00*	6.61
FVS (corrected)	Moosehorn	-31.50*	6.61
	Densitometer (live crown)	-33.25*	6.61
	Moosehorn (polygon)	-46.00*	6.61
	Densitometer (polygon)	-48.00*	6.61
	Photo	-63.00*	6.61
	FVS (uncorrected)	-3.00	6.61
FVS (uncorrected)	Moosehorn	-28.50*	6.61
	Densitometer (live crown)	-30.25*	6.61
	Moosehorn (polygon)	-43.00*	6.61
	Densitometer (polygon)	-45.00*	6.61
	Photo	-60.00*	6.61
	FVS (corected)	3.00	6.61

*. The mean difference is significant at the .05 level.

Ponderosa pine covertype:

A One-way ANOVA showed significant differences in mean estimates of percent cover between methods (Table 32).

Table 32. ANOVA for PP covertype

	Sums of Squares	df	Mean square	F	p
CC Method	5763.38	5	1152.68	25.61	<.0005
Error	810.25	18	45.01		
Total	6573.63	23			

Mean estimates of cover ranged from 29.5% (FVS corrected) to 71% (densitometer "polygon") (Table 33). The primary differences were between ground instruments and FVS projections (Table 34). Aerial photo interpretation was not included in this analysis because a Levine's test showed it violated the homogenous variance assumption for ANOVA ($L = 3.1; p = .034$).

Table 33. Summary statistics for PP covertype

Method	Mean	Standard error
Moosehorn (live crown)	54.50	4.17
Densitometer (live crown)	56.75	3.99
Moosehorn (polygon)	67.75	3.97
Densitometer (polygon)	71.00	3.34
FVS (corrected)	29.50	1.50
FVS (uncorrected)	34.75	2.25

(n=4)

Table 34. Tukey's procedure for PP covertype (n=4)

		Mean Difference	Std. Error
Moosehorn (live crown)	Densitometer (live crown)	-2.25	4.74
	Moosehorn(polygon)	-13.25	4.74
	Densitometer(polygon)	-16.50*	4.74
	FVS (corrected)	25.00*	4.74
	FVS (uncorrected)	19.75*	4.74
Densitometer (live crown)	Moosehorn	2.25	4.74
	Moosehorn(polygon)	-11.00	4.74
	Densitometer(polygon)	-14.25	4.74
	FVS (corrected)	27.25*	4.74
	FVS (uncorrected)	22.00*	4.74
Moosehorn (polygon)	Moosehorn	13.25	4.74
	Densitometer (live crown)	11.00	4.74
	Densitometer(polygon)	-3.25	4.74
	FVS (corrected)	38.25*	4.74
	FVS (uncorrected)	33.00*	4.74
Densitometer (polygon)	Moosehorn	16.50*	4.74
	Densitometer (live crown)	14.25	4.74
	Moosehorn(polygon)	3.25	4.74
	FVS (corrected)	41.50*	4.74
	FVS (uncorrected)	36.25*	4.74
FVS (corrected)	Moosehorn	-25.00*	4.74
	Densitometer (live crown)	-27.25*	4.74
	Moosehorn(polygon)	-38.25*	4.74
	Densitometer(polygon)	-41.50*	4.74
	FVS (uncorrected)	-5.25	4.74
FVS (uncorrected)	Moosehorn	-19.75*	4.74
	Densitometer (live crown)	-22.00*	4.74
	Moosehorn(polygon)	-33.00*	4.74
	Densitometer(polygon)	-36.25*	4.74
	FVS (corrected)	5.25	4.74

*. The mean difference is significant at the .05 level.

Western Larch:

A One-way ANOVA showed significant differences in mean estimates of percent cover between methods (Table 35).

Table 35. ANOVA for WL covertype

	Sums of Squares	df	Mean square	F	p
CC Method	6202.00	6	1033.67	5.22	.002
Error	4159.25	21	198.06		
Total	10361.25	27			

Mean cover ranged from 31.25% (FVS corrected) to 75% (photo) (Table 36).

The primary differences were between field instruments and FVS projections

(Table 37)

Table 36. Summary statistics for WL covertype

Method	Mean	Standard error
Moosehorn (live crown)	55.75	7.92
Densitometer (live crown)	56.50	8.15
Moosehorn (polygon)	66.00	8.27
Densitometer (polygon)	68.00	7.51
Photo	75.00	9.13
FVS (corrected)	31.25	1.70
FVS (uncorrected)	37.75	2.56

(n=4)

Table 37. Tukey's procedure for WL covertype (n=4)

		Mean Difference	Std. Error
Moosehorn (live crown)	Densitometer (live crown)	-.75	9.95
	Moosehorn (polygon)	-10.25	9.95
	Densitometer (polygon)	-12.25	9.95
	Photo	-19.25	9.95
	FVS (corrected)	24.50	9.95
	FVS (uncorrected)	18.00	9.95
Densitometer (live crown)	Moosehorn (live crown)	.75	9.95
	Moosehorn (polygon)	-9.50	9.95
	Densitometer (polygon)	-11.50	9.95
	Photo	-18.50	9.95
	FVS (corrected)	25.25	9.95
	FVS (uncorrected)	18.75	9.95
Moosehorn (polygon)	Moosehorn (live crown)	10.25	9.95
	Densitometer (live crown)	9.50	9.95
	Densitometer (polygon)	-2.00	9.95
	Photo	-9.00	9.95
	FVS (corrected)	34.75*	9.95
	FVS (uncorrected)	28.25	9.95
Densitometer (polygon)	Moosehorn (live crown)	12.25	9.95
	Densitometer (live crown)	11.50	9.95
	Moosehorn (polygon)	2.00	9.95
	Photo	-7.00	9.95
	FVS (corrected)	36.75*	9.95
	FVS (uncorrected)	30.25	9.95
Photo	Moosehorn (live crown)	19.25	9.95
	Densitometer (live crown)	18.50	9.95
	Moosehorn (polygon)	9.00	9.95
	Densitometer (polygon)	7.00	9.95
	FVS (corrected)	43.75*	9.95
	FVS (uncorrected)	37.25*	9.95
FVS (corrected)	Moosehorn (live crown)	-24.50	9.95
	Densitometer (live crown)	-25.25	9.95
	Moosehorn (polygon)	-34.75*	9.95
	Densitometer (polygon)	-36.75*	9.95
	Photo	-43.75*	9.95
	FVS (uncorrected)	-6.50	9.95
FVS (uncorrected)	Moosehorn (live crown)	-18.00	9.95
	Densitometer (live crown)	-18.75	9.95
	Moosehorn (polygon)	-28.25	9.95
	Densitometer (polygon)	-30.25	9.95
	Photo	-37.25*	9.95
	FVS (corrected)	6.50	9.95

*. The mean difference is significant at the .05 level.

