Assessment of Canopy Closure Projections by the PROGNOSIS Model

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Abstract. We studied the relationship between canopy closure derived from vertical projection and stand density index (SDI) during September 1993 on the Kaibab National Forest in northern Arizona to test predictions from the PROGNOSIS model. Management recommendations for wildlife species within southwestern ponderosa pine (*Pinus ponderosa*) forests frequently include desired canopy closures. Canopy closure estimates can be expensive to obtain beyond information collected during forest stand exams. Hence, foresters have developed models to predict canopy closure from existing data. PROGNOSIS is a model that predicts canopy closure based on SDI; the model has not been validated in Arizona. We sampled 230 random plots across 10,000 ha to develop a data set for testing. The relationship between SDI and canopy closure explained less than 50% of the variation within the data set, and PROGNOSIS consistently overestimated canopy closure when compared with estimates from vertical projection. By placing 95% confidence limits around the observed relationship between SDI and field measurements of canopy closure, we found PROGNOSIS estimates of canopy closure consistently outside the upper bounds of the relationship. PROGNOSIS should not be used in its current form to estimate canopy closure for wildlife habitat evaluations.

Key words: Habitat evaluation, habitat model, SDI, stand density index, wildlife.

Numerous authors have discussed the relationship between variations in forest structure and the relative quality of that structure as it pertains to wildlife habitat (Leopold 1949, Thomas et al. 1979, Hoover and Willis 1987). One important component of forest stand structure is crown closure. Species such as elk (*Cervus elaphus*) (Thomas et al. 1979, Brown 1991), northern goshawk (*Accipiter gentilis atricapillus*) (Kennedy 1989, Austin 1991), Merriam's turkey (*Meleagris gallopavo merriami*) (Mollohan et al. 1995), tassel-eared squirrels (*Sciurus aberti*) (Patton and Vahle 1986), and black bear (*Ursus americana*) (LeCount and Yarchin 1990) seemingly include variations in canopy closure in their selection of habitat for various behaviors. Thus, canopy closure has been established as a measure of habitat quality for many species.

Management recommendations frequently use canopy closure as a criteria for desired habitat structure (Reynolds et al. 1992, Hoffman et al. 1993). Both the U.S. Forest Service (Reynolds et al. 1992) and the Arizona Game and Fish Department (Arizona Game and Fish Department 1993) assessed proposed timber harvest effects using the timber growth and yield model PROGNOSIS (Wykoff et al. 1982). One of the outputs of this model is predictions of forest canopy closure based on stand exam data. Arizona Game and Fish Department (1993) used the model to evaluate effects of managing ponderosa pine forests in Arizona at varying tree densities, expressed in terms of Stand Density Index (SDI, Reineke 1933, McTague and Patton 1989). PROGNOSIS predicted that an SDI of 140 would yield 40% canopy closure. However, the relationship between SDI and canopy closure as predicted by PROGNOSIS has not been validated in Arizona.

The absence of this validation raised questions as to the accuracy of canopy closure predictions and reliability of subsequent applications. In addition to this concern, SDI was developed for even-aged forests and is frequently applied to forest stands that are not. Further, PROGNOSIS allows canopy closure estimates to exceed 100%, a value it then uses to provide a crown competition factor. This assumption is also often ignored in practice.

Our study was designed to evaluate the accuracy of the PROGNOSIS model in predicting canopy closure from SDI values while ignoring some underlying assumptions, as it is often used in practice. Our objectives were to (1) determine the relationship between SDI and canopy closure and (2) compare measured values with those predicted by PROGNOSIS.

Study Area

Our study was conducted on the North Kaibab Ranger District of the Kaibab National Forest, northern Arizona, in stands that had not been harvested for ≥10 years. Common forest trees on the area included ponderosa pine, Douglas-fir (*Pseudostuga menziesii*), white fir (*Abies concolor*), aspen (*Populus tremuloides*), and Gambel oak (*Quercus gambelii*).

Methods

Vegetation Sampling

We sampled 230 randomly located 0.04-ha circular plots. We computer-generated random Universal Transverse Mercator (UTM) coordinates to locate initial sampling points, then paced a computer-generated random distance (<100 m) on a random compass bearing to locate plot centers.

Each plot was classified by dominant trees on the sample plot. Stands with oak trees growing within ponderosa pine were considered ponderosa pine-Gambel oak type. Stands with ≥2 conifer species were considered mixed-conifer type. Those composed completely by ponderosa pine or aspen were so noted.

