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Timbra H. Coates

The University of Montana

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A COMPARISON OF CANOPY CLOSURE MEASUREMENTS USED IN STAND INVENTORIES

by

Timbra H. Coates

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Approved by:

Donald J Bedunah

Chairperson

Dean, Graduate School

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Date

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A Comparison of Canopy Closure Measurements Used In Stand Inventories

Director: Donald J. Bedunah DJB

Today's forest management requires a better understanding of all variables measured in stand inventory for management of healthy and diverse forest ecosystems. One such variable which needs more study is canopy closure. Therefore, the objectives of this study were: 1) to compare the canopy closure estimates obtained by field techniques (the spherical densiometer and the moosehorn) to each other and to data calculated from previously recorded stand inventory variables; 3) to compare the canopy closure estimates to measurements of light transmittance; and 4) to determine if there is any correlation of the canopy closure estimates and the light measurements with cover (%) of understory vegetation.

Canopy closure was measured using a moosehorn and a spherical densiometer on previously cruised point sample plots. Percent total PAR (photosynthetically active radiation) was measured with a Sunfleck ceptometer. Canopy closure and cover (%) of understory vegetation were also predicted using the Stand Prognosis Model. Field measured vegetation cover estimates were previously recorded in the stand inventory.

The moosehorn and the densiometer mean canopy closure estimates were found to be significantly different ($p < 0.001$). They were strongly correlated at the stand level ($r = 0.90$). The moosehorn and the predicted estimates of canopy closure were not significantly different ($p = 0.005$) but only weakly correlated ($r = 0.66$) at the stand level. The densiometer estimates of canopy closure were significantly different from those predicted ($p < 0.001$) but strongly correlated at the stand level ($r = 0.84$). The canopy closure estimates of the densiometer were the most highly correlated with the ceptometer ($r = 0.88$) at the stand level. The canopy closure estimates of the moosehorn and Prognosis were only moderately correlated with % PAR ($r = 0.79$ and $r = 0.71$, respectively). Brush >4.0 ft tall was found to confound the measurements of the ceptometer. Correlations of the canopy closure and light measurements with the vegetation were inconsistent. The strongest correlations were made at the stand level and the greatest number of significant correlations were made with the predicted percent canopy cover and average height.

It was concluded that predicted canopy closure estimates do not approximate those made with field techniques and that the estimates of the moosehorn and the densiometer are not equivalent.

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CHAPTER I:

INTRODUCTION

Justification

Forest management requires the consideration of many forest values and uses. With the adoption of the paradigm of "ecosystem management" the U. S. Forest Service is attempting to consider all parts of an ecosystem, biotic and abiotic, during the decision-making process. This shift in Forest Service policy is largely a result of society demanding more than timber from forest ecosystems. In addition, forest management has been increasingly dictated by state and federal regulations in recent years thereby requiring an examination of ecosystem variables other than those measured in stand inventory. Other ecosystem variables, such as canopy closure and quantity of understory vegetation, play a role in how well a given portion of the forest ecosystem is suited for wildlife habitat.

A Habitat Suitability Index (HSI) has been developed to evaluate how well key habitat components are able to supply the life requisites of selected species of fish and wildlife. This index is outlined for each priority species based upon unique characteristics of the ecosystem which they require for survival (101 Ecological Services Manual 5.1). A priority species is defined as any "wildlife species requiring protective measures for their perpetuation due to their population, their sensitivity to habitat alteration, and/or their recreational importance." Many of these species are only given the rating of "priority" within limiting habitats such as breeding areas or winter range found within their overall range (Washington Dept. of Wildlife 1993). Definition of these limiting ranges and the habitat characteristics which they encompass aids in the management of the species which use them.

A stand level variable indirectly included in a species' HSI is canopy closure. Canopy closure has been defined as the area covered by the vertical projection of plant crowns to the ground surface (Gysel and Lyon 1980, cited in Vora 1988). As an example, the HSI of a priority bird species may include specific characteristics of a particular stand habitat that indicate suitable cover. Such characteristics may include a description of diameter at breast height (dbh) classes and basal area of the trees in a stand found in the habitat used by the species for mating, nesting or foraging. These characteristics, while not a direct measure, contribute to the definition of the canopy closure for a particular habitat. In addition, there may also be a description of the food value of the stand which is inferred from the understory vegetation structure including height classes and herbaceous canopy cover (%) (103 ESM 3.3B).

One might assume that since canopy closure is an important component in an HSI for a priority species and/or habitat, it would be routinely measured. However, despite its importance, canopy closure is not regularly measured in a stand inventory. Other variables, such as tree diameter distribution and basal area, are routinely measured and from these measurements an estimate of canopy closure can be calculated using equations such as Equation [1] which is used by the Cover extension of the Stand Prognosis Model (Moeur 1985):

$$[1] \quad \text{Percent canopy closure} = \frac{\Sigma \text{ Crown areas } (\text{ft}^2/\text{ac})}{43{,}560 \text{ ft}^2/\text{ac}} \times 100$$

Since a direct canopy closure measurement is relatively simple and may be more accurate and useful when managing forest stands on an ecosystem basis, these field techniques should be considered for use in stand inventory.

A number of instruments (i.e. the moosehorn and spherical densiometer) and methods (i.e. ocular estimation and wide angle photography) have been designed to measure canopy closure. The moosehorn is a periscope-type instrument which approximates a vertical projection of canopy closure. With a very narrow angle of view (3° to 6°, depending on the style of instrument used) it is able to sample only the canopy directly over the sample point. In the same way it is also able to sample small gaps in the canopy.

The spherical densiometer, another instrument designed to measure canopy closure, has a much wider angle of view (approximately 60°). The densiometer reflects the canopy over the sample point in a convex mirror. Due to the wide angle of view, the mirror reflects not only canopy but tall brush (> 5.0 ft), tree boles and shade. The inclusion of tall brush in the estimation of overstory canopy closure could conceivably result in overestimation unless the brush is easily disregarded from the canopy reflection. The wide angle of view of the densiometer also prevents it from sampling the small openings in the canopy.

The predictions made with Prognosis are based upon tree height, diameter and crown ratio which are used to calculate the individual tree crown areas. The data used for predictions were collected in a point sample inventory which consists of variable radius plots. As Equation [1] illustrates, the canopy closure (%) is calculated using the sum of the crown areas in each plot. This calculation allows for the exclusion of brush from the canopy closure estimation producing a more pure estimate similar to the moosehorn but unlike the densiometer.

A fourth method of canopy closure estimation, while indirect, is measurement of the proportion of total PAR (photosynthetically active radiation) which is being transmitted through the overstory canopy. This measurement can be made using a light meter such as the Sunfleck ceptometer which measures incoming PAR ($\mu mol/m^2/s$) 180°.

Only a few studies (Vora 1988; O'Brien 1989; Bunnell and Vales 1990) have been published comparing the canopy closure estimates of these instruments and methods. In addition, these studies have examined only a limited number of forest types and structures and they have indicated that some provide variable or biased results or are time consuming to use. Therefore, there is a need first, to compare the canopy closure estimates of field techniques to those calculated using the stand inventory data. Second, to evaluate the precision of a moosehorn and compare the estimates of that moosehorn to those of the more commonly used spherical densiometer. Finally, to compare the estimates of canopy closure from both instruments to light transmittance and the amount of understory vegetation cover (%) in a stand. A comparison of the canopy closure estimators will aid in selecting the most efficient method of canopy closure estimation and to determine if a direct measurement is even necessary.

Objectives

There are four major goals of this study. First, I will describe and compare the canopy closure estimates obtained by the spherical densiometer and the moosehorn in a range of forest canopy structures.

Second, I will examine the relationship of calculated canopy closure (%) predictions to the estimates made using the moosehorn and the spherical densiometer. This will be done by calculating canopy closure with Equation [1] using the stand variables that were previously measured in the stand inventory (tree diameter, height, and crown ratio). If there is a strong relationship the addition of a direct canopy closure measurement to the stand inventory would not be necessary.

Third, I will compare the canopy closure estimates, to measurements of light transmittance, specifically PAR, measured on the same plots.

Finally, I will determine if there is a significant difference between the mean cover (%) of understory vegetation predicted by Prognosis and that estimated by the cruisers. In addition, I will determine if the canopy closure estimates and light measurements are correlated with the understory vegetation classes. In other words, is it possible to make a reliable estimate of the cover (%) of understory vegetation that will be present in a stand by examining only the stand inventory and/or the canopy closure measurements?

The null hypotheses that I will test in order to achieve these objectives are as follows:

H_o: There is no significant difference between the canopy closure estimates of the spherical densiometer and the moosehorn.

H_o: There is no significant difference between the canopy closure measurements predicted from the stand inventory data and the canopy closure field measurements from either the spherical densiometer or the moosehorn.

H_o: There is no significant correlation between the PAR measurements of the ceptometer and canopy closure measurements of the moosehorn and the spherical densiometer and those predicted by Prognosis.

H_o: There is no significant correlation between the canopy closure estimates, PAR measurements, and the cover (%) and average height of understory vegetation.

H_o: There is no significant difference between a calculated prediction of the cover (%) and average height of understory vegetation and actual field measurements.

Literature Review

The traditional stand inventory process has often included a simple ocular estimation of canopy closure. As would be expected, estimates made with this method vary considerably (Daniel et al. 1979, O'Brien 1989). While these canopy closure estimates were not always a standard measurement in stand inventory, they have been made in the past to establish spacing standards in thinning and to determine light requirements for regeneration (Lemmon 1956). They are currently being used to define habitat for wildlife species as well. Numerous instruments and methods of estimating canopy closure have been developed. Examples include: photometers (Weaver and Clements 1929, Matusz 1953), light meters (Jackson and Harper 1955), photographic methods (Suzuki and Satoo 1955), vertical crown projection methods (Jackson and Petty 1973), and ocular estimations of canopy closure. In an attempt to standardize canopy closure estimations Lemmon (1956) designed a spherical densiometer. The spherical densiometer has a convex mirror which provides a wide angle of view of the forest canopy. The instrument was then subjected to a series of field tests in several ponderosa pine (*Pinus ponderosa*) forests in south central Oregon and south central Washington. In these field tests it was determined that there were no significant differences among measurements made by different operators. However, differences were highly significant due to forests (above the 99% level of probability) (Lemmon 1957).

Further evaluation of the densiometer in comparison with other methods has revealed a bias toward overestimating the amount of canopy closure. This is believed to be associated with the densiometer's wide angle of view (approximately 60°). Bunnell and Vales (1988) made a comparison of 13 different methods of measuring canopy closure in southern British Columbia using plots with western hemlock (*Tsuga heterophylla*), Douglas-fir (*Pseudotsuga menziesii*) and western red cedar (*Thuja plicata*) in the overstory. The techniques they evaluated included ocular estimation, a gimbal site, concentric grids with angles of view ranging from 10° to 50°, 50- and 100-mm lenses, a moosehorn and spherical densiometer. They found that the estimates of canopy closure increased with the angle of view of the instrument. These comparisons were made relative to their moosehorn which approximates a vertical projection with a angle of view of 6°.

Vora (1988) found no significant difference between ocular estimates of canopy closure and those he made with a spherical densiometer. However, he made no comparison of the ocular estimates of different observers which O'Brien (1989) found to yield varying results. Vora (1988) conceded that, while ocular estimation is "fairly accurate with a trained observer", neither it nor the spherical densiometer provide an easy estimation of light penetration through the canopy. The light penetration is of greater biological significance both in a direct manner to the understory vegetation that is present and indirectly to the wildlife species that use the stand.

The amount of stand canopy closure largely controls the level of available light that penetrates to the vegetation below (Anderson et al. 1968). Anderson et al. (1968) used regression analysis to illustrate a strong relationship ($r = 0.75$) of canopy closure to understory vegetation in eastern white pine (*Pinus strobus*) and red pine (*Pinus resinosa*) forests in northern Wisconsin. McLaughlin (1978) found that the amount of open canopy, which was measured using a spherical densiometer, in the east, south, and west directions, accounted for a significant proportion ($R^2 = 0.56$) of the variance of light penetration in an Arizona ponderosa pine forest. Pyke and Zamora (1982) found a positive correlation ($R^2 = 0.80$) between canopy closure and the amount of understory vegetation biomass production in the grand fir (*Abies grandis*)/myrtle boxwood (*Pachistima myrsinities*) habitat type in north central Idaho. Using the stand inventory data they were also able to determine that the sum of tree diameters was a good predictor of shrub and total understory production. Conversely, they found that basal area was not a good predictor of understory production. In a similar study, Kie (1985) found that production of deerbrush (*Ceanothus integerrimus*) and mountain whitethorn (*C. cordulatus*) had a tendency to decrease with increasing canopy closure.

In summary, a few studies have evaluated the accuracy of the spherical densiometer (Lemmon 1956, Bunnell and Vales 1990). Other studies have evaluated the relation of the canopy closure estimates of the spherical densiometer to the production of understory shrubs (Kie 1985) and the amount of light penetration (Anderson et al. 1968). However, no studies have been done to evaluate the estimates of a moosehorn with a 3° to 4° angle of view and its relation to the spherical densiometer and/or a canopy closure prediction calculated from stand inventory variables. There have also been few studies relating the canopy closure estimates of the moosehorn, spherical densiometer and/or a calculated canopy closure to the PAR measurements of a ceptometer or their relation to the cover (%) of understory vegetation in a given stand. There is, therefore, a need for an examination of these, especially in the forest types found in northeastern Washington where these instruments have not been evaluated.

CHAPTER II:

INSTRUMENTS AND METHODS

Instrument Description

Spherical densiometer. Lemmon (1957) designed convex and concave models of the spherical densiometer. The convex spherical densiometer was the model which was examined in this study. This model has a polished chrome mirror 2.5 inches in diameter which had the curvature of a 6-inch sphere. The mirror is mounted in small wooden recessed box with a hinged lid. The overall dimensions of the instrument are about 3.5 x 3.5 x 1.12 inches. A spirit level is recessed into the wood next to the mirror (Fig. 1).

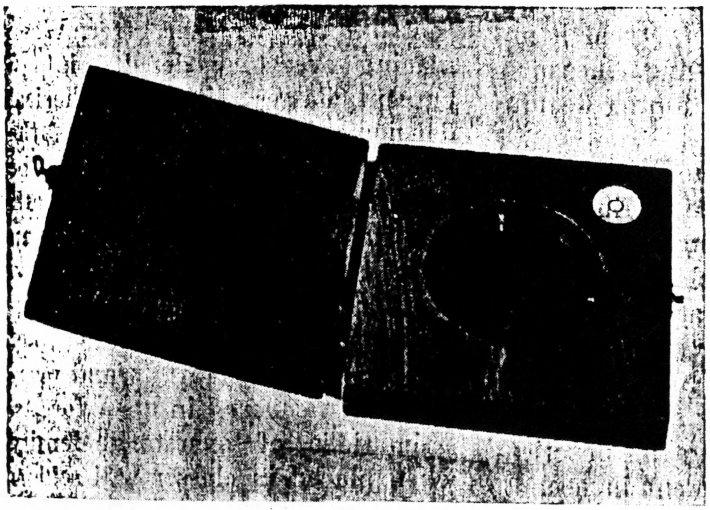
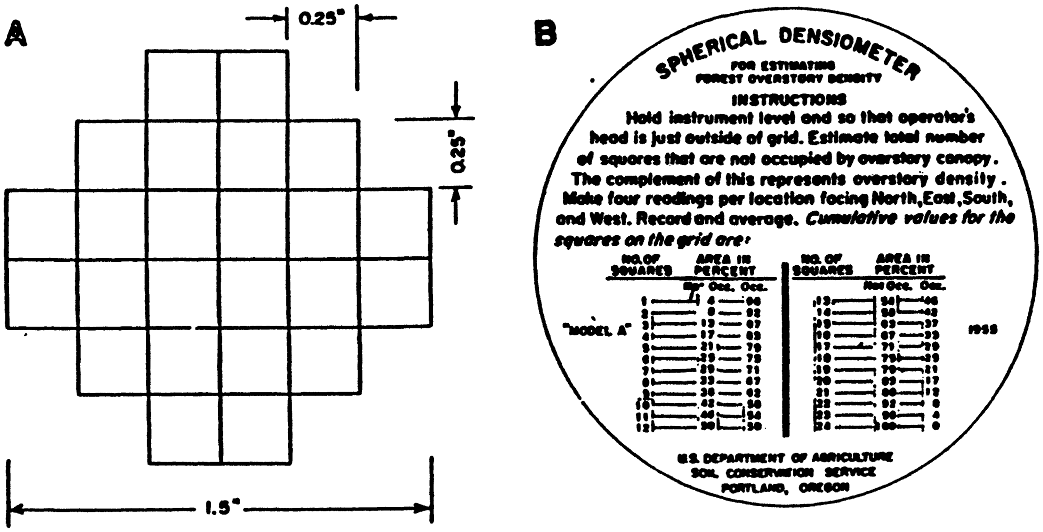


Fig. 1. Spherical densiometer, Model A, with estimating grid scratched on the surface of the convex mirror (Lemmon 1957).

The convex mirror has a grid of twenty-four 0.25-inch squares etched on it (Fig. 2).



SPHERICAL DENSIOMETER
FOR ESTIMATING
FOREST OVERSTORY DENSITY
INSTRUCTIONS

Hold instrument level and so that operator's head is just outside of grid. Estimate total number of squares that are not occupied by overstory canopy. The complement of this represents overstory density. Make four readings per location facing North, East, South, and West. Record and average. *Cumulative values for the squares on the grid are:*

"MODEL A" 1955

NO. OF SQUARES	AREA IN PERCENT Not Occ.	Occ.	NO. OF SQUARES	AREA IN PERCENT Not Occ.	Occ.
1	4	96	13	54	46
2	8	92	14	58	42
3	13	87	15	63	37
4	17	83	16	67	33
5	21	79	17	71	29
6	25	75	18	75	25
7	29	71	19	79	21
8	33	67	20	83	17
9	38	62	21	88	12
10	42	58	22	92	8
11	46	54	23	96	4
12	50	50	24	100	0

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
PORTLAND, OREGON

Fig. 2. (A) Cross-shaped grid scratched on the convex surface of the mirror in Model A. Each square is 0.25 inch on the side. (B) Instructions for using Model A. This is fastened to the inside of the lid of the mounting box (Lemmon 1957).

The canopy closure of the overstory is estimated by visualizing four equi-spaced dots in each square and by counting the dots that are not covered by canopy. Because the spherical densiometer is frequently used to estimate canopy closure, it may be possible to minimize the amount of error by using only the 37 intersections or by using subsets of the intersections. This may prove to be a more practical method of estimation in the field, as well.

Moosehorn. The moosehorn was originally developed by the Air Surveys Division of the Dominion of Canada Forest Service, Department of Mines and Resources. Garrison (1949) described some modifications to the original instrument to better adapt it to measurements at permanent observation points (Fig. 3).

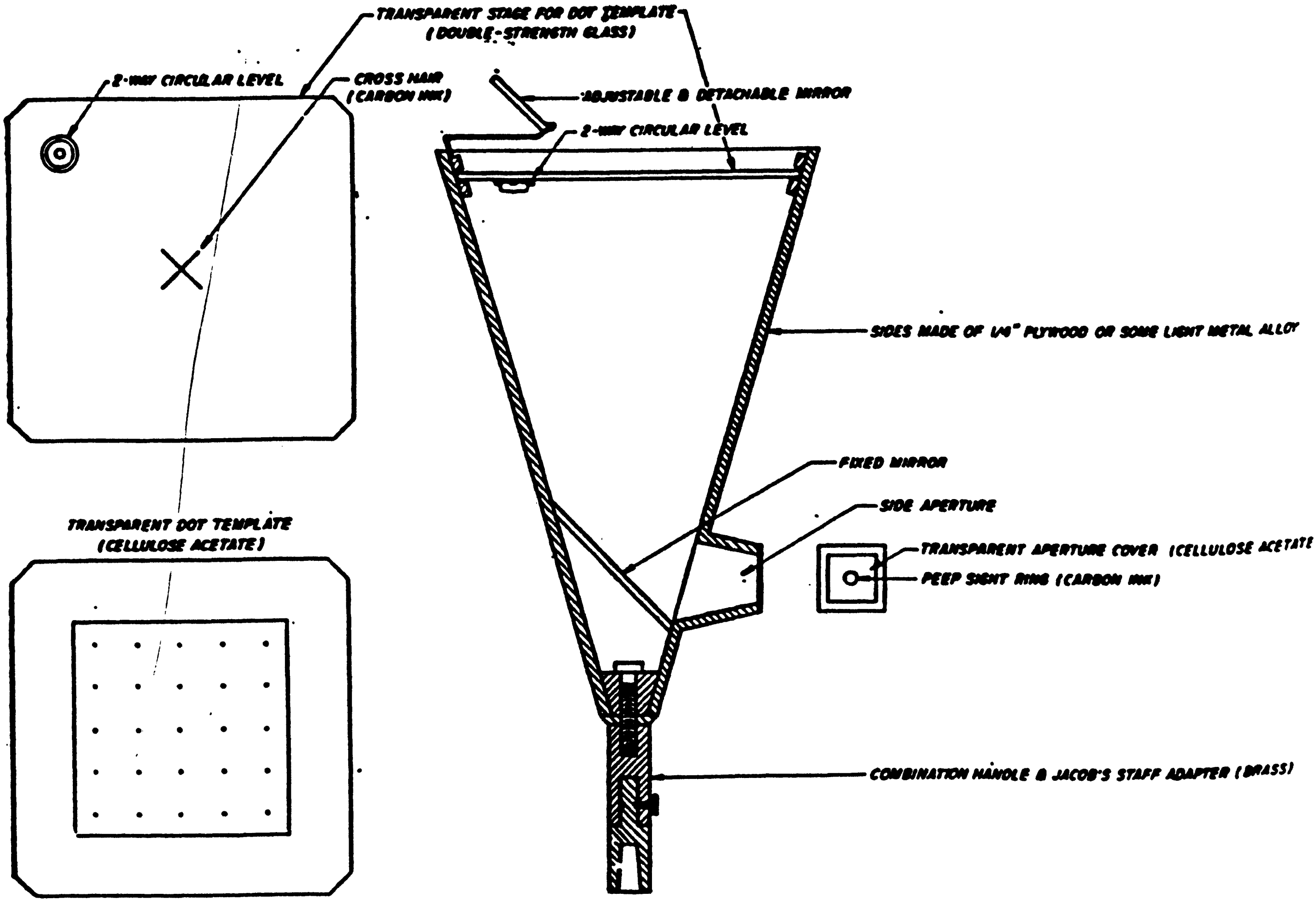


Fig. 3. Sectional view and parts of the "moosehorn" crown closure estimator (Garrison 1949).