Chapter IV.

Discussion:

Field instruments and canopy definitions (plot level)

Using the downward projection of a tree's crown (in the shape of a convex polygon), instead of just the live crown portion to measure canopy cover, resulted in higher estimates of canopy cover on 107 and 103 plots using the moosehorn and densitometer, respectively. The remaining 4 plots had equal values of canopy cover when using the densitometer. This makes intuitive sense since a greater area of ground may be covered by the outline of a tree's perimeter than by the living portion of a tree's crown (depending on species, age and vigor). Differences between the moosehorn and densitometer ranged from 0 - 19%, and 0 - 16% for the live crown and convex polygon definitions, respectively. However, the mean difference for all plots between each instrument regardless of definition was 3%. These results indicate that if a live crown approach is accepted as truth, and the convex polygon approach is used to determine canopy cover, there is a minimum mean overestimate from ~ 8% - 15%, depending on covertype and instrument used.

Using five equal-interval canopy classes (confusion matrices) the moosehorn and densitometer agree 80.4% when using the live crown definition of canopy cover, and 70.1% agree when a convex polygon approach is used. However, the densitometer yielded higher estimates of canopy cover than the moosehorn on 76 (71%) and 83 plots (77.6%) for the live crown and convex polygon definitions of canopy cover, respectively. This is unusual in that previous work with these instruments has shown that percent cover values obtained with a moosehorn were consistently higher than with point estimates (Bonner 1967, Bunnell and Vales 1990). This is largely due to the greater area sampled with a moosehorn and the properties of a binomial distribution when using a point estimate. Since the number of sampling points per plot that are required to attain accurate estimates of canopy cover with a densitometer was met (as described in the literature), it is possible that there were field errors in using either the moosehorn or densitometer.

The densitometer has a smaller viewing window to see the canopy than the moosehorn. As such, it was difficult to determine if a particular sample point was within a convex polygon around the tree crown. It is possible that points were counted as "in" when they were in fact just outside of the polygon. Also, the dot grid on the moosehorn is made up of points that are 1.0 mm in diameter, but the single dot of the densitometer is 3.0mm in diameter. The single dot has a larger area and sometimes a sample point had a partial "hit", i.e. half of the single dot hit canopy and half of the dot did not. On those occasions, those points were counted as "in" but in retrospect, perhaps alternate counting of those points as "in" may have been a more appropriate protocol. The drop in agreement between the moosehorn and densitometer when using a convex polygon approach may lend evidence to support the above supposition.

The DF-WL covertype showed significant differences between the moosehorn and densitometer for the live crown definition of canopy cover; all other covertypes showed no difference between them. This may be due to this covertype having the largest mean difference in canopy cover between the moosehorn and densitometer of all the covertypes

(3.4%). The PP-DF and WL covertypes showed no difference between the moosehorn and densitometer for the convex polygon definition of canopy cover; all other covertypes showed a difference between them. The level of agreement between these instruments regardless of definition is less than 5 (Table 38).

Table 38. Mean difference in percent cover between the moosehorn and densitometer

	Live crown	Polygon
	mean diff.	mean diff.
DF-WL	3.4*	4.1*
PP-DF	1.6	1.5
LP	1.6	2.1*
PP	2.2	3.3*
WL	2.8	1

* significant at the 0.05 level

Field instruments and canopy definitions (stand level)

Canopy cover at the stand level was determined by averaging individual plot means to obtain an overall stand mean and then averaging all stand means to get a covertype mean. Estimating canopy cover by this method reduced the variation at the plot level (for the moosehorn) and stand level (both instruments) resulting in no significant differences. This was seen on stands with a DF-WL, LP and WL covertypes, and to a lesser extent on stands with PP-DF and PP covertypes.

FVS predictions (v. 6.2)

FVS underpredicted canopy cover on all plots with the degree of underprediction varying by cover definition, covertype and the density within those covertypes. Since FVS uses the downward projection of a tree crown to calculate canopy cover, it would make intuitive sense for the convex polygon approach to canopy cover to be the most similar technique to FVS predictions. That was not observed. The greatest degree of underprediction occurred when using a convex polygon to define percent canopy cover. The underprediction compared to the moosehorn ranged from 3 - 51% and 9 - 60% when using the live crown and convex polygon definitions, respectively. The underprediction compared to the densitometer ranged from 2 - 58% and 13 - 64% when using the live crown and convex polygon definitions, respectively. The mean percent of underprediction compared to the moosehorn was 26% for the live crown and 36% for the convex polygon definitions of canopy cover. The mean percent of underprediction compared to the densitometer was 29% for the live crown and 39% for the convex polygon definitions of canopy cover.

At the stand level, FVS predictions matched those of the moosehorn and densitometer (live crown) only for the western larch covertype. This could in part be possibly due to the relatively low amount of foliage present in larch crowns. Its also possible that since some plots needed to be remeasured in late October, the deciduous nature of larch resulted in lesser amounts of canopy cover than what would be present before leaf senescence. However, the tendency of FVS to underpredict canopy cover needs further review.

FVS predicts canopy cover based on crown diameters of 370 dominant and codominant trees originally measured in 1978. The original field procedure reads, "...crowns were visually divided into two or three horizontally partitioned live sections................boundaries between live crown sections were located where diameters and lengths of branches changed distinctly" with crown width measured as the average of two perpendicular measurements for each section (Brown 1978). Crown width for a single tree was the average of these measurements. Therefore it is not surprising that canopy cover is being underpredicted. Perhaps a better approach would have been to take the largest crown width for a tree.