Canopy closure was determined by vertical projection from 20 points within each 0.04-ha plot (Johansson 1985). These 20 points were placed along a line following a randomly determined bearing, and on a second line at 90° from the first bearing (10 points on each line). Sample point placement was such that concentric rings through points equidistant from site center encompassed approximately the same area (i.e., first points were 4 m from site center and a concentric ring on plot center encompassed 50.24 m^2, second points were 5.7 m from site center and encompassed 102.02 m^2, third points were 6.8 m and encompassed 145.19 m^2, fourth points were 7.9 m from site center and encompassed 195.97 m^2, and fifth points were 8.9 m from site center and encompassed 248.72 m^2).

We read vertical projection at each point using a custom-fabricated, gimbal-suspended sighting periscope, 2.5 cm in diameter and 30.5 cm in length, with crosshairs constructed at its upper end. A mirror was mounted at the bottom of the tube to allow the observer to see the crosshair intersection while the tube was vertical. Each vertical projection reading was recorded as either under canopy or not, and what type of vegetation formed the canopy. The crosshairs had to be covered by vegetation in order to be recorded as a hit.

We measured the diameter at breast height (dbh) with a Biltmore stick for all trees on the plot >8.9 cm dbh. Each conifer tree measured on the plot was classified into one of four size classes (Table 1). A plot was then classified into one of four vegetation structural stage (VSS) classes (classes 3–6) by determining which size class yielded the greatest SDI value (Reynolds et al. 1992).

Data Analysis

Canopy closure was regressed on SDI across all dominant tree types collectively and within dominant tree type and structural stage. SDI values

Table 1. Range of tree diameters used to classify forest stands into vegetation structural stage classes.

Class lower limit (cm)	Class upper limit (cm)	VSS class
12.7	<30.5	3
30.5	<45.8	4
45.8	<61.0	5
61.0	none	6

were determined separately for all conifers, and all trees combined. SDI was calculated according to Reineke (1933) and McTague and Patton (1989) as:

$$SDI = 10n\left(\frac{\sqrt{1/n \sum_{i=1}^{n} d_i^2}}{10}\right)^{1.605}$$

where d_i represents dbh of the ith tree on the sample plot, and n represents the number of trees occurring on the plot. SDI values were calculated for each size class for each plot. Each plot was placed into VSS categories based on the dominant SDI value.

Canopy closure was computed as the percent of the 20 vertical projections in which foliage was present. Canopy closure was calculated for each dominant tree type and across all dominant tree types.

Canopy closure was also predicted for each plot according to PROGNOSIS. Logarithmic regression equations are used by PROGNOSIS to predict individual tree crown width from species, dbh, height, and crown length of trees ≥8.9 cm dbh (Moeur 1981, 1985). Height and crown length are estimated from dbh and basal area of the plot (Wykoff et al. 1982). Coefficients used in the equations were derived for the Idaho variant of ponderosa pine. We used the following equations from Wykoff et al. (1982) to predict canopy closure for each plot:

where: D = diameter at breast height
H = tree height
CL = crown length

BA = basal area
CW = crown width
CA = crown area
PA = plot area
CC = canopy closure, then

$$H = e^{4.6024 - [11.4693 / (D + 1)]} + 4.5$$

$$CL = 4.35671 + 0.84714 (D) + 0.32549 (H) - 0.03802 (BA)$$

$$\ln CW = 1.62365 + 1.08137 \ln D - 0.68098 \ln H + 0.29786 \ln CL$$

$$CW = e^{½(0.04898)} \text{ (antilog ln CW)}$$

$$CA = \pi (CW/2)^2$$

where n represents the number of trees on a plot. This canopy closure estimate was regressed on conifer SDI and canopy closure measured on the plots.

$$CC = \frac{\sum_{i=1}^{n} CA_i}{PA}$$

Results

A total of 230 plots were sampled across 10,000 ha. Samples were distributed in similar proportion across VSS classes 3–6, ranging from 20% to 33% of all observations (Table 2).

Table 2. Distribution of sample plots by vegetation structural stage on the North Kaibab Ranger District, Arizona, 1993.

VSS category	Frequency	Percent
3	50	21.7
4	46	20.0
5	58	25.2
6	76	33.1
Total	230	100.0

Regression analysis of SDI and canopy closure were conducted for the total data set and for several subsets (Table 3). All regression relations resulting from the analyses were significant ($P \leq 0.001$), indicating that the slopes of the lines differed from zero. The coefficient of simple determination (r^2) for the regressions ranged between 0.15 and 0.46 (Table 3), indicating that a relatively weak relationship existed between SDI and canopy closure. Despite a high degree of variability, SDI values related to canopy closure (Fig. 1).