The instrument used in this study was further modified for ease of use and was constructed of plastic PVC pipe approximately 1.75 inches in diameter and approximately 7.75 inches long. Similar to the Garrison's model in Figure 3, it has a fixed mirror which reflects the grid at the top of the instrument. The grid is composed of 25 equi-spaced black dots and has a two-way circular level mounted next to it.

Ceptometer. The Sunfleck Ceptometer (model SF-80, Decagon Devices, Incorporated) is a hand-held instrument with 80 independent light sensors located at 0.39-inch intervals along a sensor probe. It was designed to measure photosynthetically active radiation (PAR) ($\mu mol/m^2/s$) which occurs in the 400 to 700 nm wavelength range of light. The light sensor probe is attached to a battery-powered datalogger which averages and stores the measurements for later transfer into a computer for analysis (Decagon Devices 1987).

Study area description

My study area included 11 stands located in three counties of northeastern Washington state (Spokane, Stevens and Ferry counties). The dominant overstory species varied with each stand sampled. The two most dominant overstory species in the stands were Douglas-fir and ponderosa pine. Grand fir, western larch (*Larix occidentalis*), western hemlock and western red cedar also occurred occasionally as subdominant species.

Table 1 is a summary of the habitat type, slope, aspect, elevation, and number of plots in each of the stands.

Table 1. Characteristics of stands sampled.

Stand Name	Habitat Type	Slope (%)	Aspect (degrees)	Elev. (ft)	Plots (n)
Barstow 011	PSME/PHMA	30	090	3300	14
EKentry 040	PSME/PHMA	60	130	3800	3
EKentry 180	PSME/PHMA	70	130	4000	2
EKentry 330	PSME/PHMA	40	090	3600	6
Galena 100	THPL/PAMY	15	070	3300	8
Galena 262	ABGR/PAMY	50	300	3700	5
Lotz Cr 081	ABGR/PAMY	40	110	4200	3
Lundimo 034	PSME/PHMA	20	090	3300	9
Nugent 181	PSME/CARU	45	180	3600	5
Nugent 190	ABGR/PAMY	45	030	3400	5
WKentry 340	PSME/PHMA	40	220	4000	10

Field Techniques

Stand and plot selection. Stands were randomly chosen by foresters at Boise Cascade Corporation for check cruising. Point sample cruise plots were located randomly in the previously cruised stands using the cruiser's plat cards and sampled. Plots taken from a total of 11 stands were sampled in this manner (Table 1).

Canopy closure estimation. An estimation of canopy closure was made using the moosehorn and the spherical densiometer. Standing directly over the chosen sample point on the plot I held the densiometer with both hands in a position such that my arms were parallel to the ground and the instrument was level. The densiometer was held so that my head was just outside the reflection area of the densiometer's mirror. I then counted and recorded the number of intersections on the grid that were not covered by canopy out of a possible 37. This number was then subtracted from 37 to determine the number of covered intersections which was then divided by 37 to give the proportion of canopy closure in each direction at the sample point. This procedure was followed facing all four cardinal directions at each sample point. These four estimates were subsequently averaged to determine the mean canopy closure at the plot. I then visualized four equi-spaced dots in each square of the grid on the densiometer's face (Fig. 4).

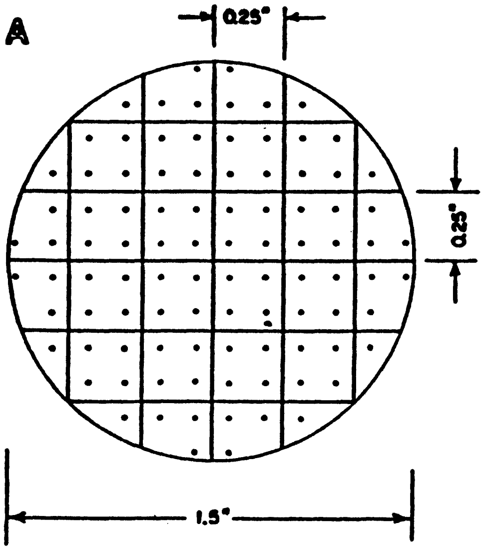


Fig. 4. Circular grid with four equi-spaced dots per square (Lemmon 1957).

The number of dots not covered by canopy were counted, recorded facing the four cardinal directions and subtracted from 96 to determine the number of covered dots. This number was then divided by 96 to give the proportion of canopy closure in each of the four directions. The four estimates were subsequently averaged to determine the mean canopy closure above each sample point. At the same point canopy closure was measured with the moosehorn. Standing directly over the sample point, I held the instrument to my eye and leveled it. I then counted and recorded the number of uncovered dots on the grid of 25 facing in all four cardinal directions. The number of uncovered dots was then evaluated like those of the densiometer determining the number of covered dots and subsequently the proportion of canopy closure over the point.

PAR. A ceptometer measurement of total available PAR ($\mu mol/m^2/s$) was made in an open area prior to any sampling on the plots. After taking the canopy closure measurements the ceptometer measurements of PAR were made at the sample point and as near the same time as possible. Standing directly over the sample point the instrument was held level and at a distance so that my shadow would not effect the light readings on the wand. Initially facing north, I made a series of 16 readings by rotating clockwise in a 360° circle. Each reading was made at an interval of approximately 22.5° (±2°). Each reading was stored in the instrument's datalogger until all 16 had been made. When all 16 readings were completed I stored their average in the datalogger for future downloading.

Data Analysis

The Cover extension (Moeur 1985) of the Stand Prognosis Model (Stage 1982) was used to calculate the predicted understory vegetation cover and canopy closure from the stand variables that had been previously measured by the cruisers on each sample plot. Visual estimates of the cover (%) and average height of understory vegetation by species had also been previously recorded by the cruisers. The cover estimates made in the field were recorded as percentage classes (e.g. 0 = trace, 1 = 1 to 10 percent cover, 2 = 11 to 20 percent cover, etc.). Prognosis divided the predicted cover estimates into height classes of low (0.0 - 1.7 ft), medium (1.7 - 7.0 ft), and high (>7.0 ft). For comparative reasons, the cover of understory vegetation estimated by the cruisers was divided into these same height classes (see Appendix A for species evaluated). In addition to these, the total cover (%) and the average height of understory vegetation on each plot were evaluated. Therefore, a total of 10 understory vegetation classes were analyzed--five each for the Prognosis predicted cover and field estimates of cover.

The understory vegetation data estimates that were predicted by Prognosis were based upon the time since the stand was harvested, the stand habitat type, the general physiographic location of the stand (e.g. lower, mid, or upper slope), and the type of disturbance the stand experienced (Moeur 1985). The resulting data was, therefore, a prediction of the understory vegetation that should be present in the stand given the above variables. For the understory vegetation data which was visually estimated by the cruisers the midpoint of each percent cover class was used to calculate the mean canopy cover estimate for each plot.

The mean PAR measurement of the ceptometer for each plot was divided by the total available PAR measurement taken in the open area prior to sampling. This proportion (x100) was evaluated as the percent of total available PAR being transmitted through the canopy.

The percentage data of all of the instruments and the Prognosis predicted data were transformed using an arcsine transformation of the square root of the data (Ott 1977). The data were transformed in order to satisfy the requirements for a normal distribution and homogeneity of variance for use in paired t-tests and correlation.

The canopy closure instrument means and the Prognosis predicted and field measured means of understory vegetation cover and average height were compared using paired t-tests. Scatterplots were used to evaluate the relationships of the variables to each other and correlation was used to examine the strength of those relationships. An alpha level of 0.05 was used. All data analyses were done using the SPSS/PC+ Studentware Plus statistics software (Norusis 1991).

CHAPTER III:

RESULTS

The data were evaluated and analyzed initially without stratification. I then removed the plots with a high incidence of brush, those plots that had brush that hindered the rotation of the ceptometer. This was done in order to evaluate the effect of a large proportion of brush on estimation techniques. Finally, I stratified all of the data (plots with and without brush) into the stands from which they were gathered to examine the relationships at a stand level.

Measurement Comparisons

There were significant differences in mean canopy closure estimates by method (Table 2). The Prognosis predicted mean canopy closure (PCC) was similar to the mean canopy closure estimates of the moosehorn (MCC) for all plots and for the stands but was significantly different for the no brush plots. The densiometer canopy closure estimates (DCC), using either method of estimation (37 intersections or 96 points), were consistently higher than the MCC and the PCC. The canopy closure means estimated by the two methods of the densiometer were very similar and different by only 1% to 3% throughout the analyses. Despite the fact that they were significantly different for all plots, no brush plots, and the stands, they were the most highly correlated of any of the instruments (r = 0.99) (Fig. 5). For this reason, future reference will be made only to the densiometer method using the 96 imaginary points for estimation.

Table 2. Mean[1] canopy closure (%) comparison for all plots, no brush plots and for stands.

Instrument	All Plots (n = 70)	No Brush (n = 20)	Stands (n = 11)
Moosehorn	0.50 a*	0.16 a	0.56 a
Densiometer (37)**	0.91 d	0.72 c	0.89 d
Densiometer (96)**	0.90 c	0.69 d	0.87 c
Calculated	0.59 a	0.47 b	0.56 a

[1] Transformed using the arcsine of the square root of the mean.

* Means followed by the same letter within the same column were not significantly different ($p < 0.05$).

** Densiometer measurements taken counting the covered intersections out of a possible 37 and imaginary dots out of a possible 96.

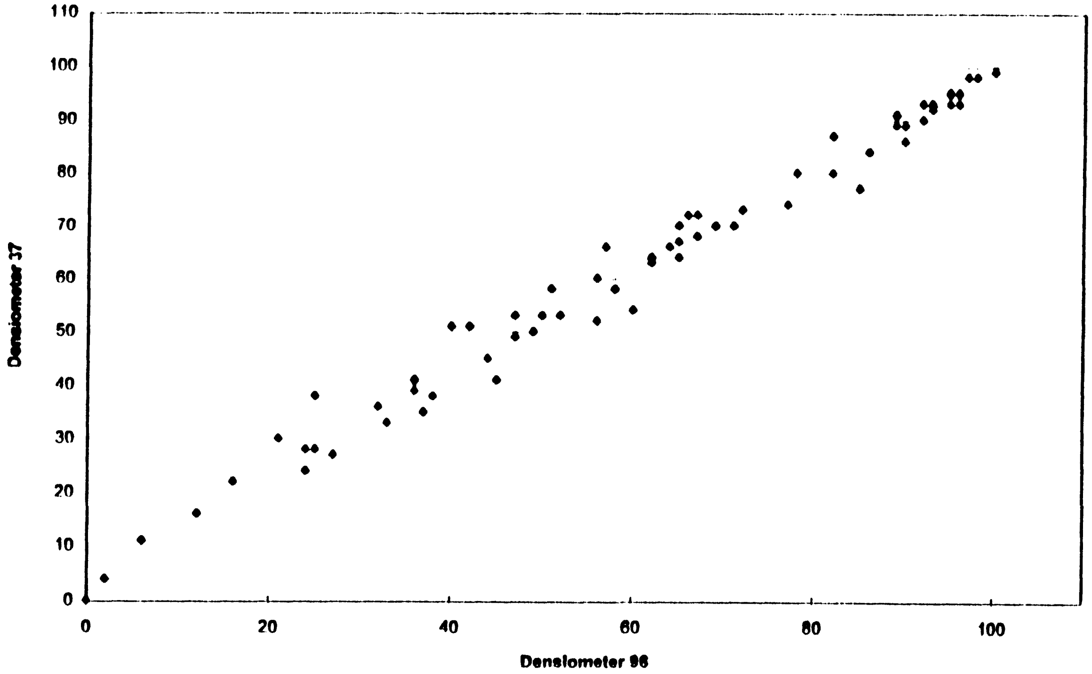


Fig. 5. Scatterplot of canopy closure (%) as measured by the densiometer 37 method (y) and the densiometer 96 method (x) for all plots.

All Plots. The DCC correlated weakly (see Appendix B for definitions of the correlation descriptors) with both the PCC (r = 0.62) and the MCC (r = 0.56) as well as with the ceptometer measurements of percent PAR (r = 0.68) (Table 3).

Table 3. Summary table of the correlation statistics for the data from all plots (n = 70), the no brush plots (n = 20) and the stands (n = 11).

	ALL PLOTS		**NO BRUSH**		**STANDS**	
Correlation	r	SE	r	SE	r	SE
Dens37 vs dens96	0.99	0.04	0.99	0.04	1.00	0.01
DCC and PCC	0.62	0.26	0.74	0.27	0.84	0.15
MCC and DCC	0.56	0.44	0.66	0.29	0.90	0.15
MCC and PCC	0.33	0.50	0.27*	0.37	0.66	0.26
% PAR and MCC	-0.41	0.40	-0.51	0.46	-0.79	0.23
% PAR and DCC	-0.68	0.32	-0.79	0.33	-0.88	0.18
% PAR and PCC	-0.41	0.40	-0.57	0.44	-0.71	0.26

* No significant linear correlation.

The scatterplot of the MCC with the DCC produced only a moderate positive linear relationship (Appendix C). A large concentration of the data occur in the low moosehorn/high densiometer quadrant of the plot. A moderate linear relationship is shown between the DCC and the PCC (Appendix D). There is no linear relationship shown in the scatterplot of the ceptometer percent PAR measurements and the PCC (Appendix E). The inverse relationship which would be expected between the ceptometer measurements of percent PAR and the canopy closure estimates is evident in the data. Unexpectedly, a large portion of the data are located in the low canopy closure/low PAR transmitted quadrant of the scatterplot. No linear relationship is apparent in the scatterplot of the MCC with the PCC (Appendix F). In similar scatterplots, while there is a clear negative slope, there appears to be no linear relationship between the ceptometer measurements of percent PAR and the MCC (Appendix G) or the ceptometer and the DCC (Appendix H).

No brush plots. When the plots with a high incidence of brush were removed from the analyses the coefficients of correlation (r) increased in all of the relationships. An increase of approximately 0.11 occurred between the ceptometer measurements and the DCC estimates. With the PCC it increased by 0.16 and by 0.10 with the MCC (Table 3). The scatterplot of the ceptometer PAR measurements and the PCC shows a weak linear relationship with a negative slope (Appendix I) much like that produced for all plots. A scatterplot of the DCC and the PCC shows a weak linear relationship (Appendix J). The correlation between the MCC and the DCC increased approximately 10% with the removal of the plots having a high incidence of brush but the linearity of the relationship decreased considerably (Appendix K). Conversely, there was no linear correlation of the MCC with the PCC (Table 3, Appendix L).

Stands. Stratification of the plots into their respective stands (n = 11) for analysis resulted in stronger correlations for all of the methods of canopy closure estimation (Table 3). The DCC measurements were highly correlated with the MCC, the PCC and the ceptometer measurements of percent PAR.

A strong linear relationship was found to exist among the DCC, the MCC and the PCC (Figs. 6, 7 and 8). The relationships of the ceptometer with the DCC, MCC and PCC are more strongly linear than were seen in the previous analyses of individual plots (Figs. 9, 10, and 11).

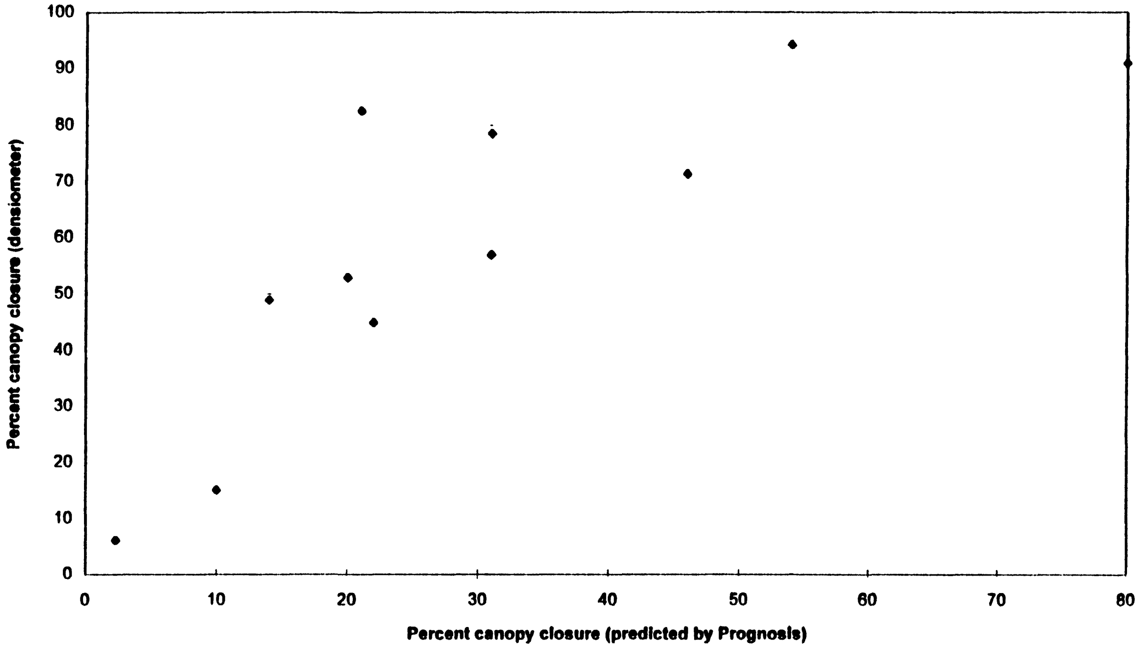


Fig. 6. Scatterplot of canopy closure (%) as measured by the densiometer (y) and predicted by Prognosis (x) for the stands.

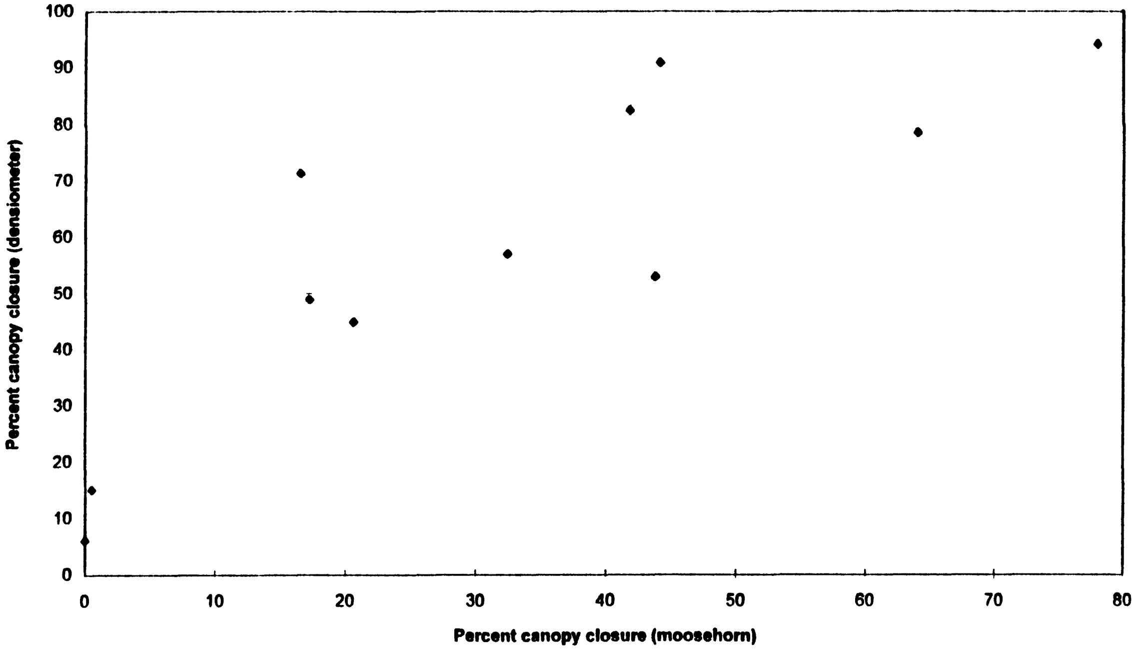


Fig. 7. Scatterplot of canopy closure (%) as measured by the densiometer (y) and the moosehorn (x) for the stands.