All trees in this study were within the ranges of species and diameter for the FVS canopy equations. The large non-zero values of the intercepts from the regression equations indicate that a substantial bias is present within the mode (Table 41). This could be caused by basing the crown width equations which FVS uses, on a relatively small number of trees, across a range of unknown stand densities and site qualities, resulting in extrapolation across a very large area for the NI variant (Tables 39, 40). Only one hundred-sixty of those trees were ≥ 3.5" dbh (trees in this study needed to be ≥ 4.6" dbh to be measured for canopy cover)

Table 39. Summary of trees used to predict crown width in with FVS

species	# of trees ≥ 3. 5"	dbh range
DF	23	0 – 33.9
PP	29	0 – 34.0
WL	9	0 – 21.8
LP	7	0 – 15.6
GF	22	0 – 20.4
ES	8	0 – 23.2
Total	98	

Table 40. Summary of trees measured in this study

species	# of trees ≥ 4.6"	dbh range	BA range
DF	472	4.6 - 31.4	50 - 229
PP	521	4.6 - 18.7	74 - 229
WL	466	4.6 - 21.9	41 - 229
LP	336	4.6 - 16.6	40 - 220
GF	11	8.5 - 21.2	100 - 200
ES	5	13.5 - 16.3	60 - 100
Total	1811		

Correcting for Canopy Overlap

As stated previously, the latest version of FVS (v 6.2) reduces canopy cover estimates by adjusting for canopy overlap. Since FVS (v 6.2) underpredicted canopy cover, this researcher was interested in determining how the uncorrected canopy projections compared to the modified projections.

At the plot level, without adjusting for crown overlap, FVS still underpredicted canopy cover albeit to a lesser extent. However, at the stand level, there were no significant differences between the uncorrected FVS projections and mean estimates of percent cover using the moosehorn (live crown) for the DF-WL covertype. There were also no significant differences between FVS and both the moosehorn and densitometer, regardless of canopy cover definition for the WL covertype. This may be partly due to the low foliar biomass of western larch.

Despite its underprediction the latest version of FVS does seem to have an advantage over its former self. If estimated canopy cover by the moosehorn (or densitometer) is accepted as truth, then the regression equations indicate that FVS tends to capture the observed increase in canopy cover per unit increase in basal area better by correcting for canopy cover (the slopes of the regression lines become closer to 1), intercepts closer to 0, and smaller variances (MSE) when correcting for crown overlap than without. However, this tendency varies by covertype (Table 41).

Table 41. Regression comparisons between the two versions of FVS and ground-truthing techniques

Covertype	n	Method (y)	B_0 FVS_c	B_0 FVS_n	B_1 FVS_c	B_1 FVS_n	MSE FVS_c	MSE FVS_n
DF-WL	41	Densitometer (live crown)	37.2	42.1	0.85	0.57	112.7	114.3
DF-WL	41	Densitometer (polygon)	49.6	53.9	0.74	0.49	113.2	114.8
DF-WL	41	Moosehorn (live crown)	33.7	38.19	0.86	0.58	92.6	92.7
DF-WL	41	Moosehorn (polygon)	43.5	47.9	0.81	0.55	94.1	94.4
PP-DF	30	Densitometer (live crown)	21.16	25.1	1.06	0.72	92.55	78.6
PP-DF	30	Densitometer (polygon)	33.78	40	0.97	0.6	103.38	91.54
PP-DF	30	Moosehorn (live crown)	19.6	26.7	1.05	0.72	80.2	91.07
PP-DF	30	Moosehorn (polygon)	35.3	38.9	0.88	0.66	92.37	102.3
LP	12	Densitometer (live crown)	12.08	18.09	1.96	2	85.99	53.42
LP	12	Densitometer (polygon)	13.57	18.4	2.58	1.47	97.32	88.99
LP	12	Moosehorn (live crown)	14.94	21.3	1.76	1.96	47.08	99.01
LP	12	Moosehorn (polygon)	10.53	20.1	2.63	1.34	53.4	47.42
PP	12	Densitometer (live crown)	9.86	28.7	1.58	1.2	40.76	40.6
PP	12	Densitometer (polygon)	20.36	18.47	1.71	1.08	82.61	80.1
PP	12	Moosehorn (live crown)	-0.59	9.98	1.86	1.26	42.53	43.5
PP	12	Moosehorn (polygon)	17.91	27.32	1.68	1.14	41.63	42.14
WL	12	Densitometer (live crown)	2.72	12.03	1.69	1.36	263.58	219.37
WL	12	Densitometer (polygon)	1.46	11.9	1.98	1.16	224.22	260.4
WL	12	Moosehorn (live crown)	-7.3	2.87	1.92	1.58	222.45	226.1
WL	12	Moosehorn (polygon)	-9.99	3.14	2.31	1.32	230.93	218.4

The ability to accurately project the increase in canopy cover with increasing basal area may be explained by the correction factor developed by Crookston and Stage (1999). The mathematical correction factor has a physiological interpretation based on the Beer-Lambert law, a commonly used relation for calculating the absorption of light by foliage (Crookston and Stage 1999). The corrected model tends to deviate the most from its former self with increasing levels of basal area (Figures 25, 28, 31, 34, 37). This makes intuitive sense because increasing stand density increases the probability of crown overlap.

Aerial photographs

Aerial photographs were included in this study because they are a practical tool for estimating canopy cover over large areas. Although air photo analyses of all stands were conducted, due to statistical reasons, only three of the five covertypes were studied. Photo analysis of stands with a DF-WL covertype and WL covertype were shown not to be different from either the moosehorn or densitometer for both definitions of canopy cover. Photo analysis of stands with a LP covertype were shown not to be different from either the moosehorn or densitometer only for the convex polygon definition of canopy cover. This makes intuitive sense because when one views a stand stereoscopically, within crown gaps are rarely visible. Therefore any air photo analysis involves assuming canopy cover is defined as the downward projection of a tree crown. Patton (1998) drew similar conclusions.

Limitations

The limitations in applying the results from this research should be articulated. Only estimates of overstory canopy cover (dominant and codominant trees > 4.6" dbh) were evaluated in this study. All stands were even-aged with one single canopy strata. While a range of canopy cover was measured, the bulk of the measurements were between 40% - 80% canopy cover (Figures 44, 45). Ranges of stand densities were from 30 to 230ft^2/acre of basal area.

Figure 44. Canopy cover of plots used in this study (live crown)

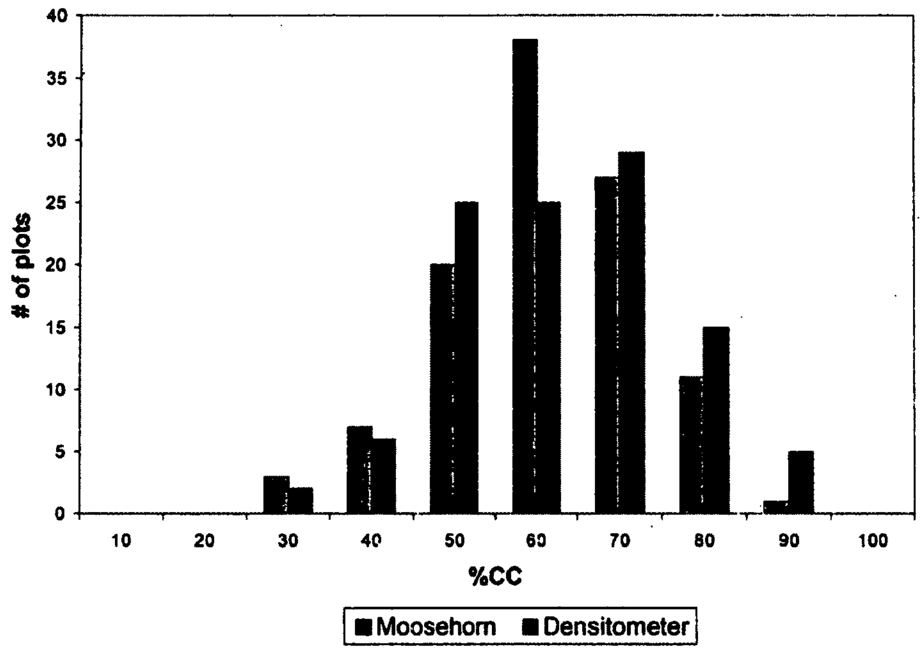
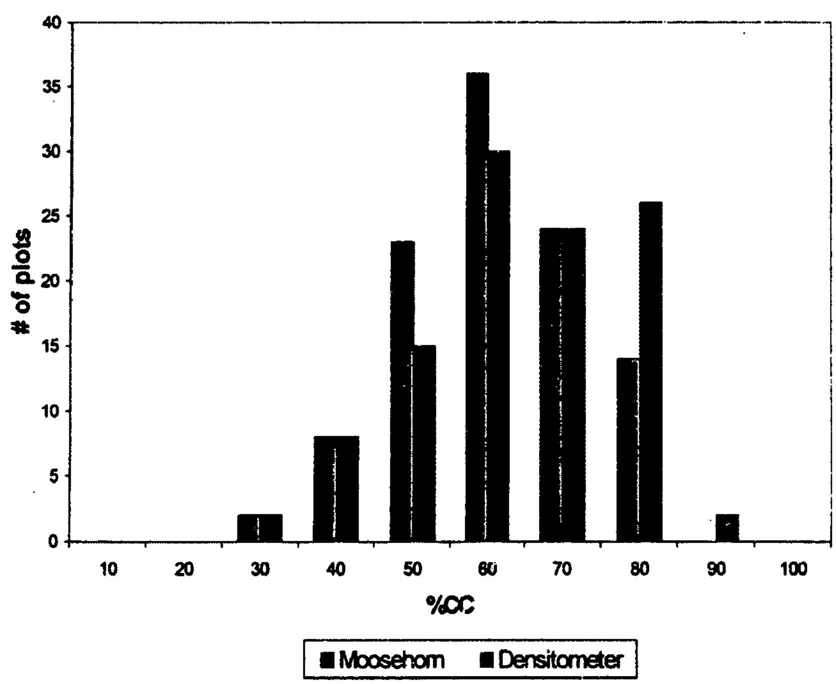


Figure 45. Canopy cover of plots used in this study (polygon)



The inventory procedures used on both study sites involved sub-sampling of heights and crown ratios for "in" trees based on diameter class. On the Flathead National Forest, 60% of the "in" trees had actual tree heights measured and 95% had actual live crown ratios measured. On LEF, that ratio falls to 50% for both the actual tree heights and live crown measurements. While sub-sampling for heights is a common inventory procedure in the Inland west, it does add a degree of error in assessing the ability of FVS to predict overstory canopy cover. With this data missing, FVS is estimating tree height and crown ratio, two of the three variables needed to estimate crown width, from internal equations. Tree heights are estimated from diameter-height curves calibrated using the inventory treelist, while crown ratio is estimated as a function of dbh, height, crown competition factor (CCF) and the basal area percentile rank of a tree (PCT) as determined from the inventory data by FVS (Wykoff and others 1982). If those estimates of tree height and crown ratio are underestimated or biased, so will be the crown width estimates (Eq. 2, pg. 11).

Perhaps the greatest limitation of this research is the sample sizes used for some covertypes. Three of the five covertypes (PP-WL-LP) studied had four stands in each, all thinned to a different mean TPA. Although there was replication of plots within every stand, there was no replication of stand-density combinations within a covertype. As such, the results from those covertypes are at best a case study, applicable only to those particular LSG units on LEF. The PP-DF and the DF-WL covertypes offer slightly more meaningful inferences. Both covertypes had relatively large sample sizes at the plot level, and had replication of their respective stand-density combinations. At the stand level, air photo interpretation was based on either three or four stands.

Flathead National Forest

It should be noted that although 41 plots were inventoried on the Flathead National Forest, 46 were originally installed. Five plots were excluded from analysis due to a significant hardwood overstory. The understory of these stands had significant amounts of advanced hardwood regeneration above 10' in height. As such, canopy measurements of the overstory had to be conducted in the fall following leaf senescence.

Trees in the FVS tree list were not necessarily trees for which canopy cover was recorded. Trees may have been within the limiting distance for variable-radius plot cruising, and so included in FVS, but outside the plot used to measure canopy cover and conversely, canopy cover at plot locations included crowns of trees not in the FVS treelist.

Lubrecht Experimental Forest

As previously stated, stands used in this study are part of the LGS study (MFCES 1986). A minimum of three, 0.1-acre permanent plots were established in each treatment of each stand of each unit. Canopy measurements were made on three randomly selected plots before attaining the 1995 inventory data from the School of Forestry, University of Montana personnel. Once obtained, it was discovered that only three plots were remeasured in each stand of each unit and did not necessarily correlate with the three randomly selected by this researcher. Therefore, some plots were disregarded in favor of plots for which inventory records did exist. Canopy measurements for those plots were made in late September and early October.

Conclusions

There were no significant differences between the moosehorn and densitometer in estimating overstory canopy cover when using a live crown definition for 4 of 5 covertypes. There were no significant differences between the moosehorn and densitometer in measuring overstory canopy cover when using a convex polygon approach on two of the five covertypes. The moosehorn consistently gave the most conservative estimate of overstory canopy cover and has a large enough viewing window to be an effective instrument regardless of how canopy cover was defined (live crown, convex polygon). Results from using the GRS Densitometer should be restricted to that instrument and not extrapolated to include other point estimate instruments due to the unique size of the viewing window and dot used to measure canopy cover. Although significant differences between these instruments were found in some cases, the level of difference may be acceptable depending on individual needs.