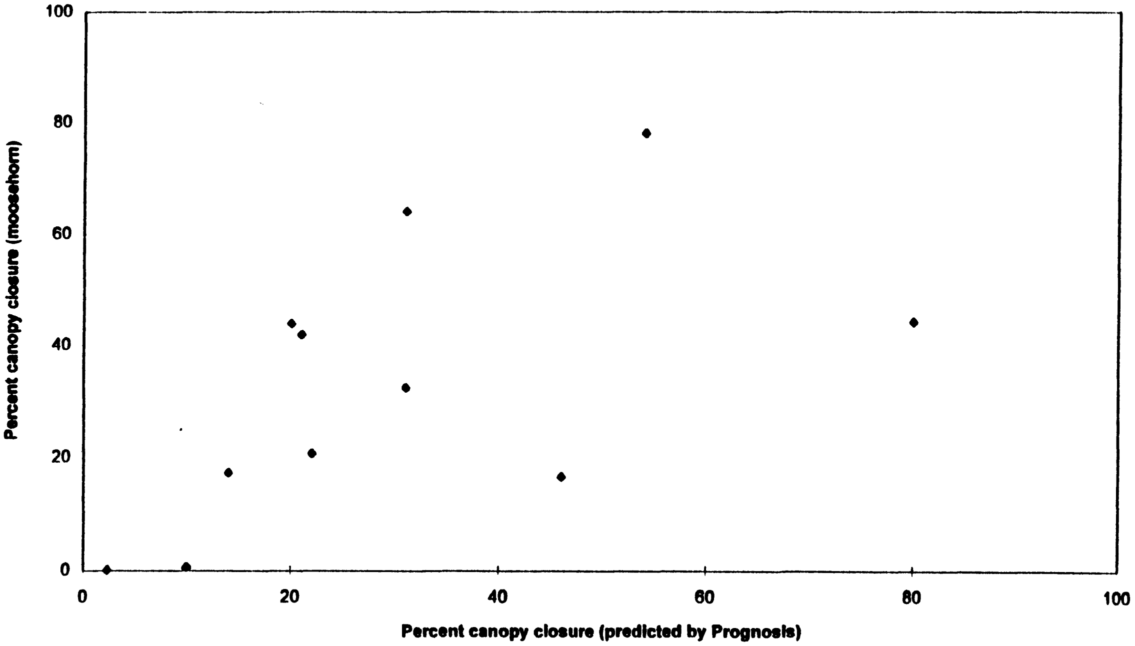


Fig. 8. Scatterplot of canopy closure (%) as measured by the moosehorn (y) and predicted by Prognosis (x) for the stands.

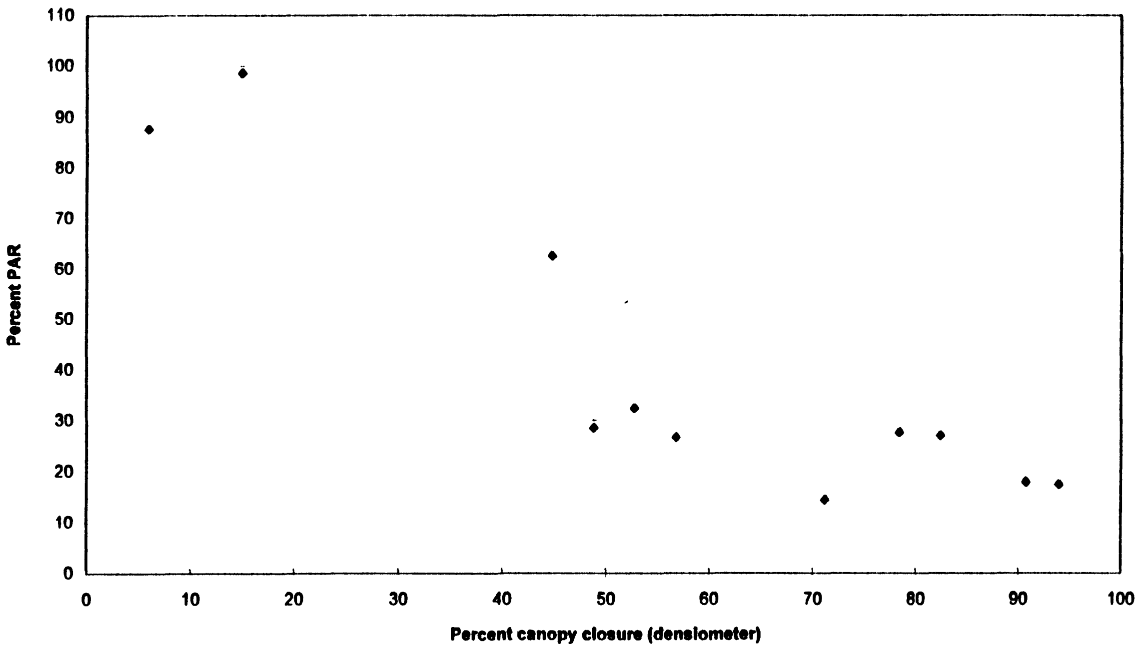


Fig. 9. Scatterplot of light transmitted (% PAR) as measured by the ceptometer (y) and canopy closure (%) as measured by the densiometer (x) for the stands.

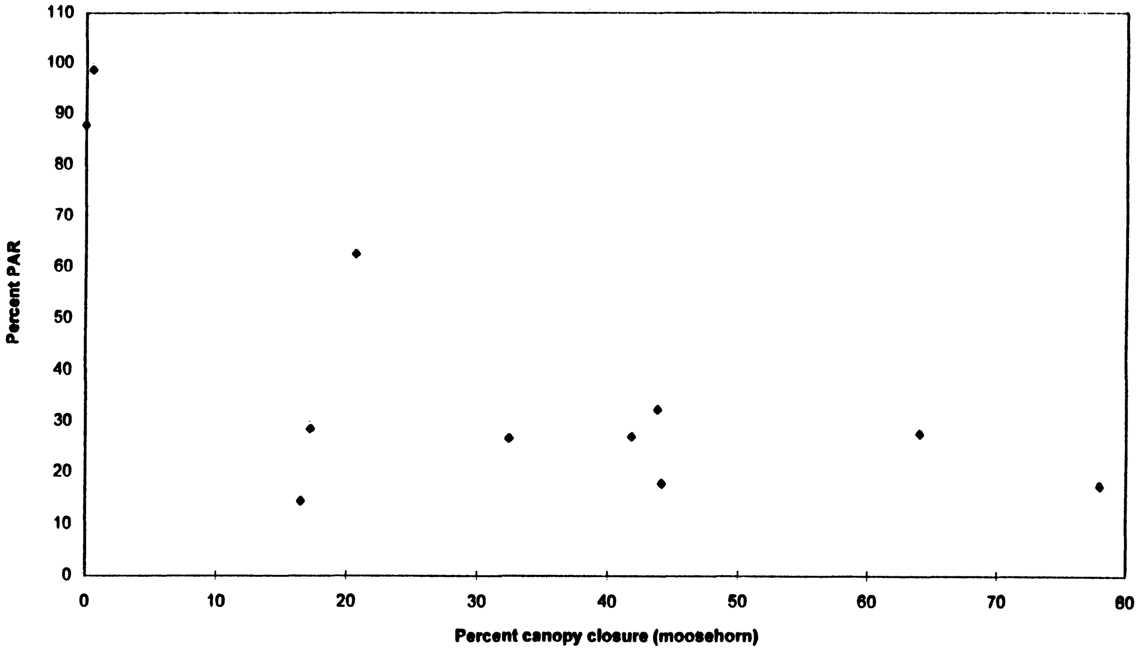


Fig. 10. Scatterplot of light transmitted (% PAR) as measured by the ceptometer (y) and canopy closure (%) as measured by the moosehorn (x) for the stands.

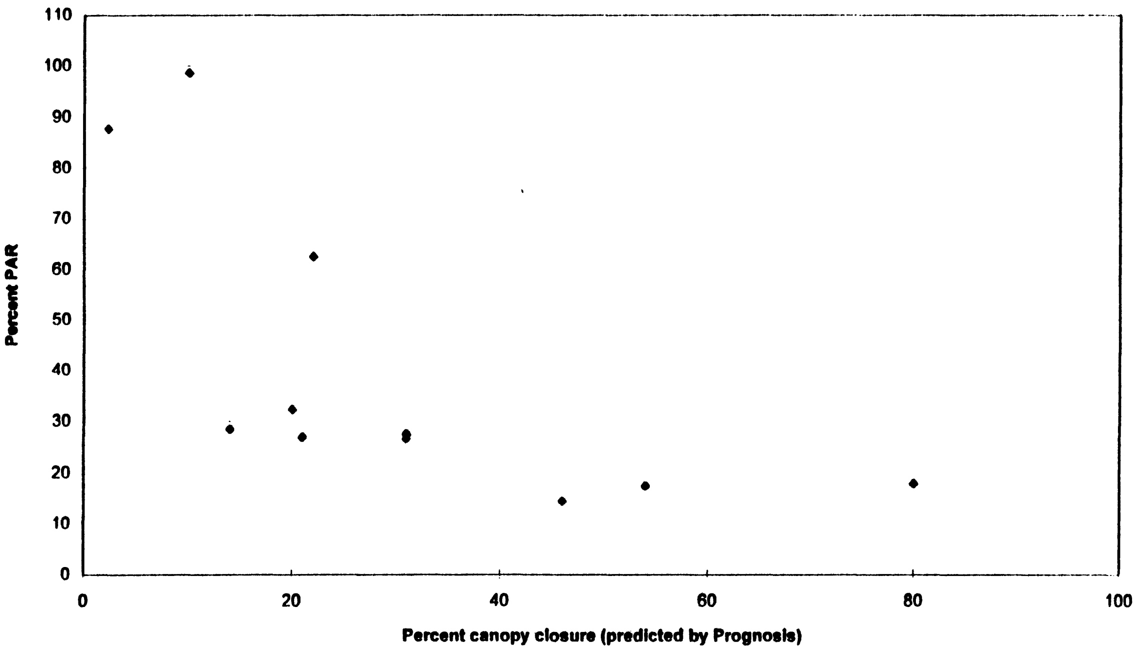


Fig. 11. Scatterplot of light transmitted (% PAR) as measured by the ceptometer (y) and canopy closure (%) as predicted by Prognosis (x) for the stands.

Understory Vegetation

All plots. The means of each of the Prognosis predicted (hereafter referred to as predicted percent cover) and cruiser estimated (hereafter referred to as the field measured percent cover) vegetation categories were significantly different except for the percent cover of medium vegetation (Table 4). Thus, the Prognosis model did not accurately predict the field measured mean except for possibly with the medium height vegetation.

The MCC correlated weakly with the Prognosis predicted percent cover of medium, high, total and mean height of the vegetation. With the field measured estimates of vegetative cover the MCC correlated weakly with the low and total vegetation percent cover (Table 5).

Table 4. Mean[1] estimates of cover (%) and height of understory vegetation predicted by Prognosis and estimated by the cruisers for all plots (n = 70).

Vegetation Height Classes	Predicted Mean	Field Measured Mean	p-value
Low (0.0 - 1.7 ft)	0.34	0.70	0.00
Medium (1.7 - 7.0 ft)	0.63	0.59	0.23
High (> 7.0 ft)	0.54	0.38	0.01
Total	1.00	1.20	0.00
Mean height (ft)	5.06	2.60	0.00

[1] Transformed using the arcsine of the square root of the mean.

Table 5. Correlation statistics for the **moosehorn** with the cover (%) and the mean height of the understory vegetation predicted by Prognosis and estimated by the cruisers for all plots (n = 70).

Vegetation Height Classes	Prognosis predicted			Field Measured		
	r	SE	p-value	r	SE	p-value
Low (0.0 - 1.7 ft)	0.21	0.13	0.09	0.25	0.33	0.04
Medium (1.7 - 7.0 ft)	0.39	0.20	0.00	0.21	0.33	0.09
High (> 7.0 ft)	0.35	0.40	0.00	0.03	0.28	0.80
Total	0.41	0.41	0.00	0.36	0.41	0.00
Mean height (ft)	0.29	4.16	0.01	0.15	1.78	0.22

The strongest correlations of the MCC were with the predicted percent cover of medium and total vegetation (Appendices M and N, respectively). The scatterplots show no indication of the expected negative linear relationship with either of the vegetation categories.

The DCC estimates also correlated weakly with the field measured mean height of the vegetation (Table 6). The strongest correlations of the DCC were with the predicted percent cover of high vegetation (Appendix O) and field measured percent cover of low vegetation (Appendix P). Again, there is no linear relationship shown in either of the scatterplots.

Table 6. Correlation statistics for the **densiometer** and the cover (%) and mean height of the understory vegetation predicted by Prognosis and estimated by the cruisers on all plots (n = 70).

Vegetation Height Classes	Prognosis Predicted			Field Measured		
	r	SE	p-value	r	SE	p-value
Low (0.0 - 1.7 ft)	0.14	0.13	0.25	0.43	0.31	0.00
Medium (1.7 - 7.0 ft)	0.32	0.20	0.00	0.17	0.33	0.19
High (> 7.0 ft)	0.42	0.38	0.00	0.13	0.28	0.29
Total	0.36	0.42	0.00	0.38	0.41	0.00
Mean height (ft)	0.36	4.05	0.00	0.39	1.66	0.00

The PCC correlated weakly with all of the predicted understory vegetation categories. With the field measured percent cover, though, it only correlated with the medium and the total categories (Table 7). The strongest correlations with the PCC were the predicted percent cover of high vegetation (Appendix Q) and the mean height (Appendix R). The scatterplots of the predicted high cover and mean height show very weak negative linear relationships.

The ceptometer PAR measurements correlated weakly with the predicted percent cover of low, medium and high vegetation and the average height. There were no significant correlations made with the actual percent cover estimates of vegetation (Table 8). The strongest correlations with the ceptometer were predicted percent cover of high vegetation (Appendix S) and the average height (Appendix T). Both scatterplots indicate very weak positive linear relationships.

Table 7. Correlation statistics for the Prognosis **predicted canopy closure** and the cover (%) and mean height of the understory vegetation categories predicted by Prognosis and estimated by the cruisers for all plots (n = 70).

Vegetation	Prognosis Predicted			Field Measured		
Height Classes	r	SE	p-value	r	SE	p-value
Low (0.0 - 1.7 ft)	0.41	0.12	0.00	0.23	0.33	0.06
Medium (1.7 - 7.0 ft)	0.49	0.18	0.00	0.27	0.32	0.02
High (> 7.0 ft)	0.57	0.35	0.00	0.16	0.27	0.19
Total	0.51	0.39	0.00	0.46	0.39	0.00
Mean height (ft)	0.48	3.82	0.00	0.05	1.80	0.70

Table 8. Correlation statistics for the **ceptometer** PAR measurements and the cover (%) and mean height of the understory vegetation categories predicted by Prognosis and estimated by the cruisers for all plots (n = 70).

Vegetation	Prognosis Predicted			Field Measured		
Height Classes	r	SE	p-value	r	SE	p-value
Low (0.0 - 1.7 ft)	0.26	0.13	0.03	0.21	0.33	0.08
Medium (1.7 - 7.0 ft)	0.24	0.21	0.05	0.06	0.33	0.62
High (> 7.0 ft)	0.37	0.39	0.00	0.11	0.28	0.37
Total	0.22	0.44	0.07	0.12	0.44	0.33
Mean height (ft)	0.36	4.06	0.00	0.18	1.77	0.13

No brush plots. For plots without a high incidence of brush all of the means of the predicted and field measured percent cover of vegetation were significantly different except the medium height and total vegetation (Table 9).

Table 9. Mean[1] estimates of cover (%) and height of understory vegetation predicted by Prognosis and estimated by the cruisers for the no brush plots (n = 20).

Vegetation Height Classes	Predicted Mean	Field Measured Mean	p-value
Low (0.0 - 1.7 ft)	0.40	0.78	0.00
Medium (1.7 - 7.0 ft)	0.76	0.63	0.06
High (> 7.0 ft)	0.76	0.37	0.01
Total	1.27	1.30	0.68
Mean height (ft)	7.12	1.96	0.00

[1] Transformed using the arcsine of the square root of the mean.

Analyses of the plots without brush produced different significant correlations between the instruments and the vegetation categories than those seen in the all plot analyses. The MCC correlated only with the predicted percent cover of the medium and total vegetation and with the field measured estimate of mean height (Table 10).
The strongest correlations with the MCC for these plots were the predicted percent cover of total vegetation and the field measured average height (Appendices U and V, respectively). Removal of the plots with a high incidence of brush improved the linearity of the scatterplots.

The DCC estimates of canopy closure correlated moderately with the predicted percent cover of the low vegetation and weakly with the predicted cover of high vegetation and mean height (Table 11). With the field measured vegetation estimates the DCC correlated only with the percent cover of high vegetation and the mean height. The strongest correlations were those with the predicted percent cover of the low and high vegetation (Appendices W and X, respectively). Both scatterplots show moderately strong negative linear relationships as would be expected.

Table 10. Correlation statistics for the **moosehorn** and the cover (%) and mean height of the understory vegetation predicted by Prognosis and estimated by the cruisers on the no brush plots (n = 20).

Vegetation Height Classes	Prognosis Predicted r	SE	p-value	Field Measured r	SE	p-value
Low (0.0 - 1.7 ft)	0.20	0.08	0.40	0.35	0.40	0.13
Medium (1.7 - 7.0 ft)	0.49	0.19	0.03	0.09	0.34	0.70
High (> 7.0 ft)	0.40	0.48	0.08	0.43	0.20	0.06
Total	0.54	0.33	0.01	0.02	0.39	0.93
Mean height (ft)	0.28	5.40	0.23	0.58	0.73	0.01

Table 11. Correlation statistics for the **densiometer** and the cover (%) and mean height of the understory vegetation predicted by Prognosis and estimated by the cruisers for the no brush plots (n = 20).

Vegetation Height Classes	Prognosis Predicted r	SE	p-value	Field Measured r	SE	p-value
Low (0.0 - 1.7 ft)	0.75	0.05	0.00	0.30	0.41	0.20
Medium (1.7 - 7.0 ft)	0.24	0.21	0.32	0.19	0.34	0.42
High (> 7.0 ft)	0.69	0.35	0.00	0.65	0.17	0.00
Total	0.37	0.37	0.11	0.10	0.39	0.68
Mean height (ft)	0.65	4.29	0.00	0.56	0.74	0.01

Correlation of the percent cover and average height estimates of the vegetation with the PCC produced results somewhat similar to those of the DCC (Table 12). The PCC correlated with the predicted percent cover of the low and high vegetation and the mean height but not with any of the field measured estimates of vegetation. The strongest correlations, like those of the DCC, were the predicted percent cover of the low and high vegetation (Appendices Y and Z, respectively). These two scatterplots are very similar to those of the DCC. They also show a moderately strong negative linear relationship.

Table 12. Correlation statistics of the Prognosis **predicted canopy closure** and the cover (%) and mean height of the understory vegetation predicted by Prognosis and estimated by the cruisers on the no brush plots (n = 20).

Vegetation Height Classes	Prognosis Predicted			Field Measured		
	r	SE	p-value	r	SE	p-value
Low (0.0 - 1.7 ft)	0.77	0.05	0.00	0.02	0.43	0.94
Medium (1.7 - 7.0 ft)	0.02	0.22	0.80	0.19	0.34	0.42
High (> 7.0 ft)	0.58	0.40	0.00	0.36	0.21	0.11
Total	0.28	0.38	0.24	0.22	0.38	0.35
Mean height (ft)	0.52	4.80	0.02	0.28	0.86	0.24

Correlation of the percent cover and average height estimates of the vegetation with the percent PAR measurements of the ceptometer produced results similar to those of the DCC and the PCC (Table 13). The percent PAR measurements of the ceptometer correlated weakly with the predicted percent cover of the low and high vegetation and with the field measured percent cover of the high vegetation. The strongest correlation with the ceptometer was the predicted percent cover of the low vegetation (Appendix AA). The expected positive linear relationship is shown in the scatterplot.

Table 13. Correlation statistics for the **ceptometer** PAR measurements and the cover (%) and mean height of the understory vegetation predicted by Prognosis and estimated by the cruisers on the no brush plots (n = 20).