How canopy cover is defined is important to the measure of percent canopy cover. Using the downward projection of a tree's crown in the shape of a convex polygon yielded higher measures of percent cover than when using just the live crown of a tree. Using a convex polygon resulted in between ~8 – 15% higher estimates of canopy cover.
The downward projection method is typically how canopy cover is defined and is used when viewing aerial photographs stereoscopically.

The NI variant of FVS (v 6.2) underpredicts canopy cover. The NI variant was developed to encompass a large geographic region of northern Idaho and western Montana. The range of tree crown widths that the model is based on is very small and does not encompass the ranges of site quality and stand density needed to accurately predict canopy cover for these two study areas. Localized calibration may be necessary to incorporate FVS projections into stand and forest management when canopy cover is a concern. In order to better determine the full applicability of FVS in modeling canopy cover, further research is needed to encompass all 11 coniferous species of the Inland Empire across a range of site qualities, stand densities, and size classes.

Recommendations

Of the ground instruments used in this study, the moosehorn handled the most efficiently in the field. It has a large enough viewing window so that, regardless of how canopy cover is defined, it is a useful instrument. The large dot on the densitometer may have contributed to the higher values of mean percent cover obtained by it. The small viewing window was difficult to see the polygon in with open or sparse crowns.

The live crown approach is a physiologically relevant approach to defining canopy cover. Not all species or individuals within a species have dense crowns at all stages of development. A live crown approach captures the within crown canopy gaps. For shade tolerant species, canopy cover when using a live crown approach may be the same as when using a polygon approach (due to denser crowns of those species).

Literature Cited:

Avery, T. E and Burkhart, H. E. 1994. Forest measurements 4th ed. New York: McGraw-Hill. 1 408p.

Belt, G.H, O'Laughlin, J, and Merrill, T. 1992. Design of forest riparian buffer strips for the protection of water quality: analysis of scientific literature. Idaho Forest, Wildlife and Range Policy Analysis Group, Report no. 8.

Bojang, F.N.B. 1980. The predictions of residual merchantable volume of four coniferous species in western Montana. [M.S. thesis]. Missoula, (MT): University of Montana. 59p. Available from: The University of Montana.

Bonner, G.M. 1967. Estimation of ground canopy density from ground measurements. Journal of Forestry 65(8): 544-7.

Bonner, G.M. 1968. A comparison of photo and ground measurements of canopy density. The Forestry Chronicle 44(3): 12-16.

Belanger, R.P. and Anderson, R.L. 1992. A guide for visually assessing crown densities of loblolly and shortleaf pines USDA For. Ser. Res. Note SE-352.

Bennett, D.L., Lemme, G.D., and Evenson, P.D. 1987. Understory herbage production of major soils within the Black Hills of South Dakota. Journal of Range Management 40(2): 166-170.

Biging, G.S. and Wensel, L.C. 1990. Estimation of crown form for six conifer species of Northern California. Canadian Journal of Forest Research 20: 1137-1142.

Brown, J.K. 1978. Weight and density of Rocky Mountain conifers. USFS Res. Paper INT-197.

Bunnell, F.L., McNay, R.S., and Shank, C.C. 1985. Trees and snow: the deposition of snow on the ground – a review and quantitative synthesis. Res. Branch B.C. Minist. Environ. For. Pub. No. IWIFR –17.

Bunnell, F.L. and Vales, D.J. 1990. Comparison of methods for estimating forest overstory cover II. differences among techniques. Canadian Journal of Forest Research 20:101-107.

Busing, R.T. 1994. Canopy cover and tree regeneration in old-growth cove forests of the Appalachian mountains. Vegetatio 115(1): 19-27.

Caccia, F.D., and Ballare, C.L. 1998. Effects of tree cover, understory vegetation, and litter on regeneration of Douglas-fir (Pseudotsuga menziesii) in southwestern Argentina. Canadian Journal of Forest Research 28(5): 683-692.

Cade, B. S. 1997. Comparison of tree basal area and canopy cover in habitat models: subalpine forest. Journal of Wildlife Management 61(2): 326-335.

Coates, T. 1995. A comparison of canopy closure measurements used in stand inventories [M.S. thesis]. Missoula, (MT): University of Montana. 78p. Available from: The University of Montana.

Cook, J.G., Stutzman, T.W., Bowers, C.W., Brenner, K.A., and Irwin, L.L. 1995. Spherical densiometers produce biased estimates of forest overstory canopy cover. Wildlife Society Bulletin 23(4): 711-717.

Crookston, N.L. and Stage, A.R. 1999. Percent canopy cover and stand structure statistics from the forest vegetation simulator. USDA For. Ser. RMRS-GTR-24.

Daubenmire R. 1959. A canopy coverage method of vegetational analysis. Northwest Science 33(1): 43-63.

Dealy, J.E. 1960. The densiometer for measurement of crown intercept above a line transect. USDA For. Ser. Res. Note PNW-199.

Draper, N.R. and Smith, H. 1981. Applied regression analysis. 2nd edition. Wiley series in probability and mathematical statistics. New York City, NY.

Eastham, J. and Rose, CW. 1988. Pasture evaporation under varying tree planting density in an agroforestry experiment. Agricultural Water Management 15(1): 87-105.

Franklin, J. 1986. Thematic mapper analysis of coniferous forest structure and composition. International Journal of Remote Sensing 7: 1287-1301.

Ganey, J.L. and Block, W.M. 1994. A comparison of two techniques for measuring canopy closure. Western Journal of Applied Forestry 9(1): 21-3.

Garrison, G. A. 1949. Uses and modifications for the moosehorn crown closure estimator. Journal of Forestry 43: 733-747.

Gysel, L.W. and Lyon, L.J. 1980. Habitat analysis and evaluation. Wildlife Management Techniques Manual. Washington, D.C. Wildlife Society Press.

Hanks, L.F. and Thomson, G.W. 1964. Aerial stand volume tables for Iowa hardwoods. Iowa State Journal of Science 38(4): 415-426.

Helms, John A., editor. 1998. The dictionary of forestry. Maryland. The Society of American Foresters.

Hess, G. 1994. Pattern and error in landscape ecology: a commentary. Landscape Ecology 9(1): 3-5.

Ingebo, P.A. 1955. An instrument for measurement of the density of plant cover over snow course points. Proceedings of the 23rd western snow conference. Portland, Oregon. April. Discussion by Paul E. Lemmon.

ICRBEIS. Interior Columbia River Basin Environmental Impact Statement. 1996. USDA Forest Service.