Vegetation Height Classes	Prognosis Predicted			Field Measured		
	r	SE	p-value	r	SE	p-value
Low (0.0 - 1.7 ft)	0.66	0.06	0.00	0.11	0.42	0.66
Medium (1.7 - 7.0 ft)	0.04	0.22	0.87	0.32	0.32	0.17
High (> 7.0 ft)	0.50	0.42	0.02	0.52	0.19	0.02
Total	0.10	0.39	0.66	0.32	0.37	0.17
Mean height (ft)	0.43	5.07	0.06	0.38	0.83	0.10

Stands. When I stratified the plots into stands only the predicted and field measured means of the percent cover of low vegetation were significantly different (Table 14).

Stratification of the plots into their respective stands improved the linearity of the scatterplots for the vegetation categories with the canopy closure and light measurements. There was also an overall increase in the coefficients of correlation. The MCC correlated with the predicted percent cover of the medium, high and total vegetation as well as the mean height estimate. There were also moderate correlations with the field measured percent cover of the low and total vegetation and the mean height (Table 15). The strongest correlation with the MCC in the predicted data was the estimate of mean height while in the field measured data it was the percent cover of the low vegetation (Appendices BB and CC, respectively). Both scatterplots indicate a moderate negative linear relationship.

Table 14. Mean[1] estimates of cover (%) and height of understory vegetation predicted by Prognosis and estimated by the cruisers for the stands (n = 11).

Vegetation Height Classes	Predicted Mean	Field Measured Mean	p-value
Low (0.0 - 1.7 ft)	0.36	0.70	0.00
Medium (1.7 - 7.0 ft)	0.71	0.59	0.07
High (> 7.0 ft)	0.62	0.38	0.19
Total	1.02	1.20	0.10
Mean height (ft)	5.39	2.72	0.06

[1] Transformed using the arcsine of the square root of the mean.

Table 15. Correlation statistics for the **moosehorn** and the cover (%) and mean height of the vegetation predicted by Prognosis and estimated by the cruisers for the stands (n = 11).

Vegetation	Prognosis Predicted			Field Measured		
Height Classes	r	SE	p-value	r	SE	p-value
Low (0.0 - 1.7 ft)	0.54	0.11	0.08	0.71	0.18	0.01
Medium (1.7 - 7.0 ft)	0.66	0.21	0.02	0.44	0.21	0.17
High (> 7.0 ft)	0.74	0.35	0.01	0.15	0.20	0.65
Total	0.69	0.34	0.02	0.64	0.32	0.03
Mean height (ft)	0.76	2.65	0.01	0.65	1.04	0.03

The DCC estimates correlated with the predicted percent cover of the high vegetation and the mean height. With the field measured data there were correlations with the percent cover of the low vegetation and the mean height estimates (Table 16). The strongest correlations were with the field measured estimates (Appendices DD and EE). The scatterplot of the DCC and the low vegetation shows a moderate negative linear relationship. A positive linear relationship is shown in Appendix EE where a negative relationship was expected.

Table 16. Correlation statistics for the **densiometer** and the cover (%) and mean height of the understory vegetation predicted by Prognosis and estimated by the cruisers for the stands (n = 11).

Vegetation Height Classes	Prognosis Predicted			Field Measured		
	r	SE	p-value	r	SE	p-value
Low (0.0 - 1.7 ft)	0.34	0.13	0.31	0.74	0.18	0.01
Medium (1.7 - 7.0 ft)	0.45	0.25	0.16	0.36	0.22	0.28
High (> 7.0 ft)	0.64	0.40	0.03	0.24	0.19	0.47
Total	0.47	0.41	0.14	0.58	0.34	0.06
Mean height (ft)	0.66	3.07	0.03	0.73	0.93	0.01

The PCC correlated with the predicted percent cover of the high vegetation and the mean height. There was also a correlation with the field measured percent cover of the total vegetation (Table 17). The strongest correlations were the field measured percent cover of the total vegetation (Appendix FF) and the predicted percent cover of high vegetation (Appendix GG). Both scatterplots show very weak negative linear relationships.

The percent PAR measurements of the ceptometer correlated with the predicted percent cover of the high vegetation and the mean height. There was also a correlation with the field measured percent cover of the low vegetation (Table 18). The strongest correlations were with the predicted data (Appendices HH and II). Both scatterplots show very weak positive linear relationships.

Table 17. Correlation statistics for the **predicted canopy closure** and the cover (%) and mean height of the understory vegetation predicted by Prognosis and estimated by the cruisers for the stands (n = 11).

Vegetation Height Classes	Prognosis Predicted r	SE	p-value	Field Measured r	SE	p-value
Low (0.0 - 1.7 ft)	0.38	0.13	0.24	0.57	0.22	0.06
Medium (1.7 - 7.0 ft)	0.46	0.25	0.16	0.48	0.20	0.14
High (> 7.0 ft)	0.61	0.41	0.05	0.03	0.20	0.93
Total	0.46	0.41	0.16	0.63	0.32	0.04
Mean height (ft)	0.60	3.28	0.05	0.49	1.20	0.13

Table 18. Correlation statistics for the **ceptometer** PAR measurements and cover (%) and mean height of the understory vegetation predicted by Prognosis and estimated by the cruisers for the stands (n = 11)

Vegetation Height Classes	Prognosis Predicted r	SE	p-value	Field Measured r	SE	p-value
Low (0.0 - 1.7 ft)	0.49	0.12	0.13	0.59	0.21	0.05
Medium (1.7 - 7.0 ft)	0.44	0.25	0.18	0.77	0.23	0.62
High (> 7.0 ft)	0.73	0.35	0.01	0.45	0.18	0.17
Total	0.48	0.41	0.13	0.33	0.40	0.32
Mean height (ft)	0.73	2.79	0.01	0.54	1.16	0.09

CHAPTER IV:

DISCUSSION

Instrument Comparison

The significant difference between the mean canopy closure estimations of the moosehorn and of the spherical densiometer supported the conclusions of Bunnell and Vales (1990). They assumed that the moosehorn had the greater degree of accuracy due to its smaller angle of view which approximates a vertical projection. However, there can be no certainty about the accuracy of either of the canopy closure instruments or the Prognosis predicted canopy closure in the forest types examined in this study based on the results.

The difference between the means of the two methods of estimating canopy closure with the densiometer, while statistically significant, for all practical purposes can be disregarded. The nearly perfect correlation of the two (r = 0.99, Fig. 5) indicates that either of the two methods of estimation could be used depending on the preference of the observer. Having used both of the methods in the field for this study it is my preference to use the intersection method rather than attempting to visualize four imaginary dots in each of the squares of the grid.

The presence of large quantities of brush on the plots was found to affect the canopy closure estimates made with the densiometer and the PAR measurements of the ceptometer. Brush greater than 4.0 ft tall hindered not only the rotation of the ceptometer but also interfered with the measurement of the percent of total PAR that was being transmitted through the overstory canopy. The estimates of the densiometer were also affected to a certain degree by tall brush (> 5.0 ft) on the plot. In most cases tall brush reflected in the densiometer's mirror can be disregarded when estimating canopy closure but in some cases (very dense brush) it is more difficult to discern overstory canopy from understory canopy. Any inclusion of tall brush in the canopy closure estimate made with the densiometer will result in an overall estimate that is greater than it should be. The canopy closure estimates of the moosehorn and Prognosis were not affected by the brush because they were able to sample from an approximately vertical projection of the overstory canopy.

In their comparison of 13 different methods of canopy closure estimation Bunnell and Vales (1990) assumed that the estimates of the moosehorn were the most accurate due to its narrow angle of view (approximately 6°). Using this assumption and also assuming that Prognosis is able to predict an unbiased canopy closure estimate based on tree height, diameter and crown ratio, it would follow that there would be no difference in predicted and measured means and that a significant correlation would exist between the moosehorn and the Prognosis predicted canopy closure. Indeed, there was no difference between the mean canopy closure of the moosehorn and the predicted canopy closure with the exception of the estimates for the plots without brush. The difference between the two means in this case would appear to be due to the large number of zero percent canopy closure measurements from the moosehorn. Because the plots without brush were predominantly taken from open, park-like ponderosa pine stands on dry south-facing slopes the moosehorn sampled a high proportion of open canopy. Prognosis, on the other hand, calculated canopy closure using the trees recorded for each plot, which did not account for the location of the plot center, which, according to the moosehorn estimates, was not under or near a tree approximately half of the time. Prognosis also assumes an even distribution of trees when calculating canopy closure giving no allowance for any "clumpiness" of trees in the stand. As a result, the mean canopy closure estimates of the moosehorn were less than those predicted by Prognosis. A larger number of samples taken with the moosehorn on plots without brush would most likely alleviate this problem by capturing more of the variability in the canopy closure over the entire plot. Despite the assumption that there was a significant correlation between the moosehorn canopy closure and that calculated by Prognosis, this correlation was generally low ($r = 0.33$, all plots; $r = 0.66$, stands). Therefore, the predicted canopy closure did not have the strong relationship with the canopy closure estimates of the moosehorn that was expected.

Allowing for the same two assumptions discussed above (that the moosehorn is the most accurate field technique and that the canopy closure estimates of Prognosis are unbiased), the mean canopy closure estimates of the densiometer and those predicted by Prognosis would be significantly different. The results support this. This occurs for the opposite reason that the mean canopy closure estimates of the moosehorn and those calculated by Prognosis were not significantly different. Due to its narrow angle of view the moosehorn samples a larger proportion of open canopy on a plot. Conversely, the densiometer, with its wider angle of view, samples more than just the overstory canopy in the plot. The densiometer also samples any tree boles, shade or tall brush which are reflected within that angle of view, which in most cases can be disregarded from the canopy closure estimate. As a result, it fails to sample the openings in the canopy unless they are very large and directly over the plot center. Because the canopy closure estimate of Prognosis is calculated using only the sum of the crown areas of the trees recorded in the point sample, it produces an estimate that is less than that of the densiometer. Small trees not large enough to be included in the point sample may still have large enough canopies to contribute to the estimate of the densiometer. This difference in the type of canopy which is being utilized by each of these estimation methods is evident in the weak correlation at the individual plot level. At the stand level, the correlation was strengthened by the alleviation of much of the plot-to-plot variation.

The high concentration of data points with values of high canopy closure estimated by the densiometer but low predicted canopy closure would seem to support the findings of Bunnell and Vales (1990) and Stutzman et al. (unpublished) who concluded that the densiometer is biased toward overestimation due to its wide angle of view. This same behavior is evident in the scatterplot of the canopy closure estimates of the moosehorn and the densiometer for all plots (Appendix C). This supports the conclusion that the densiometer is sampling more than just the overstory canopy that the moosehorn and the Prognosis canopy closure estimates are based on. At the stand level, however, alleviation of some of the plot-to-plot variation has improved the correlation of the densiometer with both the predicted canopy closure and the moosehorn (Figs. 6 and 7, respectively).

The correlation between the moosehorn and the densiometer was moderate ($r = 0.56$) when analyzed on an individual plot level. Despite the fact that both of these instruments are designed to measure the same thing, canopy closure, the differences in their mean canopy closure estimates are due to the difference in the angle of view for each instrument. The wide angle of view of the densiometer reflects not only the canopy over the sample point but also the boles of the trees, tall brush and any shade that is found in that angle. The moosehorn, on the other hand, with its narrow angle of view, reflects only the canopy directly over the sample point. It would seem logical then, that if an estimate of only canopy closure is desired for a management objective that the moosehorn would be the more accurate instrument of the two. Conversely, if an estimate of shade (light penetration) or the effect of tall brush is desired to evaluate habitat variables such as thermal or hiding cover for wildlife, the densiometer would be more useful.

With the removal of plots with a high incidence of brush from the analysis the correlation of the canopy closure estimates of the moosehorn and the densiometer increased to $r = 0.66$. The removal of the plots with brush removed a portion of the canopy that may have been measured by the densiometer. If dense brush taller than 5.0 ft is near the sample point it will be reflected in the densiometer's mirror. If it becomes difficult to discern between the canopy of the brush and that of the overstory the brush may be counted as canopy closure thereby increasing the estimate of the densiometer. The confounding effect that brush may have on the canopy closure estimate of the densiometer, in addition to the effect of shade and tree boles, produces a different measurement than that of the moosehorn which estimates canopy closure alone. Stratification of the plots into stands strengthened the correlation of the moosehorn and the densiometer considerably to $r = 0.90$ by reducing the high plot-to-plot variation produced by the high proportion of very low moosehorn measurements. The high variation of the estimates of the moosehorn is a result of the small angle of view of the instrument which results in a small sample area, as opposed to the large angle of view of the densiometer.

Correlation of the ceptometer with the each canopy closure estimators produced similar relationships. Each of the scatterplots indicates that there is a weak linear relationship between the light measurements and the canopy closure estimations. The correlation between the ceptometer measurements and the canopy closure estimates of the moosehorn is weak. The sources of variation within this relationship are most likely the result of moosehorn's ability to measure a vertical projection while the ceptometer is sampling light from a 180° hemisphere. If the plot center is located under a tree in an otherwise open plot, the canopy closure estimate will be high as will the light measurement of the ceptometer. Conversely, if the plot center is located under an opening in the trees in an otherwise dense plot, the canopy closure estimate and the light measurement will both be low.

Removal of the plots with a high incidence of brush increased the correlation between the ceptometer and the moosehorn to $r = 0.51$. This slightly improved correlation is the result of the absence of the brush on the plots which was more likely to produce a lower light measurement than what was representative of the stand. The weak negative linear relationship between the two (Appendix F) is evidence of the lack of ability of the moosehorn to predict the amount of PAR that is being transmitted through the canopy.

Stratification of the plots into stands increased the correlation between the ceptometer's light measurement and the canopy closure estimates of the moosehorn to r = 0.79. The linearity of the scatterplot is moderately strong (Fig. 10) indicating that there may be some predictive ability of the moosehorn at this level.

The correlations of the ceptometer measurements with the canopy closure estimations of the densiometer were the highest of all those analyzed on the individual plot levels. Only the correlation between the moosehorn and the densiometer estimates of canopy closure at the stand level was higher. The strength of the correlation between the percent PAR measurements and the canopy closure estimates of the densiometer was due in large part to the large angles of view over which each instrument samples. The moderate correlation for all of the plots was improved with the removal of the plots with a high incidence of brush. Without the brush to hinder the movement of the ceptometer and to interfere with the measurement of the percent PAR transmitted through the overstory, a more representative sample was obtained. The reduction of the plot-to-plot variation produced the strong correlation between the two at the stand level. The strength of these correlations would appear to suggest that the densiometer may have some ability to predict the ceptometer's

PAR measurements, especially at the stand level. Some of the data in the low canopy closure/low PAR region of the scatterplots may have been due to a high incidence of brush in the plot in an otherwise open stand. Conversely, data in the high canopy closure/high PAR region may have been the result of the plot center being located under a tree.

Correlation of the ceptometer light measurements with the predicted canopy closure produced weak correlations, again due to the angles over which the samples were taken. The PAR measured by the ceptometer is affected by more than just the canopies of the trees included in the point sample. The canopies of smaller trees and tree boles also contribute to the measurement of percent PAR transmitted through the overstory, factors which Prognosis does not take into consideration when calculating canopy closure. The variation and the weak correlation at this level were most likely due to the occurrence of brush on the plot producing low light measurements even when the predicted canopy closure was low. With the removal of the brush plots the correlation improved to $r = 0.57$. At the stand level the correlation was strengthened to $r = 0.71$. The moderate linearity at the stand level was very similar to the ceptometer's relationships with the moosehorn and the densiometer (Fig. 11). Due to the low correlation between the two, the predicted canopy closure has no ability to predict the percent of total PAR transmitted through the canopy.

Understory Vegetation Analysis

The amount of variation in the understory vegetation data is large because of two major factors. Understory vegetation was estimated by several different observers in percent cover classes and predicted by Prognosis in height classes. Additional variation in the field measured data resulted from estimation by more than one observer. Five different cruisers estimated the understory vegetation data for the 11 stands used in this study. The method of percent cover estimation by species was done visually as were the estimations of the average heights. Because each person estimates cover differently based on the extent of his/her experience and other factors, such as the distribution and height of the vegetation, a certain amount of variation will occur. It is also recognized that canopy closure and light transmittance are not the only two factors that control the quantity of vegetation that grows in the understory of a stand. Other factors such as elevation, slope, aspect, and disturbance interact with soil moisture and fertility to influence understory vegetation. For these reasons, only broad generalizations can be made from the statistical analyses performed on the data.

The means of the cover (%) and height of the understory vegetation predicted by Prognosis and estimated by the cruisers were nearly all significantly different at the plot level. At the stand level only the percent cover of low height vegetation (0.0 - 1.7 ft) means were significantly different. Stratification of the plots to a stand level alleviated some of the plot to plot variation and produced results that could be used for stand level management. Neither forest stands nor habitats are managed on an individual plot level. Therefore, the integration of the plots into stands for analyses provides a more representative and useful picture of the stand for management whether it be for timber production or for wildlife habitat.

The predicted percent cover of low height understory vegetation was less than the field measured percent cover of low height vegetation due to the fact that there were 13 low height species included in the field measured estimations that were not a part of the Prognosis prediction model (Appendix A). Important species not included in the Prognosis prediction model were: strawberry (*Fragaria virginiana*), pinegrass (*Calamagrostis rubescens*), and heartleaf arnica (*Arnica cordifolia*). The mean of the predicted percent cover of medium height vegetation was consistently higher than that of the field measured vegetation. Only on the plots without brush were they significantly different. The mean of the predicted percent cover of high height vegetation was consistently greater then that of the field measured. This is most likely due to the fact that Prognosis is able to calculate the cover of a multilayer shrub canopy mathematically while a cruiser is more likely to underestimate the actual amount of canopy cover of shrubs greater than 7.0 ft tall.

The mean of the predicted percent cover of the total vegetation was only slightly less than that of the field measured data. The Prognosis model allows only 40 years as the maximum time since human disturbance. It would be expected that any stand with a time since human disturbance greater than 40 years would have less field measured vegetation than what was predicted by Prognosis due to natural processes such as mortality and natural disturbance. Five of the 11 stands sampled had not had any kind of disturbance for 75 to 85 years. The larger quantity of field measured total vegetation cover compared to what Prognosis predicted assuming only 40 years since disturbance is most likely a result of overestimation on the part of the cruisers.

Correlations of the canopy closure estimators and the light measurements with the understory vegetation classes were neither consistent nor strong and were most likely due to the high variability of the data. The most significant correlations were found at the stand level with the Prognosis predicted understory vegetation classes.

The moosehorn canopy closure estimates had the most significant correlations with the understory vegetation classes of all of the canopy closure estimation techniques that were examined. This result was unexpected for the reason that the moosehorn samples only a narrow angle of view and therefore only a small area. The densiometer and the ceptometer, with their wider angles of view, would seem more likely to have the strongest correlations with the understory vegetation classes. The moosehorn is able to sample only the overstory canopy. Conversely, the densiometer and the ceptometer are able to capture the effect of shade, tree boles and brush in the transmittance of PAR through the overstory canopy. It would also seem logical that the canopy closure estimates of Prognosis would not be well correlated with the cover (%) of understory vegetation. Prognosis, like the moosehorn, is unable to incorporate the effects of light interference factors into its calculation of canopy closure.

It would seem apparent that there is some correlation between the canopy closure of the overstory and the cover (%) of understory vegetation based on these results. Unfortunately, according to the analyses utilized in this study there was no evidence that any of the canopy closure estimators or the ceptometer had any significant or useful predictive ability for understory vegetation predicted by Prognosis or measured in the field. In future studies of this sort, the understory vegetation data should by collected in a way that will insure precision and a certain degree of accuracy. Reduction of variation due to collection by different observers should strengthen the correlations with the overstory canopy closure.

CHAPTER V:
SUMMARY AND CONCLUSIONS

Four different methods of measuring or describing canopy closure were compared. The methods included a moosehorn, a spherical densiometer, stand inventory-based calculations and measurements of percent total PAR with a Sunfleck ceptometer. The comparison included correlation to examine the strength of the relationships among the methods. The strongest correlations were found to exist at the stand level, the level at which forest management decisions are made. The strong stand level correlations were largely a result of the alleviation of the high plot-to-plot variation for each method.

The mean canopy closure estimates of the two field techniques, the moosehorn and the spherical densiometer, were found to be significantly different but the estimates were highly correlated at the stand level ($r = 0.90$). The difference was due to the fact that they measure different angles of view. Therefore, they each sample a different part of the canopy. The moosehorn, with a 3° to 4° angle of view, samples only the overstory canopy. The densiometer, with a 60° angle of view, samples the overstory as well as tree boles, shade and tall brush. It was concluded that while these two instruments are designed to measure the same thing, their canopy closure estimates should not be considered equivalent as the estimates of the densiometer are consistently greater than those of the moosehorn.

The mean canopy closure estimates of the moosehorn and those of calculated from the stand inventory variables (tree height, diameter and crown ratio) by the Stand Prognosis Model were not significantly different at the stand level. They were also only weakly correlated (r = 0.66). While both methods approximate a vertical projection of the overstory canopy, the moosehorn has a tendency to sample a high proportion of open spaces in the canopy. This is especially true in open, park-like stands with low overall canopy closure. An increase in the number of samples taken with the moosehorn in each stand should result in a more representative estimate of canopy closure for the stand.

The mean canopy closure estimates calculated by Prognosis were significantly different from those of the densiometer. Again, the difference was due to the angle of view. In this case, the densiometer samples not only overstory canopy, shade and tall brush but also the canopy of trees not large enough to be included in the cruise point sample. The result is a consistently higher canopy closure estimate from the densiometer when compared to the predictions of Prognosis. The estimates of canopy closure made with these two methods were moderately correlated (r = 0.84) at the stand level. It was concluded that the estimates of these two methods are not equivalent and should not be substituted for one another.

The presence of a high concentration of brush (>4.0 ft) on the sample points was found to severely hinder the rotation of the ceptometer. It also interfered with measuring the percent of total PAR that was being transmitted through the overstory canopy. To a certain extent, any brush taller than 5.0 ft affected the estimates of the densiometer as well. This effect can be easily alleviated by not including the canopy of the brush in the estimate of overstory canopy. In certain cases, such as very dense brush, it can become difficult to discern between the canopy of the understory and the canopy of the overstory. In such cases, an overestimation of the overstory canopy closure estimated with the densiometer may result.

The canopy closure estimates of the densiometer were the most highly correlated with the percent PAR measurements of the ceptometer at the stand level ($r = 0.88$). This is a result of the wide angles of view that each of the instruments is able to sample from (60° and 180°, respectively). Each instrument is able to capture more of the factors that affect transmittance of percent of total PAR such a tree boles, shaded areas and a variety of canopies, both overstory and understory. The moosehorn and Prognosis are unable to sample these extra factors due to their narrow sampling angles. As a result, they both correlated only moderately with the percent PAR measurements at the stand level ($r = 0.79$ and $r =$

0.71, respectively). Based upon these results, it was concluded that the ceptometer should not be used to sample in areas with high quantities of brush. In addition to this, any prediction of percent PAR transmitted through the overstory canopy should be done using the densiometer rather than the moosehorn or the canopy closure estimates of Prognosis.

Correlation of the canopy closure estimates and the ceptometer measurements with the predicted and field measured vegetation categories of the plots produced inconsistent results. Overall, the strongest correlations were made at the stand level and the most significant correlations were made with the vegetation estimates that were predicted by Prognosis. The number of observers and the manner in which it were collected produced a lack of precision and accuracy in the field measured data that ultimately affected their correlation with the canopy closure and light measurements.

The estimation of canopy closure in a stand inventory could have any number of applications, each of them requiring a different amount of accuracy in the estimation. A larger sample size than what was used here for evaluating the moosehorn on an individual plot level would most likely remove some of the effect of the high proportion of open canopy sampled.

The discrepancy that was found to exist between the canopy closure estimates made with the moosehorn and those of the densiometer was largely due to the difference in their angles of view. For this reason, it may be feasible for future research to examine the possibility of developing an instrument with an angle of view greater than that of the moosehorn (approximately 3° to 4°) but less than that of the densiometer (approximately 60°). Based on the results of this study, it would seem logical that an instrument with an intermediate angle of view could produce a more representative estimate of canopy closure for the stand.

For reasonably efficient and relatively inexpensive canopy closure estimation in the field the moosehorn and the spherical densiometer are the instruments of choice. The ceptometer, while it produces an accurate measurement of PAR transmittance, is an expensive instrument and difficult to transport in field sampling. This is especially true in stands with steep slopes and brush in the understory.

Examination of the results of this study should be done in the light of the definition that the manager is using for canopy closure and the manner in which he/she will be applying these results. The use of these results would be beneficial in evaluation of overstory or understory canopy closure at the stand level. If an estimate of canopy closure for use in evaluating variables such as thermal or hiding cover in wildlife habitat is desired, then the densiometer would probably be the more useful instrument. Conversely, if an estimate of only the overstory canopy is desired for use in timber harvesting decisions, then the moosehorn would produce a more appropriate reading. Despite the fact that the two produce different estimates of canopy closure, both instruments can be a useful addition to the stand inventory.

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Appendix A. Understory species for which predictions are made in the SHRUBS portion of the COVER program and height class (Moeur 1985).

Scientific Name	Common Name	Height class[1]
Acer glabrum	Rocky Mtn. Maple	T
Alnus sinuata	Sitka alder	T
Amelanchier alnifolia	Serviceberry	T
Aralia nudicaulis	Wild sasparilla	L*
Arnica cordifolia	Heartleaf arnica	L*
Artostaphylos uva-ursi	Kinnikinnick	L
Balsamorhiza sagittata	Arrowleaf balsamroot	L*
Berberis spp.	Oregon grape	L
Betula spp.	Birch	T*
Carduus spp.	Thistles	L*
Carex spp.	Sedge	L
Calamagrostis rubescens	Pinegrass	L*
Ceanothus sanguineus	Redstem ceanothus	T
Ceanothus velutinus	Shinyleaf ceanothus	T
Centaurea spp.	Knapweed	M*
Cercocarpus montanus	Mountain mahogany	T*
Chrysothamnus spp.	Rabbitbrush	M*
Clintonia uniflora	Clintonia	L*
Cornus stolinifera	Red-osier dogwood	T
Festuca spp.	Fescues	L*
Fragaria virginiana	Strawberry	L*
Athyrium filix-femina *Pteridium aquilinum*	Fern	M
Gaultheria spp.	Wintergreens	L*
Holodiscus discolor	Oceanspray	T
Linnaea borealis	Twinflower	L
Lonicera spp.	Honeysuckle	M
Menziesia ferruginea	Menziesia	M
Pachistima myrsinites	Pachistima	L
Physocarpus malvaceus	Ninebark	M
Potentilla spp.	Cinquefoil	L*
Prunus emarginata	Bittercherry	T
Prunus virginiana	Common chokecherry	T
Ribes spp.	Currant	M
Rosa spp.	Rosa	M
Rubus parviflorus	Thimbleberry	M
Salix spp.	Willow	T
Sambucus spp.	Elderberry	T
Shepherdia canadensis	Russett buffaloberry	M
Smilacina spp.	Solomon's seal	L*
Sorbus spp.	Mountain-ash	T
Spiraea betufolia	Shinyleaf spiraea	L
Symphoricarpos spp.	Snowberry	M
Vaccinium membranaceum	Big huckleberry	M
Vaccinium globulare	Globe huckleberry	

Appendix A (continued).

Scientific Name	Common Name	Height Class
Vaccinium scoparium	Grouse whortleberry	L
Xerophyllum tenax	Common beargrass	M
	Miscellaneous shrubs	M

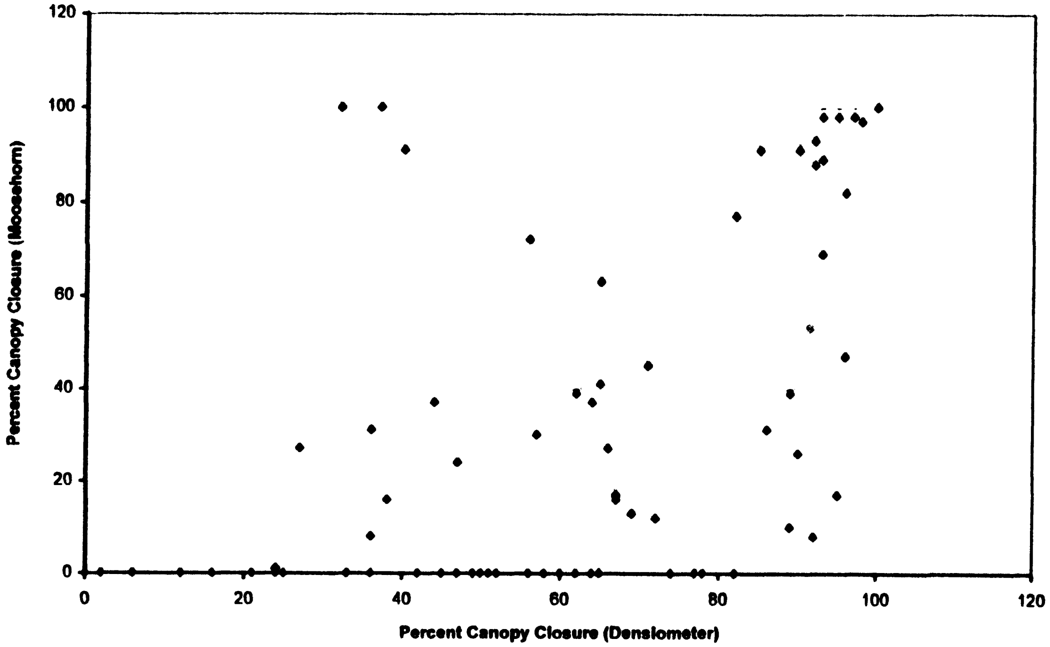
Artemisia tridentata
Clematis columbiana
Cornus nuttallii
Crataegus douglasii
Juniperus spp.
Ledum glandulosum
Lonicera caerulea
Lonicera involucrata
Oplopanax horridum
Philadelphus lewisii
Prunus pensylvanica
Purshia tridentata
Rhamnus purshiana
Rhododendron albiflorum
Rhus trilobata
Rubus leucodermis
Rubus ursinus
Spiraea pyramidata
Taxus brevifolia
Vaccinium caespitosum

* Species included in the field measurements but not in Prognosis.

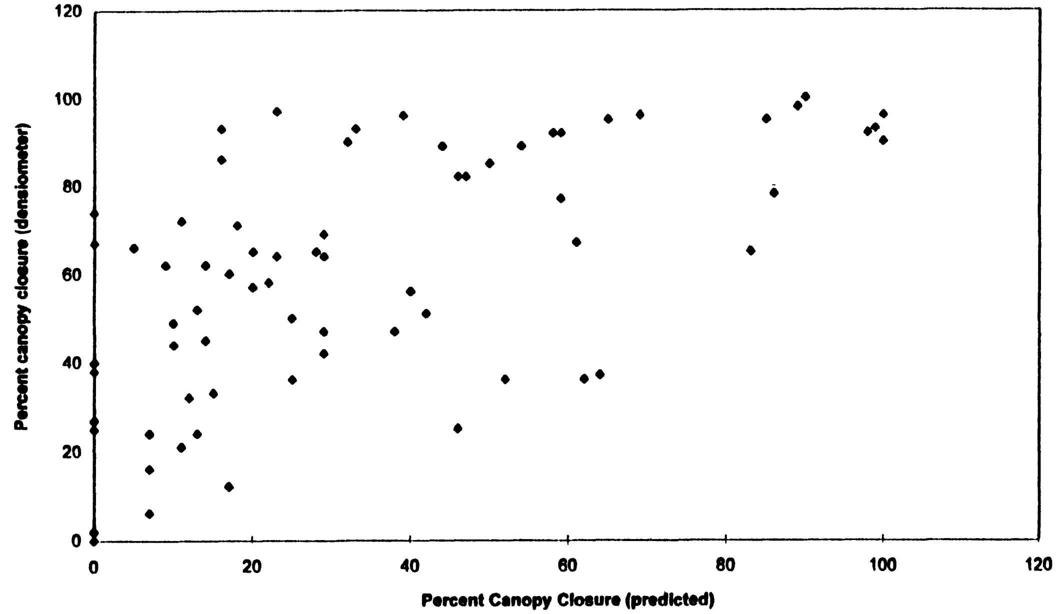
[1] T = tall, M = medium, L = low.

Appendix B. Rules of thumb for interpreting the bivariate coefficient of determination (Hamilton 1990) and modifications made for this study.

Coefficient of correlation (r)	Interpretation: Linear Relationships	Modification
> 0.80	Strong relationship	> 0.87
0.50 - 0.79	Moderate relationship	0.71 - 0.86
0.20 - 0.49	Weak relationship	0.50 - 0.70
	Very weak relationship	< 0.05

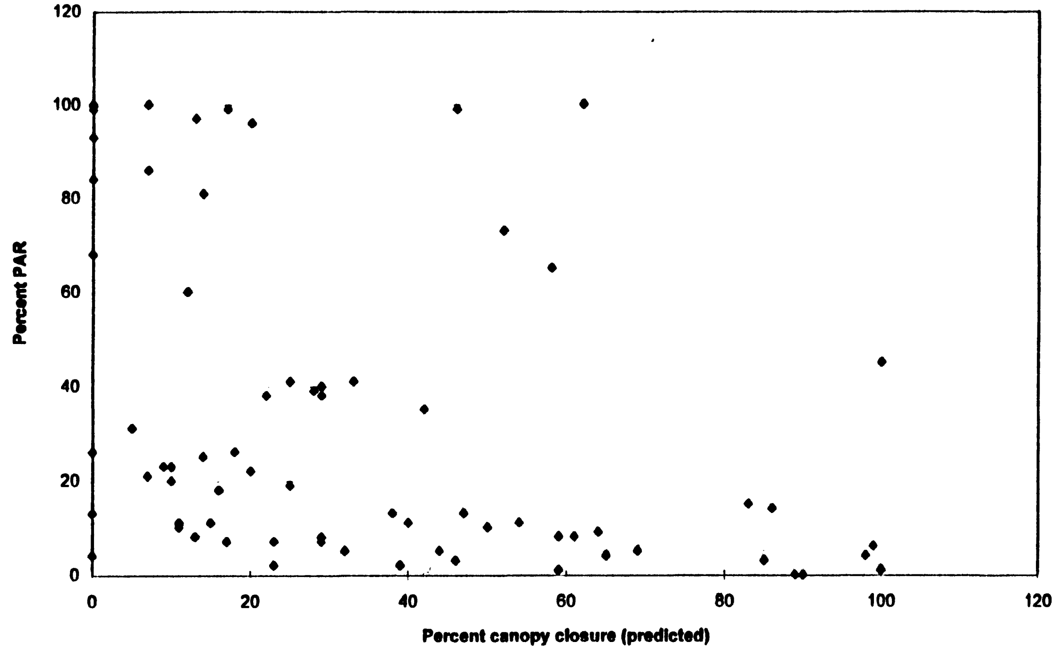


Appendix C. Scatterplot of canopy closure (%) as measured by the moosehorn (y) and the densiomenter (x) for all plots.

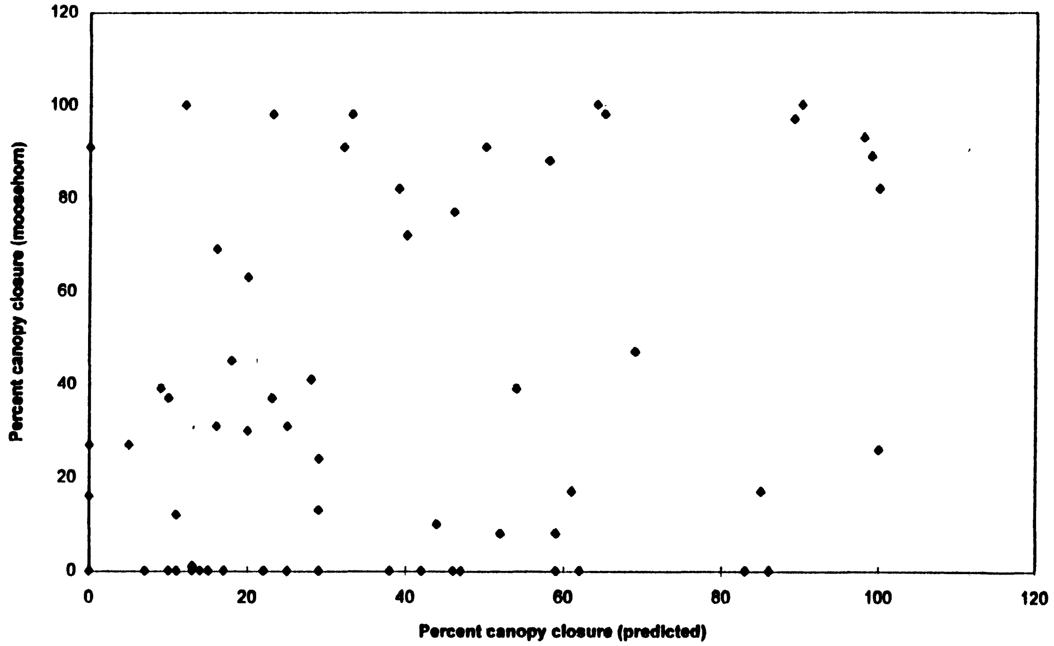


Appendix D

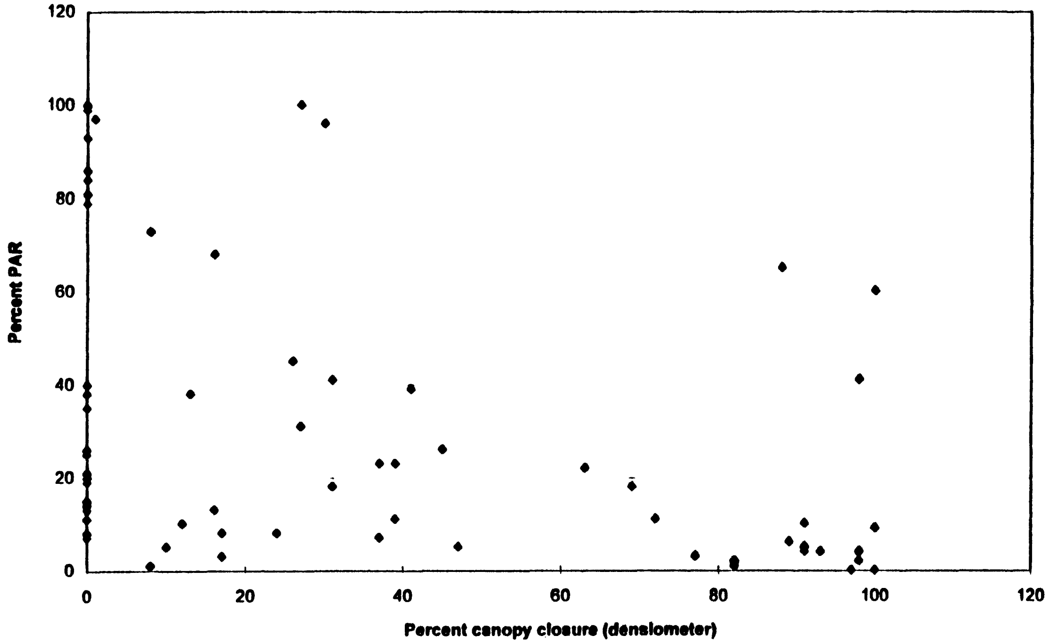
Scatterplot of canopy closure (%) as measured by the densiometer (y) and predicted by Prognosis (x) for all plots



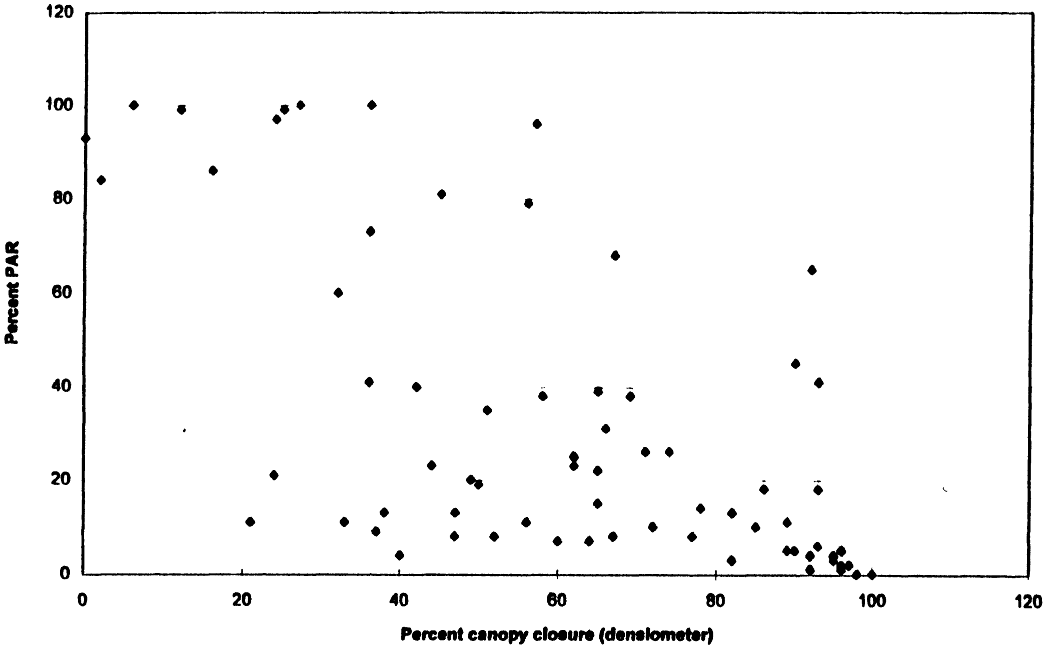
Appendix E. Scatterplot of light transmitted (% PAR) as measured by the ceptometer (y) canopy Closure (%) as predicted by Prognosis (x) for all plots.