Jackson, L.W. and Harper, R.S. 1955. Relation of light intensity to the basal area of shortleaf pine. Ecology 36: 158-9.

Johansson, T. 1985. Estimating canopy density by the vertical tube method. Forest Ecology and Management 11: 139-144.

Johansson, T. 1996. Estimation of canopy density and irradiance in 20-to 40-year-old birch stands (*Betula pubescens* ehrh. and *Betula pendula* roth). Trees 10: 223-230.

Johnson, P.L. and Vogel, T.C. 1968. Evaluation of forest canopies by photography. US Cold Regions Research and Engineering Laboratory Research Report 253.

Keane, R.E, Long, D.G., Menakis, J.P., Hann, W.J., and Bevins, C.D. 1996. Simulating coarse-scale vegetation dynamics using the Columbia River Basin Succession Model CRBSUM. USFS INT-GTR-340.

Klinka, K., Chen, H.Y.H., Wang, Q., and de Montigny, L. 1996. Forest canopies and their influence on understory vegetation in early-seral stands in West Vancouver island. Northwest Science 70(3): 193-200.

Lemmon, P.E. 1956. A spherical densiometer for estimating forest overstory density. Forest Science 2(1): 314-320.

Lemmon, P.E. 1957. A new instrument for measuring forest overstory density Journal of Forestry 55(9): 667-669.

Mackey, D.S. and Band, L.E. 1997. Forest ecosystems processes at the watershed scale: dynamic coupling of distributed hydrology and canopy growth. Hydrological Processes 11(9): 1197-1217.

Maguire, D.A., Kershaw, J.A. Jr., and Hann, D.W. 1991. Predicting the effects of silvicultural regime on branch size and crown wood core in Douglas-fir. Forest Science 37(5): 1409-1428.

Mayer, K.E. and Fox, L. III. 1981. Identification of conifer species groupings from Landsat digital classifications. Photogrammetric Engineering and Remote Sensing 48(11): 1607-1614.

McLaren, B.E. and Janke, R.A. 1996. Seedbed and canopy cover effects on balsam fir seedling establishment in Isle Royal National Park. Canadian Journal of Forest Research 26: 782-793.

Mead, R.A., Driscoll, R.S., and Smith, J.A. 1979. Effects of tree distribution and canopy cover on classification of ponderosa pine forest from Landsat-1 data. USDA For. Ser. Res. Note RM-375.

MFCES. Montana Forest and Conservation Experiment Station. 1986. Full-tree thinning and chipping demonstration project. University of Montana/Montana DNRC.

Mitchell, J.E. and Bartling, P.N.S. 1991. Comparison of linear and nonlinear overstory – understory models for ponderosa pine. Forest Ecology and Management 42: 195-204.

Mitchell J.E. and Popovich, S.J. 1997. Effectiveness of basal area for estimating canopy cover of ponderosa pine. Forest Ecology and Management 95: 45-51.

Moessner, K.E. 1964. Two aerial photo basal area tables. USDA For. Ser. Res. Note INT –23.

Moeur, M. 1981. Crown width and foliage weight of northern rocky mountain conifers. USFS Res. Paper INT-283.

Moeur, M. 1985. COVER: a user's guide to the canopy and shrubs extension of the stand prognosis model. USFS GTR-INT-190.

Nelson, M.D. and Buech, R.R. 1996. A test of 3 models of Kirkland's warbler habitat suitability. Wildlife Society Bulletin 24(1): 89-97.

Nemati, N. and Goetz, H. 1995. Relationships of overstory to understory cover variables in a ponderosa pine/gambel oak ecosystem. Vegetatio 119(1): 15-21.

Ott, R.L. 1993. An introduction to statistical methods and data analysis. 4th ed. CA. Wadsworth publishing. 1182p.

Pauley, G.R., Peek, J.M., and Zager, P. 1993. Predicting white-tailed deer habitat use in Northern Idaho. Journal of Wildlife Management 57(4): 904-913.

Plum Creek Timber Company. 1999a. Technical Report #7. Design of effective riparian management strategies for aquatic resources protection in Montana, Idaho, and Washington. J. Light, M. Holmes, M. O'Conner (O'Conner Environmental), E.S. Toth, D. Berg, D. McGreer (Western Watershed Analysts), and K. Doughty. Plum Creek Timber Company, L.P. Columbia Falls, Montana.

Quirk, B.K. and Scarpace, F.L. 1982. A comparison between aerial photography and Landsat-cover mapping. Photogrammetric Engineering and Remote Sensing 48(2): 235-240.

Rebertus, A.J. and Burns, B.R. 1997. The importance of gap processes in the development and maintenance of oak savannas and dry forests. Journal of Ecology 85(5): 635-645.

Reifsnyder, W.E. and Lull, H.W. 1965. Radiant energy in relation to forests. USFS Tech. Bul. 1344.

Salvador, R. and Pons, X. 1998. On the applicability of Landsat TM images to Mediterranean forest inventories. Forest Ecology and Management 104: 193-208.

Schrader-Patton, C.C., Pfister, R.D., and Queen, L.P. 1998. Estimation of forest stand structure attributes from aerial photographs. Intermountain Journal of Sciences. v.4 (1/2).

Skovlin, J.M. and Harris, R.W. 1974. Grassland and animal response to cattle grazing methods in the ponderosa pine zone. Proceedings, XII International Grasslands Congress, Section 5, part 2 (grassland utilization).

SNEP. 1996. Sierra Nevada ecosystem project final report to congress: the status of the Sierra Nevada. Wildland Resources Center, University of California. Report no. 36-39.

Spanner, M.A., Pierce, L.L., Running, S.W. and Peterson, D.L. The seasonality of AVHRR data of temperate coniferous forest: relationship with leaf area. Remote Sensing of the Environment 33: 97-112.

Strickler, G.S. 1959. Use of the densiometer to estimate density of forest canopy on permanent sample plots USDA For. Ser. Res. Note PNW-180.

Stage, A.R. 1973. Prognosis Model for Stand Development. Res. Pap. INT-137. U.S. Department of Agriculture. Forest Service. Intermountain Forest and Range Experiment Station.

Stumpf, K.A. 1993. The estimation of forest vegetation cover descriptions using a vertical densitometer. The GRS Densitometer. Geographic Resources Solutions.

Teck, R.T., Moeur, M. and Eav, B. 1996. Forcasting ecosystems with the forest vegetation simulator. Journal of Forestry 94(12): 7-10.

TEA. Trego Environmental Assessment: Kootenai National Forest, Fortine Ranger District. 1996. USDA Forest Service.

Vales, D.J. and Bunnell, F.L 1988. Comparison of methods for estimating forest overstory cover I. observer effects. Canadian Journal of Forest Research 18: 606-609.

Vora, R.S. 1988. A comparison of the spherical densiometer and ocular methods of estimating canopy cover. The Great Basin Naturalist. 48 (2).

Walters, J. and Soos, J. 1962. The gimbal sight for the projection of crown radius. University of British Columbia, Faculty of Forestry Research Note no. 39.

Wert, S.L. and Wickman, B.E. 1970. Impact of Douglas-fir tussock moth. USDA For. Ser. Res. Paper PSW-1970.

Whelan, R.J., Bull, M., and O'Dowd, D. 1988. The crown gap ratio (C) and crown cover: the field study The Australian Journal of Ecology 13: 101-108.

White, J.D., Kroh, G.C., and Pinder, J.E. III. 1995. Forest mapping at Lassen Volcanic National Park, California, using Landsat TM data and a geographic information system. Photogrammetric Engineering and Remote Sensing 61(3): 299-305.

Winterberger. K.C. and Larson, F.R. 1988. Measuring crown cover in interior Alaska vegetation types. Photogrammetric Engineering and Remote Sensing 54(3): 385-387.

Wykoff, W.R., Crookston, N.L., and Stage, A.R. User's guide to the Stand Prognosis Model. USDA For. Ser. GTR-INT 133.

Yang, J. and Prince, S.D. 1997. A theoretical assessment of the relation between woody canopy cover and red reflectance. Remote Sensing of the Environment 59: 428-439.

Appendix A. Summary of stands selected for this research

Forest	Plot type	Covertype	BA/acre range	Habitat type	Acres	n	Stand ID	Location
Flathead	variable	DF-WL	60-200	521*	25.0	8	12605095	T25N,R18W,S 24/25
Flathead	variable	DF-WL	80-220	520*	47.0	11	12605093	T25N,R18W,S 24/25
Flathead	variable	DF-WL	40-200	520*	66.0	22	12606095	T25N,R18W,S 24/25
LEF	fixed	PP	113-181	291	3.4	3	Rat-tail Draw (control)	T13N,R15W,S 16
LEF	fixed	PP	118-150	291	3.4	3	Rat-tail Draw (10')	T13N,R15W,S 16
LEF	fixed	PP	121-150	291	3.4	3	Rat-tail Draw (14')	T13N,R15W,S 16
LEF	fixed	PP	74-96	291	3.2	3	Rat-tail Draw (20')	T13N,R15W,S 16
LEF	fixed	WL	99-115	290	3.8	3	Coyote Park (control)	T13N,R14W,S 19
LEF	fixed	WL	86-107	290	2.7	3	Coyote Park (10')	T13N,R14W,S 19
LEF	fixed	WL	76-81	290	2.9	3	Coyote Park (14')	T13N,R14W,S 19
LEF	fixed	WL	41-62	290	3.7	3	Coyote Park (20')	T13N,R14W,S 19
LEF	fixed	LP	130-148	250	1.9	3	Jones Pond (control)	T13N,R14W, S 12
LEF	fixed	LP	95-121	250	1.9	3	Jones Pond (10')	T13N,R14W, S 12
LEF	fixed	LP	91-99	250	1.9	3	Jones Pond (14')	T13N,R14W, S 12
LEF	fixed	LP	61-74	250	1.9	3	Jones Pond (20')	T13N,R14W, S 12
LEF	fixed	PP-DF	144-157	291	3.4	3	Gate of Many Locks (control)	T14N,R15W,35
LEF	fixed	PP-DF	129-155	291	3.7	3	Gate of Many Locks (14')	T14N,R15W,35
LEF	fixed	PP-DF	84-110	291	5.5	3	Gate of Many Locks (20')	T14N,R15W,35
LEF	fixed	PP-DF	137-176	291	3.5	3	Shoestring (control)	T14N,R15W,35
LEF	fixed	PP-DF	138-175	291	3.9	3	Shoestring (14')	T14N,R15W,35
LEF	fixed	PP-DF	70-118	291	3.0	3	Shoestring (20')	T14N,R15W,35
LEF	fixed	PP-DF	50-229	291	2.5	3	Baker Road (control)	T13N,R15W, S 11
LEF	fixed	PP-DF	115-174	291	2.5	3	Baker Road (10')	T13N,R15W, S 11
LEF	fixed	PP-DF	143-168	291	2.5	3	Baker Road (14')	T13N,R15W, S 11
LEF	fixed	PP-DF	95-121	291	2.4	3	Baker Road (20')	T13N,R15W, S 11

* represents the dominant habitat type over the entire stand

Appendix B. Canopy cover values for plots on the Flathead National Forest (DF-WL covertype)

Stand_ID	Plot#	BA/acre	Moosehorn Live crown	Densitometer Live crown	Moosehorn Polygon	Densitometer Polygon	FVS (v 6.2)	FVS (v 5.0)
5093	1	120	61	58	68	75	27	31
5093	2	180	77	83	85	94	41	53
5093	3	200	71	72	75	72	41	53
5093	4	160	62	67	67	67	38	48
5093	5	100	63	75	72	78	20	22
5093	6	140	64	72	75	83	33	40
5093	8	140	55	58	68	75	33	40
5093	9	60	48	50	56	56	18	20
5093	11	60	41	36	49	50	14	15
5093	15	60	40	42	47	50	18	20
5093	16	120	53	61	58	64	31	37
5095	1	80	51	64	62	78	24	27
5095	2	120	54	64	65	75	30	36
5095	3	140	68	72	80	89	34	42
5095	4	100	40	39	43	47	30	36
5095	5	120	59	64	64	69	31	37
5095	6	100	84	83	89	86	33	40
5095	7	220	77	75	83	86	48	65
5095	8	160	78	81	86	89	31	37
6095	1	40	57	58	64	64	16	17
6095	2	180	68	72	75	75	32	39
6095	3	100	49	44	58	58	24	27
6095	4	160	70	76	75	81	33	40
6095	5	100	55	64	66	67	23	26
6095	6	160	61	64	70	69	28	33
6095	7	120	61	67	70	81	25	29
6095	8	200	58	61	68	72	35	43
6095	9	100	46	47	56	61	36	45
6095	10	100	59	61	66	72	25	29
6095	11	200	77	72	84	83	36	45
6095	12	100	71	69	80	86	25	29
6095	13	160	59	64	68	75	37	46
6095	14	120	44	47	52	56	29	34
6095	15	120	66	78	79	86	32	39
6095	16	200	69	69	78	75	48	65
6095	17	80	43	42	52	58	22	25
6095	18	140	43	50	51	50	29	34
6095	19	140	53	58	67	75	25	29
6095	20	140	48	53	60	72	31	37
6095	21	120	63	69	68	72	30	36
6095	22	200	69	75	77	78	38	48