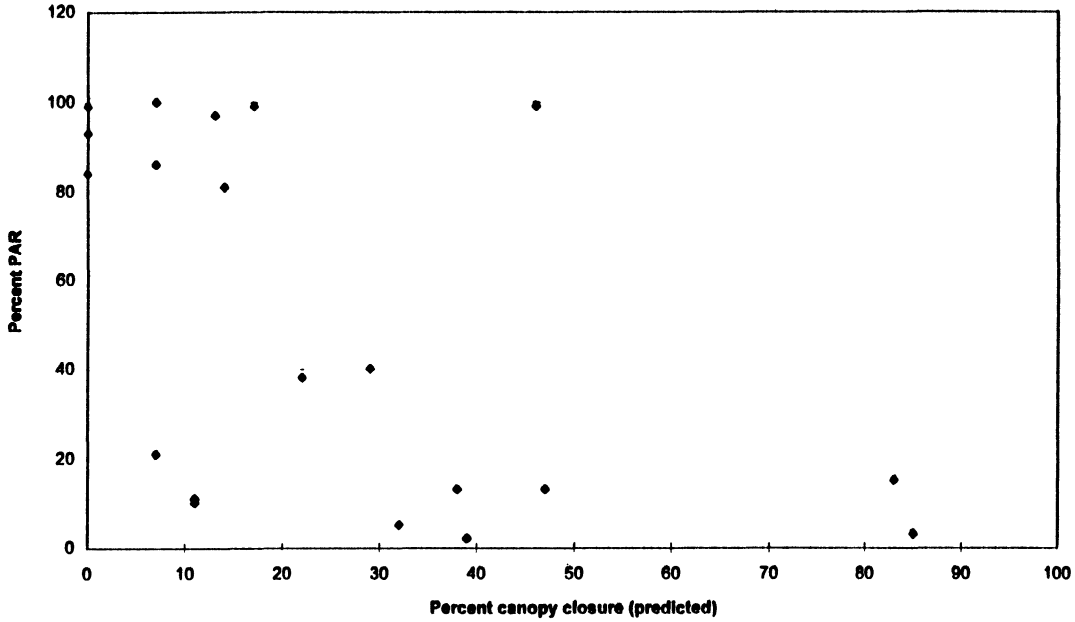
Appendix F. Scatterplot of canopy closure (%) as measured by the moosehorn (y) and predicted by Prognosis (x) for all plots.



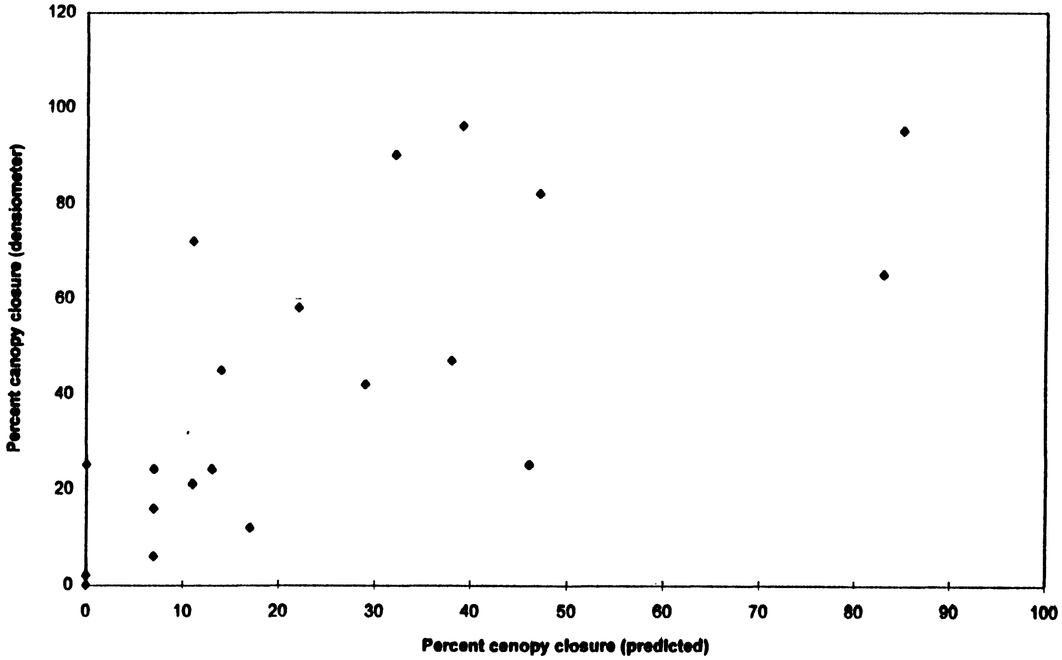
Appendix G. Scatterplot of light transmitted (% PAR) as measured by the ceptometer (y) and canopy closure (%) as measured by the moosehorn (x) for all plots.



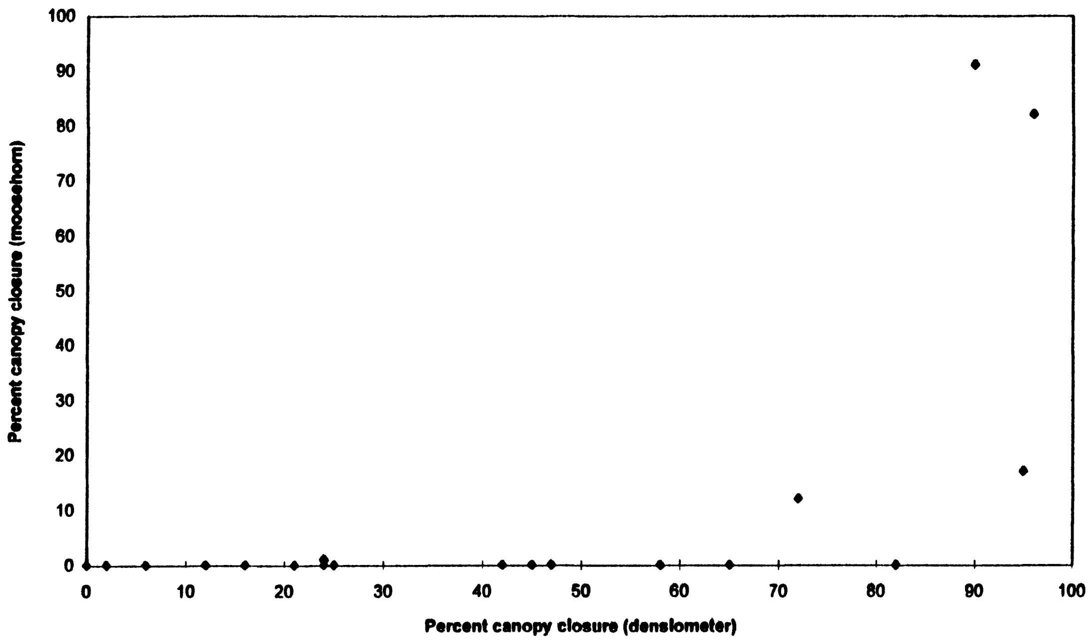
Appendix H. Scatterplot of light transmitted (% PAR) as measured by the ceptometer (y) and canopy closure (%) as measured by the densiometer (x) for all plots.



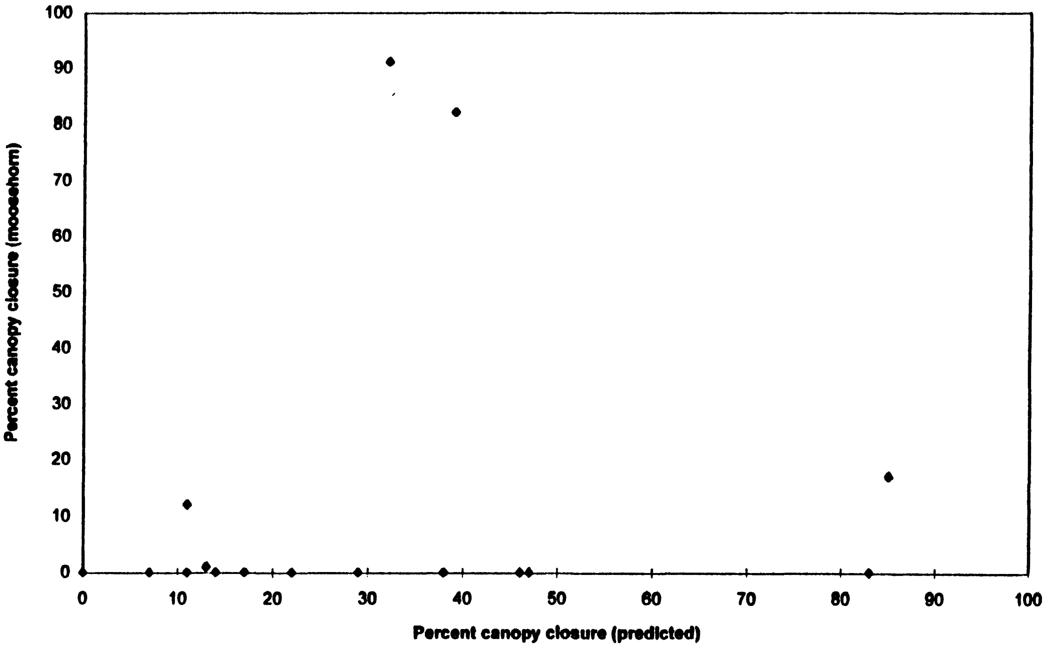
Appendix I. Scatterplot of light transmitted (% PAR) as measured by the ceptometer (y) and conopy closure (%) predicted by Prognosis (x) for the no brush plots.



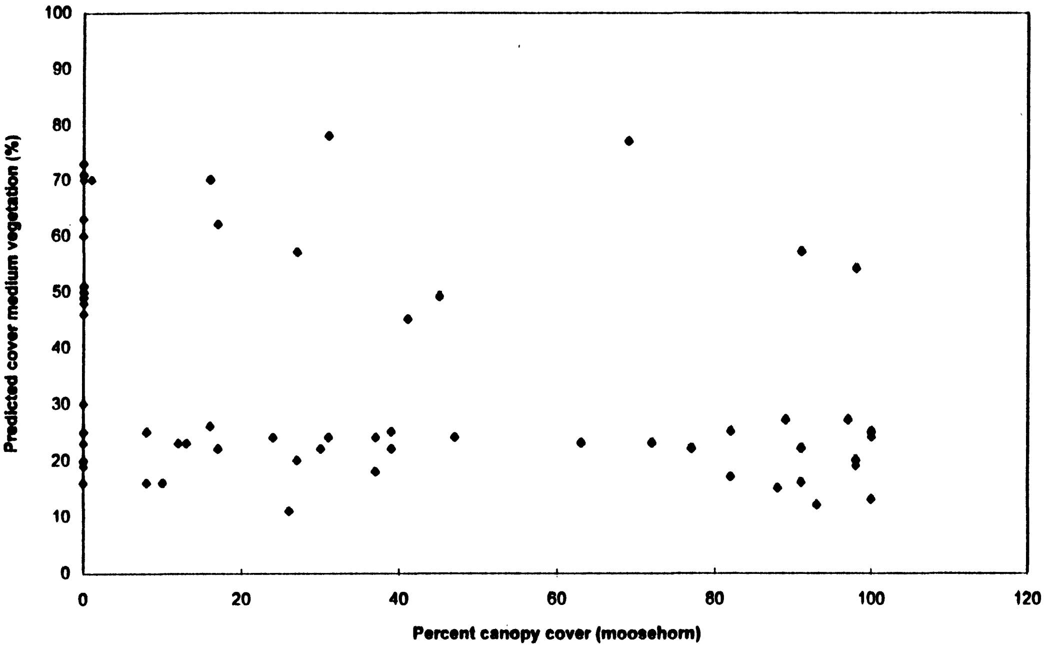
Appendix J. Scatterplot of canopy closure (%) as measured by the densiometer (y) and predicted by Prognosis (x) for the no brush plots.



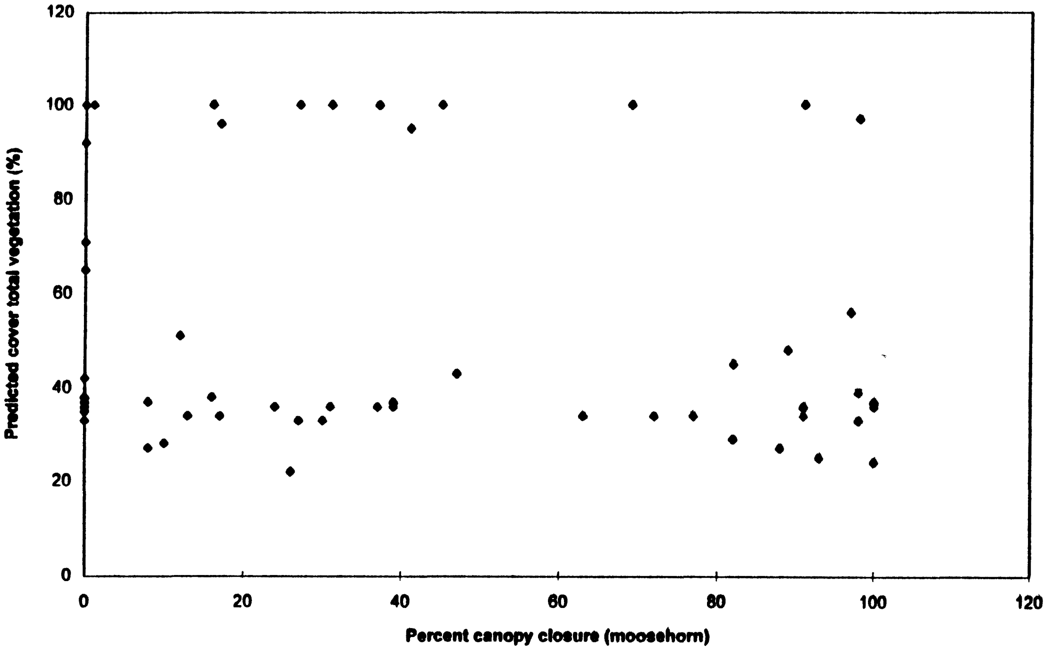
Appendix K. Scatterplot of canopy closure (%) as measured by the moosehorn (y) and the densiometer (x) for the no brush plots.



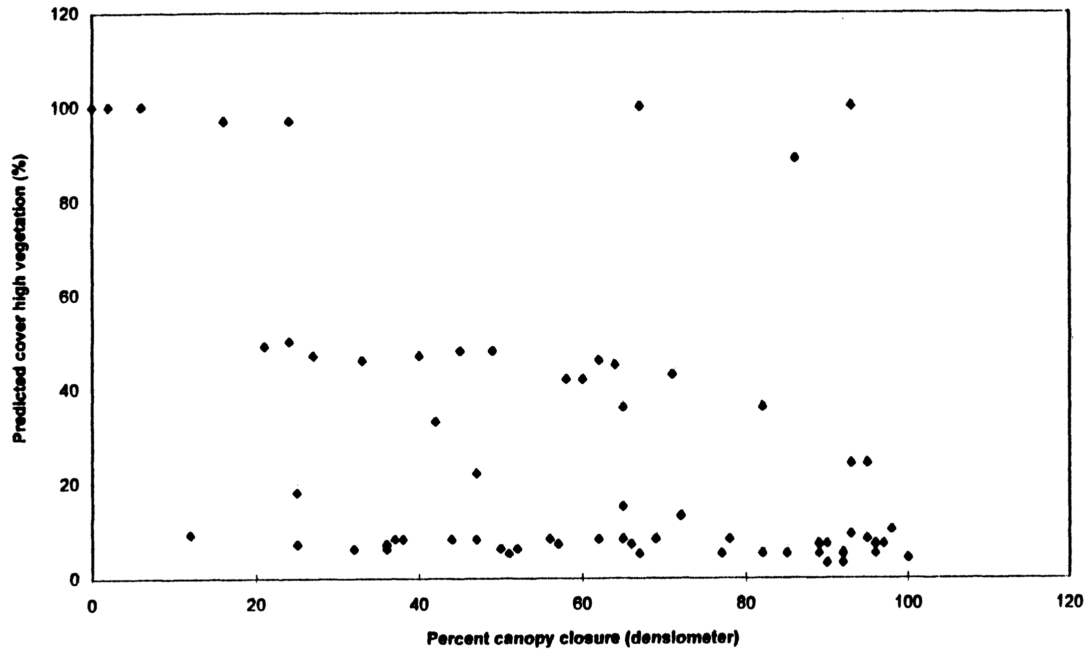
Appendix L. Scatterplot of canopy closure (%) as measured by the moosehorn (y) and predicted by Prognosis (x) for the no brush plots.



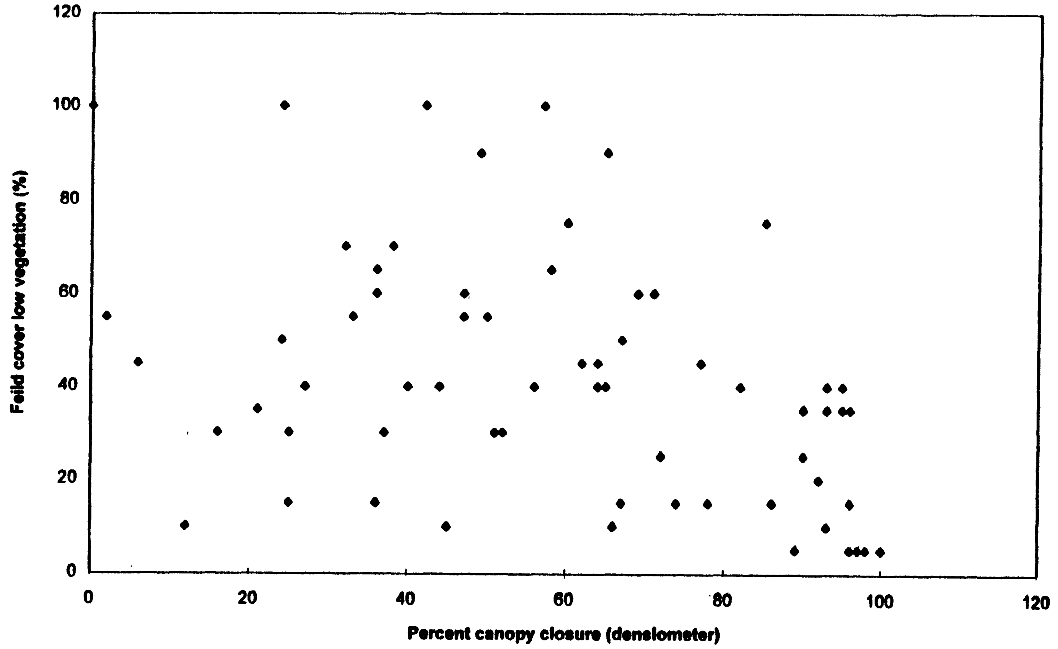
Appendix M. Scatterplot of predicted cover medium vegetation (%) (y) and canopy closure as measured by the moosehorn (x) for all plots.



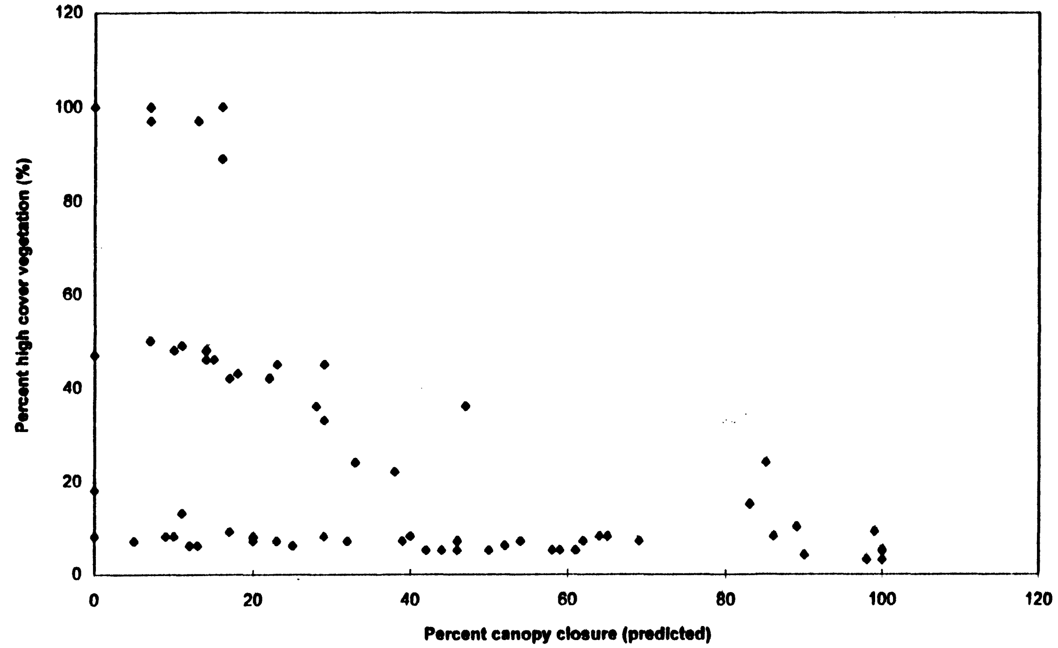
Appendix N. Scatterplot of predicted cover total vegetation (%) (Y) and canopy closure as measured by the moosehorn (x) for all plots.