Appendix C. Canopy cover values for plots on the Lubrecht Experimental Forest

LGS	Plot#	BA/acre	Moosehorn Live crown	Densitometer Live crown	Moosehorn Polygon	Densitometer Polygon	FVS (v 6.2)	FVS (v 5.0)
control	1	140	66	64	86	86	28	33
control	2	148	60	69	81	81	29	34
control	3	130	60	58	84	83	25	29
(10')	1	121	54	56	68	67	25	29
(10')	2	108	58	67	72	81	23	26
(10')	3	95	57	50	70	72	21	24
(14')	1	99	53	50	66	67	21	24
(14')	2	91	48	50	60	64	20	22
(14')	3	94	51	53	66	69	21	24
(20')	1	61	28	28	39	36	15	16
(20')	2	61	45	44	53	53	16	17
(20')	3	74	62	72	74	83	19	21

LP covertype

LGS	Plot#	BA/acre	Moosehorn Live crown	Densitometer Live crown	Moosehorn Polygon	Densitometer Polygon	FVS (v 6.2)	FVS (v 5.0)
control	1	175	75	72	83	83	37	46
control	2	181	65	72	79	86	35	43
control	3	113	55	57	70	63	27	31
(10')	1	150	59	58	71	86	32	39
(10')	2	122	45	50	59	56	31	37
(10')	3	118	51	53	67	69	32	39
(14')	1	121	55	53	68	72	27	31
(14')	2	150	61	64	78	83	30	36
(14')	3	133	53	58	65	69	26	30
(20')	1	95	51	47	61	58	29	34
(20')	2	96	45	50	58	67	28	33
(20')	3	74	40	47	54	61	23	26

PP covertype

LGS	Plot#	BA/acre	Moosehorn Live crown	Densitometer Live crown	Moosehorn Polygon	Densitometer Polygon	FVS (v 6.2)	FVS (v 5.0)
control	1	99	69	69	80	83	38	48
control	2	115	70	69	82	78	36	45
control	3	111	64	67	76	75	35	43
(10')	1	107	49	53	59	58	35	43
(10')	2	96	56	58	66	67	33	40
(10')	3	86	79	86	88	92	28	33
(14')	1	77	46	47	58	61	33	40
(14')	2	81	53	64	62	64	29	34
(14')	3	76	61	61	68	64	29	34
(20')	1	41	27	28	33	39	24	27
(20')	2	55	32	31	43	44	29	34
(20')	3	62	36	42	42	44	31	37

WL covertype

Appendix C (con't.)

LSG	Plot#	BA/acre	Moosehorn Live crown	Densitometer Live crown	Moosehorn Polygon	Densitometer Polygon	FVS (v 6.2)	FVS (v 5.0)
control	1	148	52	53	61	61	33	40
control	2	144	65	69	69	72	36	45
control	3	157	53	50	67	61	38	48
(14')	1	134	60	61	72	75	31	37
(14')	2	155	56	53	68	67	37	46
(14')	3	129	53	47	68	72	34	42
(20')	1	86	46	42	57	56	27	31
(20')	2	84	51	50	65	56	24	27
(20')	3	110	54	58	66	69	29	34
control	1	164	62	81	71	83	36	45
control	2	137	51	56	58	58	36	45
control	3	176	73	75	80	83	41	53
(14')	1	149	71	69	81	81	36	45
(14')	2	175	67	69	77	78	39	49
(14')	3	138	56	53	63	56	33	40
(20')	1	70	28	31	40	44	24	27
(20')	2	85	33	42	45	44	24	27
(20')	3	118	50	53	65	61	31	37
control	1	161	50	50	56	61	42	54
control	2	229	46	53	54	58	43	56
control	3	50	51	50	60	61	17	19
(10')	1	174	75	69	85	83	41	53
(10')	2	115	45	47	53	61	31	37
(10')	3	156	66	64	72	81	38	48
(14')	1	168	63	64	72	67	41	53
(14')	2	153	67	75	81	86	36	45
(14')	3	143	54	56	60	64	34	42
(20')	1	95	40	39	48	53	28	33
(20')	2	96	56	58	73	78	30	36
(20')	3	121	49	56	58	58	32	39

PP-DF covertype

Appendix D. Mean canopy measurements for each stand (n = 25)

Stand_ID	plots	Habitat Type	Moosehorn live crown	Densitometer live crown	Moosehorn polygon	Densitometer polygon	Photo	FVS (v 6.0)	FVS (v 5.0)
5093	12	520	58	60	65	69	70	27	31
5095	8	520	64	68	72	77	85	42	54
6095	22	520	59	60	68	71	70	32	39
BK (10')	3	291	62	60	70	75	75	37	46
BK (14')	3	291	61	65	71	72	75	37	46
BK (20')	3	291	48	51	60	63	45	30	36
BK control	3	291	49	50	56	59	55	37	46
GML (14')	3	291	56	54	69	71	85	34	42
GML (20')	3	291	50	50	63	60	35	27	31
GML control	3	291	57	57	66	65	65	36	45
SS (14')	3	291	65	64	74	72	25	35	43
SS (20')	3	291	37	42	50	50	50	26	30
SS control	3	291	62	71	70	75	85	38	48
CP (10')	3	290	67	69	77	81	85	31	37
CP (14')	3	290	54	55	65	63	65	30	36
CP (20')	3	290	34	34	43	49	55	28	33
CP control	3	290	68	68	79	79	95	36	45
JP (10')	3	250	56	58	69	73	95	23	26
JP (14')	3	250	51	51	64	67	85	21	24
JP (20')	3	250	45	48	55	57	65	17	19
JP (control)	3	250	62	64	84	83	95	27	31
RD (10')	3	291	52	54	66	70	65	31	37
RD (14')	3	291	56	58	70	75	50	27	31
RD (20')	3	291	45	48	58	62	35	27	31
RD (control)	3	291	65	67	77	77	85	33	40

* where GML = Gate of Many Locks (PP-DF), SS = Shoestring (PP-DF), BK = Baker Rd. (PP-DF), CP = Coyote Park (WL), JM = Jones Meadow (LP), RD = Rat-tail Draw (PP)