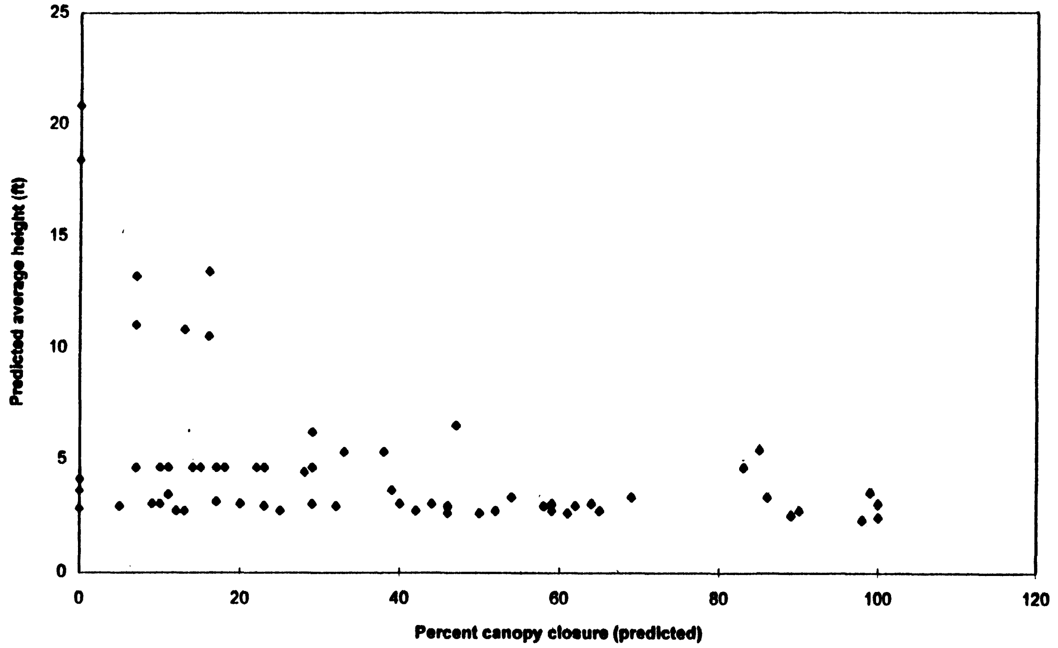
Appendix O. Scatterplot of predicted cover high vegetation (%) (y) and canopy closure as measured by the densiometer (x) for all plots.



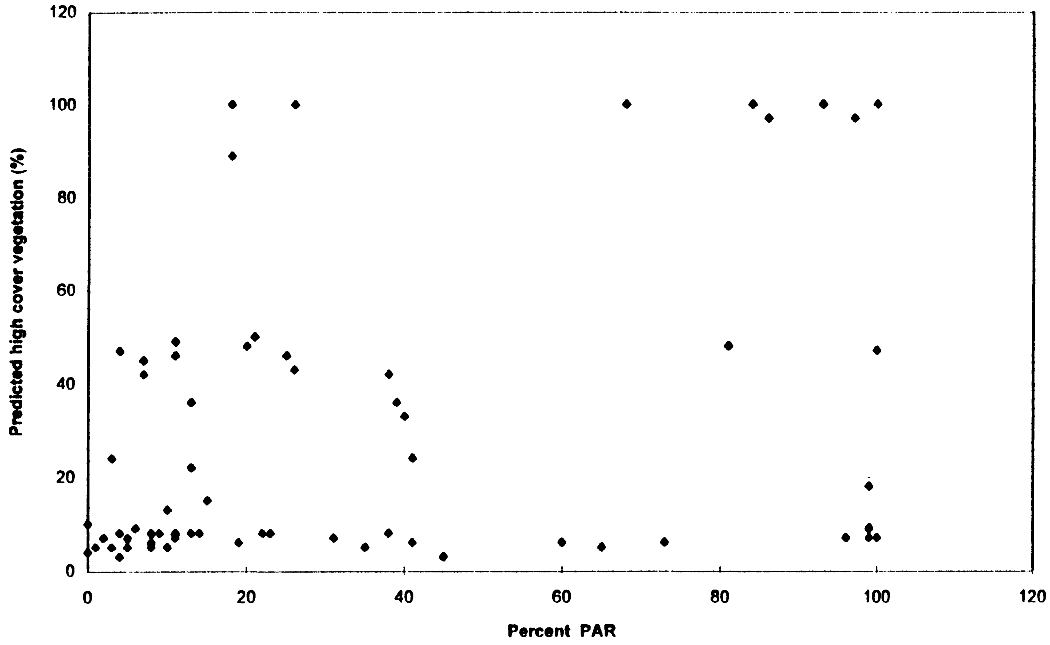
Appendix P. Scatterplot of field measured cover low vegetation (%) (y) and canopy closure as measured by the densiometer (x) for all plots.



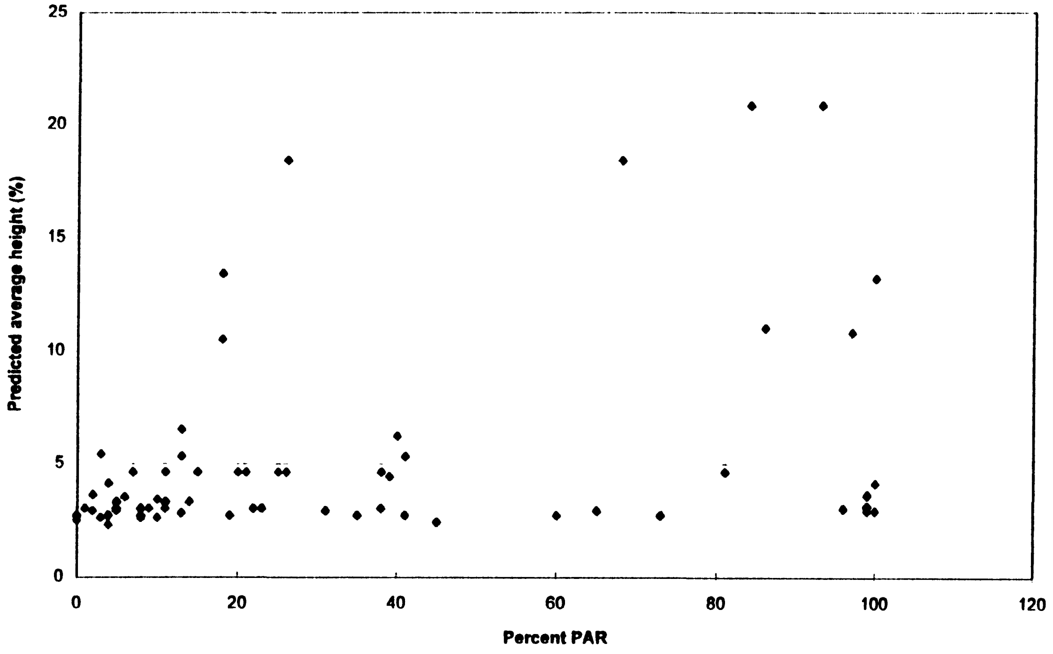
Appendix Q. Scatterplot of predicted cover high vegetation (%) (y) and canopy closure as predicted by Prognosis (x) for all plots.



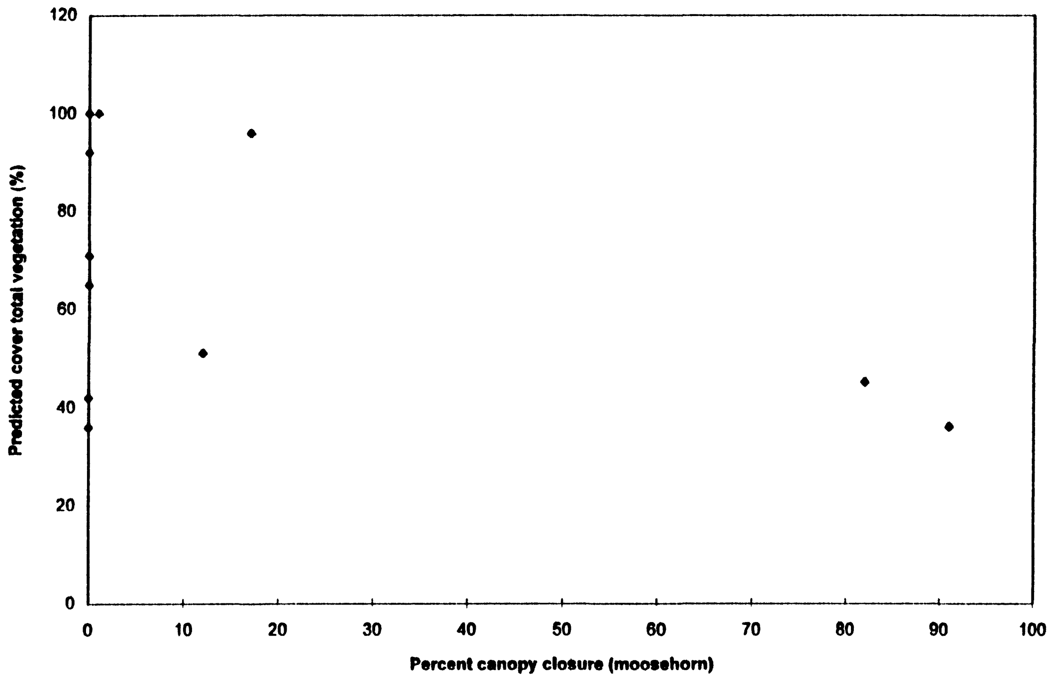
Appendix R. Scatterplot of predicted average height (ft) (y) and canopy closure as predicted by Prognosis (x) for all plots.



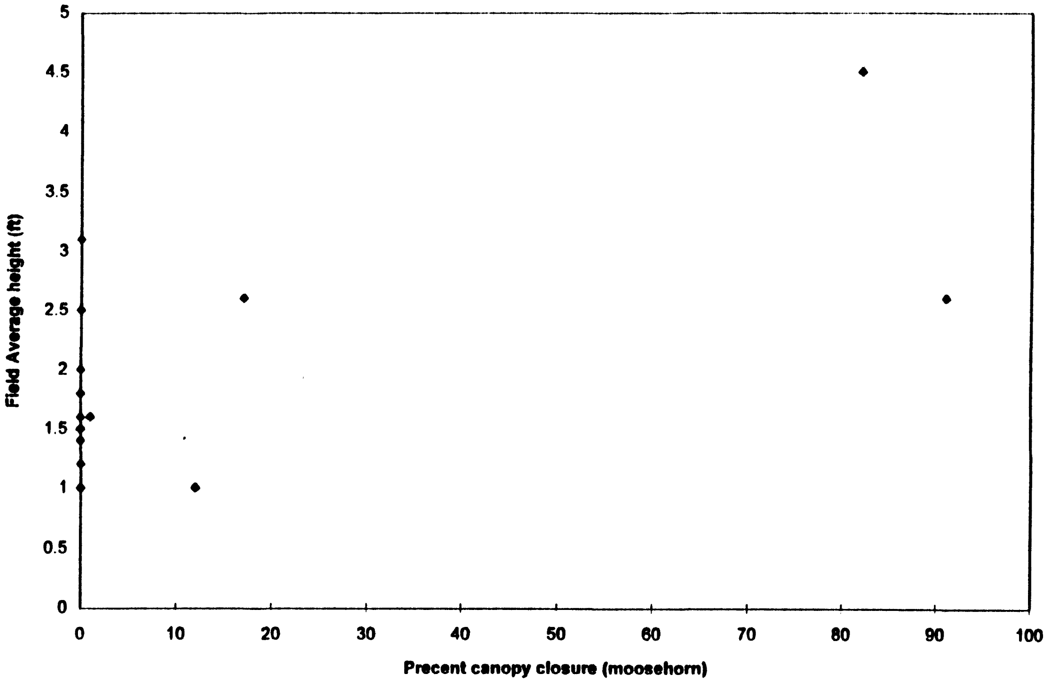
Appendix S. Scatterplot of predicted cover high vegetation (%) (y) and PAR (%) measured by the ceptometer (x) for all plots.



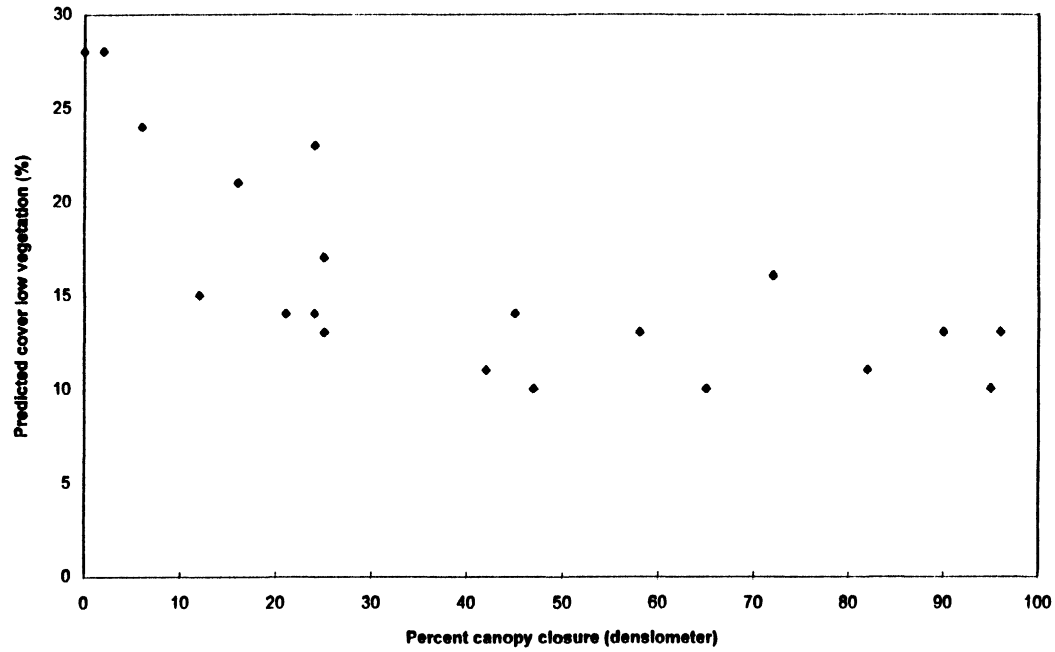
Appendix T. Scatterplot of predicted average height (ft) (y) and PAR (%) measured by the ceptometer (x) for all plots.



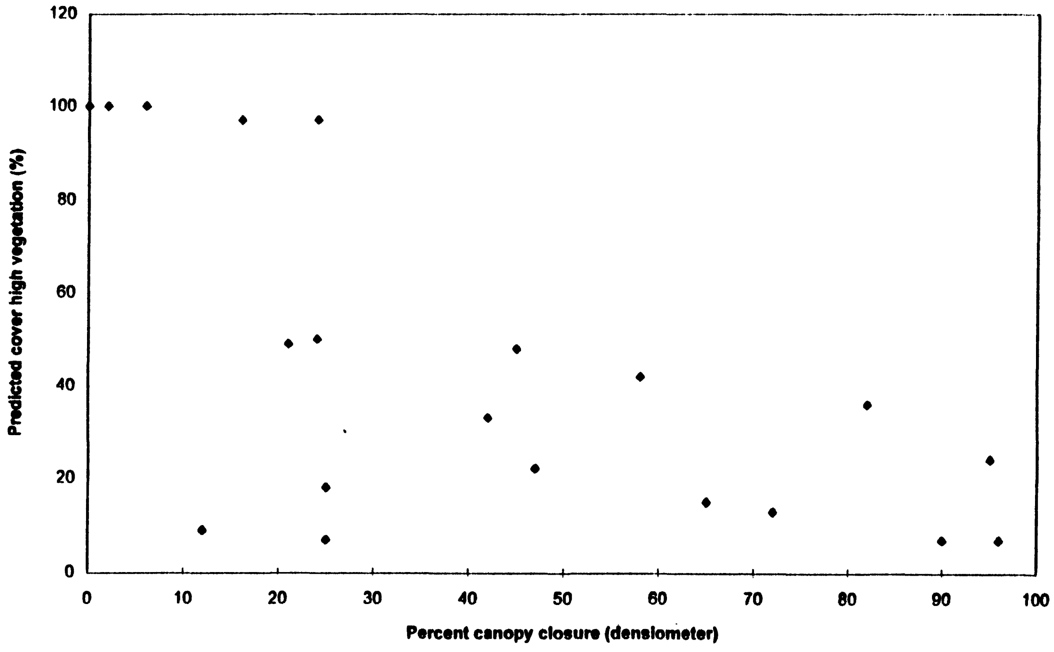
Appendix U. Scatterplot of predicted cover total vegetation (%) (y) and canopy closure as measured by the moosehorn (x) for the no brush plots.



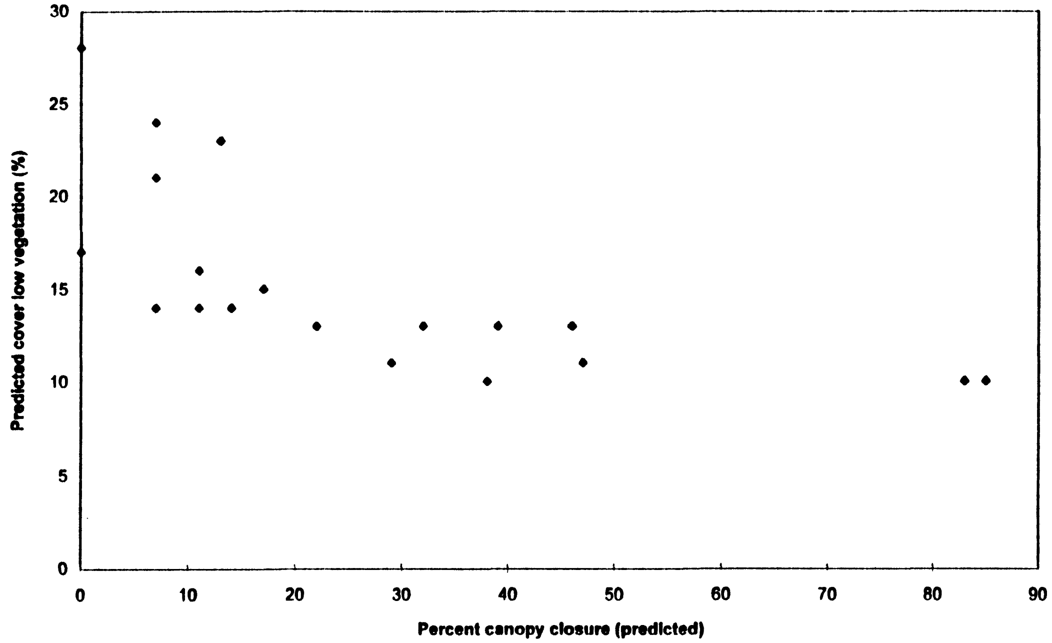
Appendix V. Scatterplot of field measured average height (ft) (y) and canopy closure as measured by the moosehorn (x) for the no brush plots.



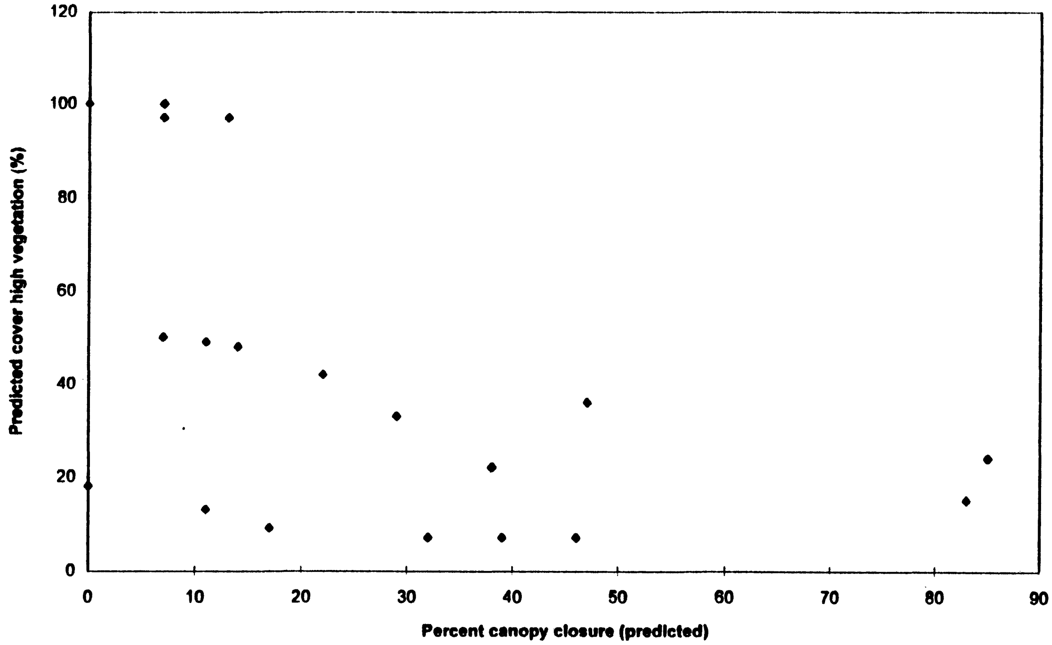
Appendix W. Scatterplot of predicted cover low vegetation (%) (y) and canopy closure as measured by the densiometer (x) for the no brush plots.



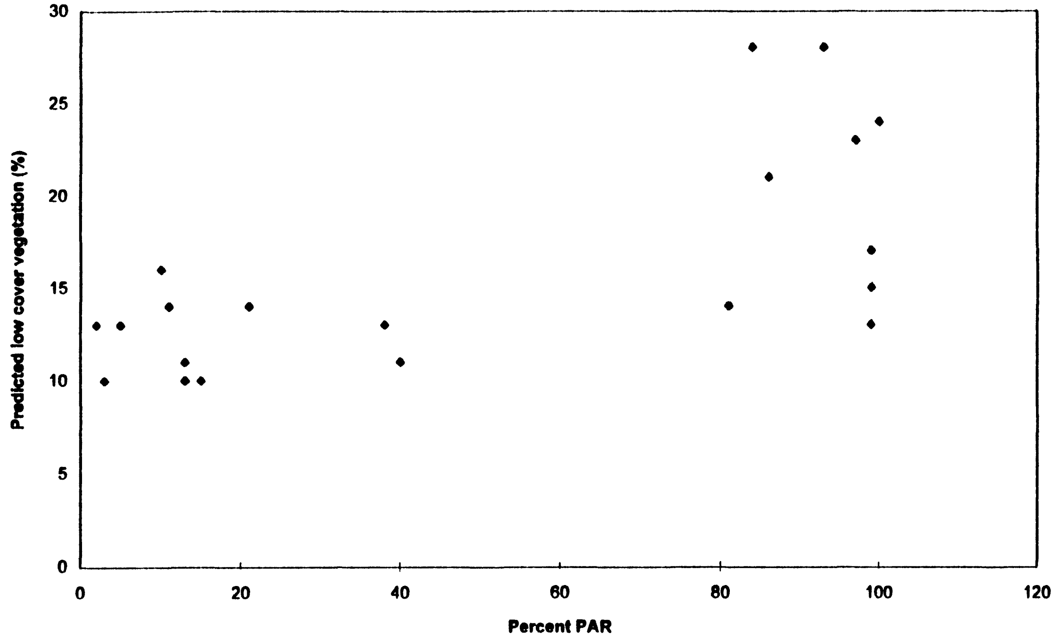
Appendix X. Scatterplot of predicted cover high vegetation (%) (y) and canopy closure as measured by the densiometer (x) for the no bruesh plots.



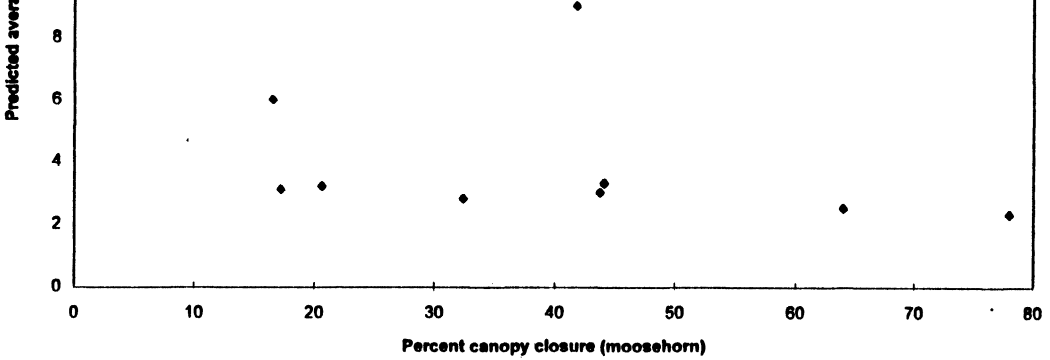
Appendix Y. Scatterplot of predicted cover low vegetation (%) (y) and canopy closure as predicted by Prognosis (x) for the no brush plots.



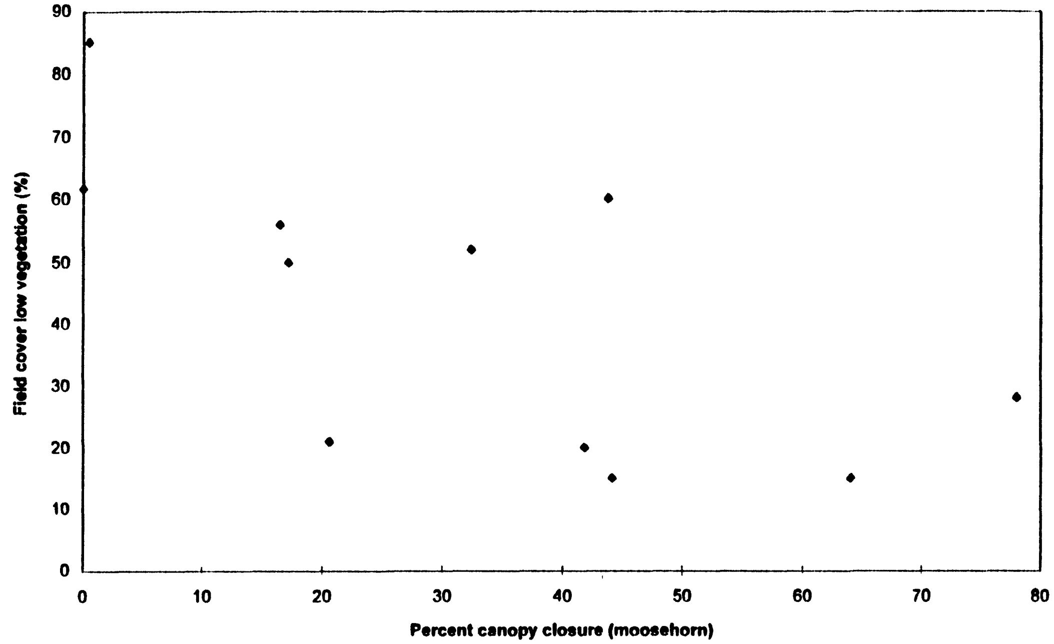
Appendix Z. Scatterplot of predicted cover high vegetation (%) (y) and canopy closure as predicted by Prognosis (x) for the no brush plots.



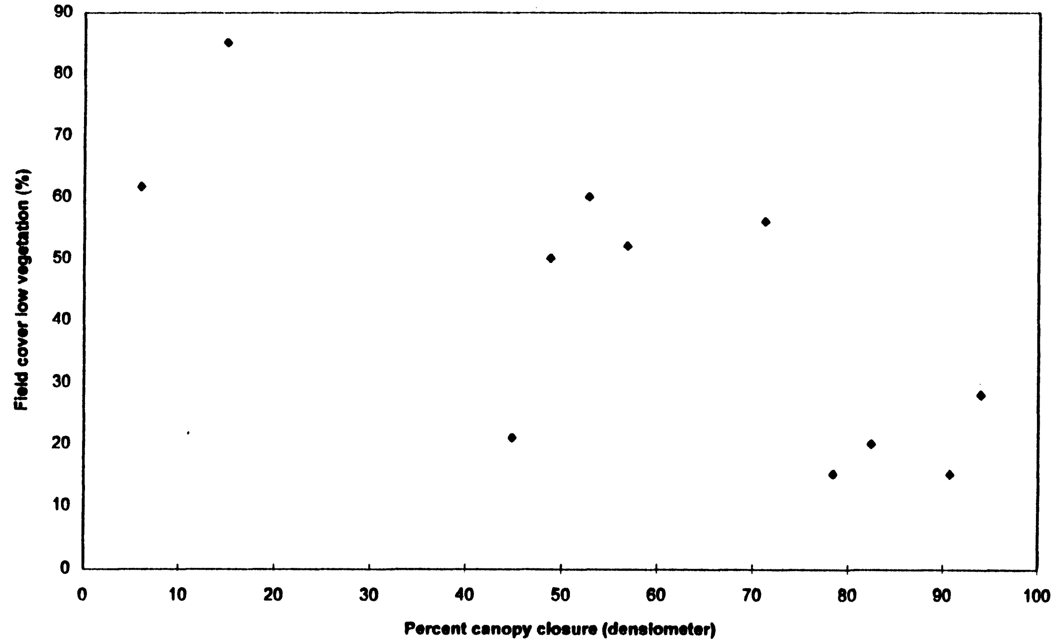
Appendix AA. Scatterplot of predicted cover low vegetation (%) (y) and PAR (%) measured by the ceptometer for the no brush plots.



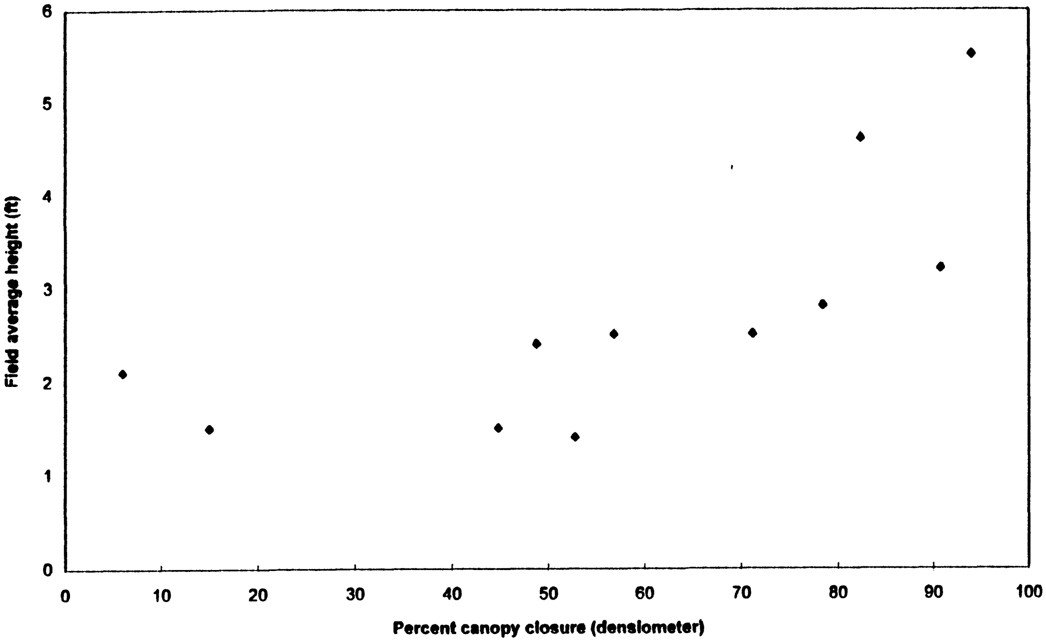
Appendix BB. Scatterplot of predicted average height (ft) (y) and canopy closure as measured by the moosehorn (x) for the stands.



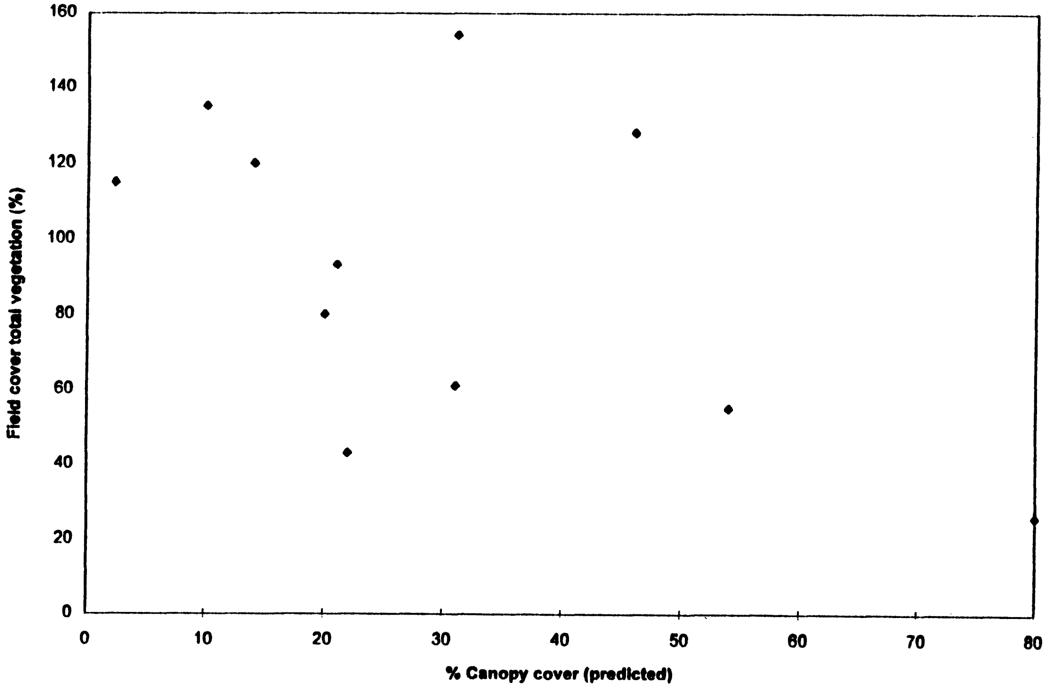
Appendix CC. Scatterplot of field measured cover low vegetation (%) and canopy closure as measured by the moosehorn (x) for the stands.



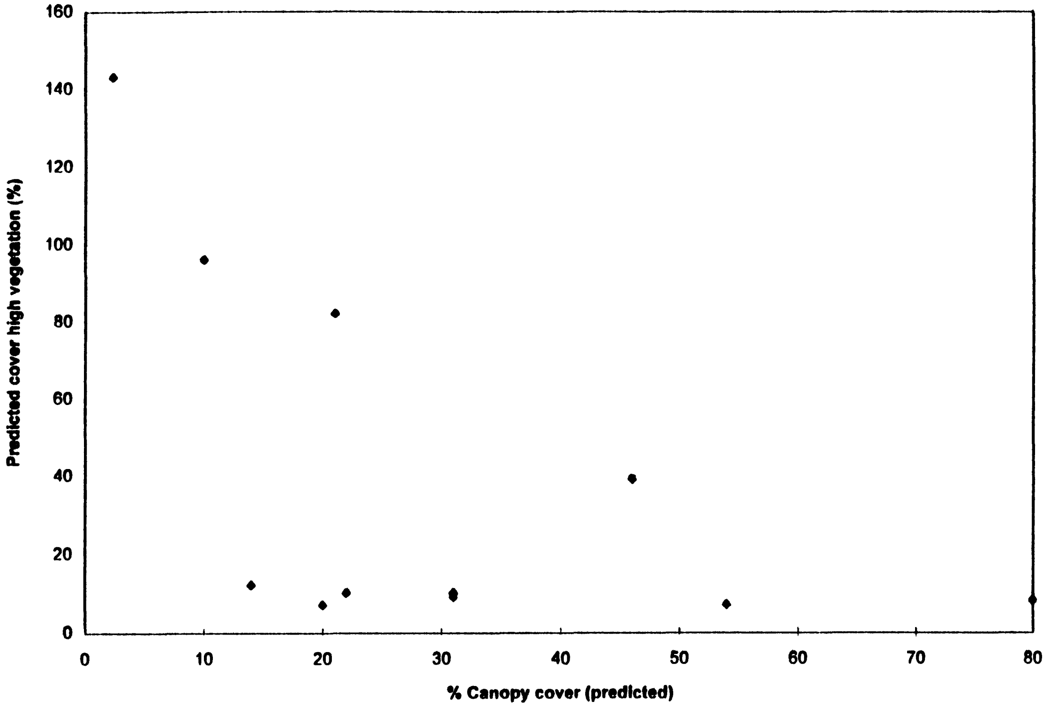
Appendix DD. Scatterplot of field measured cover low vegetation (%) (y) and canopy closure as measured by the densiometer (x) for the stands.



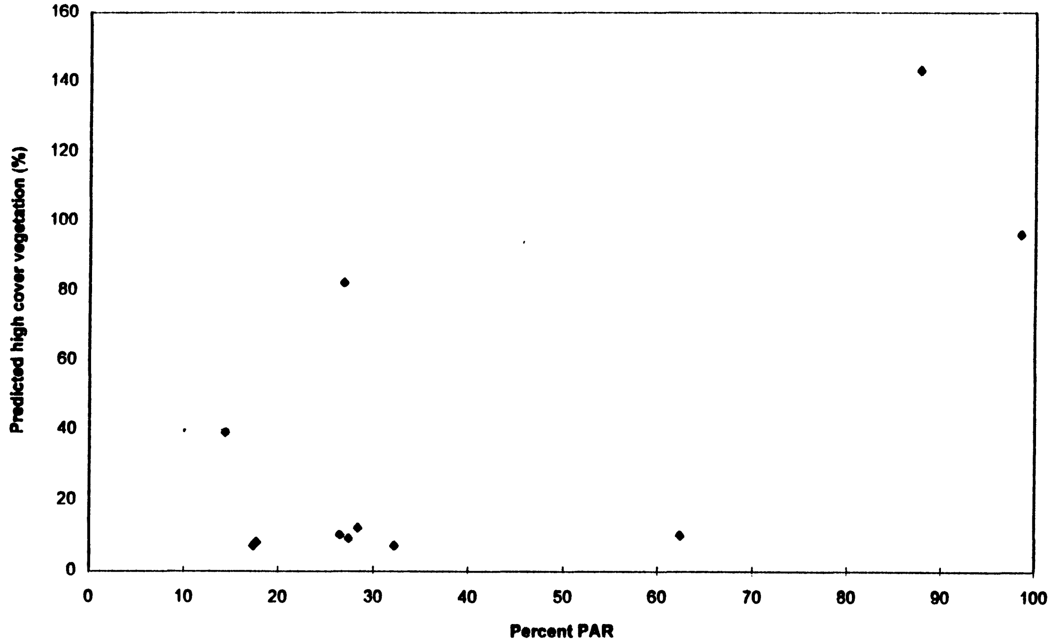
Appendix EE. Scatterplot of field measured average height (ft) (y) and canopy closure as measured by the densiometer (x) for the stands.



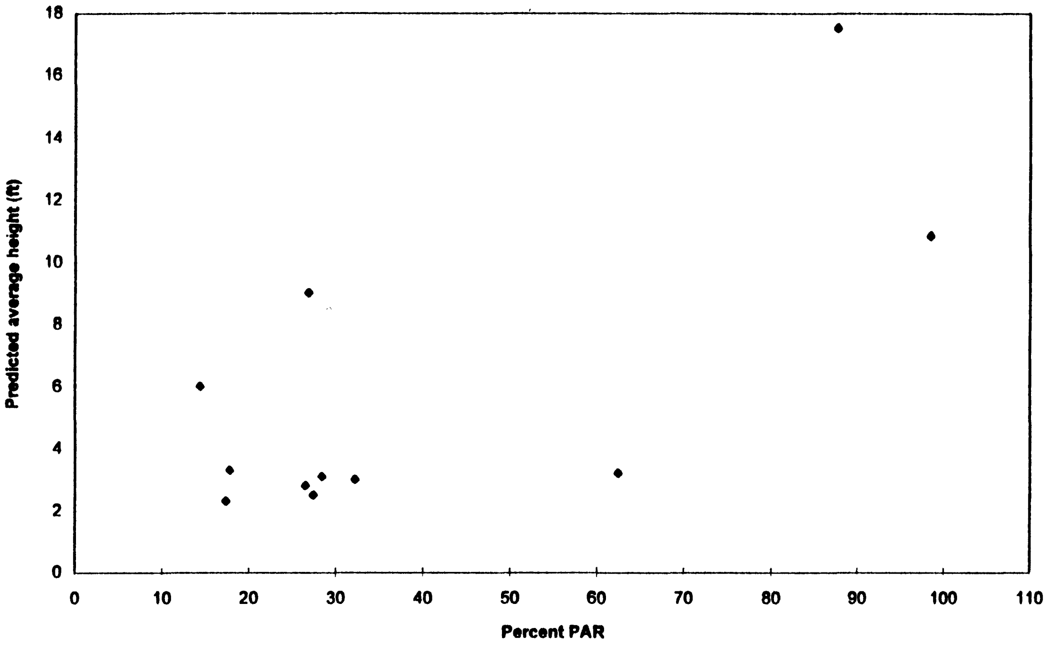
Appendix FF. Scatterplot data of field measured cover vegetation (%) (y) and canopy closure as predicted by Prognosis (x) for the stands



Appendix GG. Scatterplot of predicted cover high vegetation (%) (y) and canopy closure as predicted by Prognosis (x) for the stands



Appendix HH. Scatterplot of predicted cover high vegetation (%) (y) and PAR (%) measured by the ceptometer (x) for the stands.



Appendix II. Scatterplot of predicted average height (ft) (y) and PAR (%) measured by the ceptometer (x) for the stands.