Considering a 95% confidence interval around the regression line, both upper and lower confidence interval lines yielded meaningful results (Table 4). The strongest relationships were obtained for plots in the ponderosa pine vegetation type. The regression equation resulting from conifer canopy closure (canopy made up of only conifer leaves and limbs) regressed on conifer SDI (SDI calculated using only coniferous trees) yielded an r^2 of 0.46 (Fig. 1). This regression predicts that an SDI of 191 is needed to provide a mean conifer canopy closure of 40% in ponderosa pine. Total canopy closure (all canopy regardless of tree species) regressed on total SDI (all trees) yielded an r^2 of 0.39 for the ponderosa pine vegetation type. This regression predicts that an SDI of 176 is needed to provide a mean total (ponderosa pine) canopy closure of 40%.

SDI values required to yield 40% canopy closures were comparable across most subsets of the data. An r^2 of 0.34 and 0.24 resulted from regressions of conifer canopy closure and total canopy closure, respectively, on conifer SDI across all vegetation types. These regressions predict that SDIs of 182 for conifer canopy and 151 for total canopy are needed to produce a mean of 40% canopy closure. Conifer canopy closure regressed on conifer SDI in the mixed conifer vegetation type, with post-treatment plots excluded, yielded $r^2 = 0.30$ and 0.20 for total canopy closure regressed on total SDI. The mixed-conifer regressions predicted that SDIs of 148 for conifer canopy and 101 for total canopy were needed to provide a mean 40% canopy closure in mixed-conifer habitats.

PROGNOSIS estimates of canopy closure were weakly related, in a pairwise fashion, to canopy closure values measured at sample plots. PROGNOSIS estimates, regressed on measured canopy closure values, yielded an $r^2 = 0.14$ ($P = 0.001$), and a high degree of scatter. However, PROGNOSIS estimates regressed on conifer SDI (ponderosa pine plots only, Fig. 2) yielded a weak relationship ($r^2 = 0.40$, $P < 0.00001$). Still, a general trend can be seen in that increasing SDI results in increasing canopy closure estimates from PROGNOSIS. Both relationships between PROGNOSIS estimates and measured canopy closures demonstrated a high degree of variability when compared with SDI.

The algorithms utilized by PROGNOSIS yielded slightly higher canopy closure values in comparison to vertical projection measurements. This observation can be seen in the slopes of the canopy closure-SDI regressions (Figs. 1 and 2). Canopy closure estimates from PROGNOSIS ranged from 0

Table 3. Regression coefficients, significance level, and confidence intervals of measured canopy closure regressed on stand density index, North Kaibab Ranger District, Arizona, 1993.

Data set[a]	Variables							
	Predictor[b]	Response[c]	n	r^2	P	β_0	β_1	95% confidence interval on β_1
All data	TSDI	TCC	231	0.24	<0.0001	18.9	0.14	0.11–0.18
All data	TCSDI	CCC	231	0.34	<0.0001	12.7	0.16	0.13–0.18
All data	TCSDI	TCC	231	0.16	<0.0001	23.4	0.12	0.08–0.15
Ponderosa pine	TSDI	TCC	101	0.39	<0.0001	11.9	0.16	0.12–0.20
Ponderosa pine	TCSDI	CCC	101	0.46	<0.0001	8.5	0.17	0.13–0.20
Ponderosa pine	TCSDI	TCC	101	0.34	<0.0001	13.7	0.15	0.11–0.19
Mixed conifer	TSDI	TCC	83	0.20	<0.0001	26.1	0.14	0.08–0.20
Mixed conifer	TCSDI	CCC	83	0.30	<0.0001	16.0	0.16	0.11–0.22
Mixed conifer	TCSDI	TCC	83	0.15	0.0003	30.4	0.12	0.06–0.19

[a]All data includes all vegetation types, treated and untreated plots, both ponderosa pine and mixed conifer include only untreated plots in the respective vegetation type.

[b]TSDI is total SDI with all trees ≥12.5 cm dbh regardless of tree species. TCSDI is SDI for conifer trees ≥ 1.5 cm dbh.

[c]TCC is total canopy closure regardless of tree species. CCC is canopy closure of conifers only.

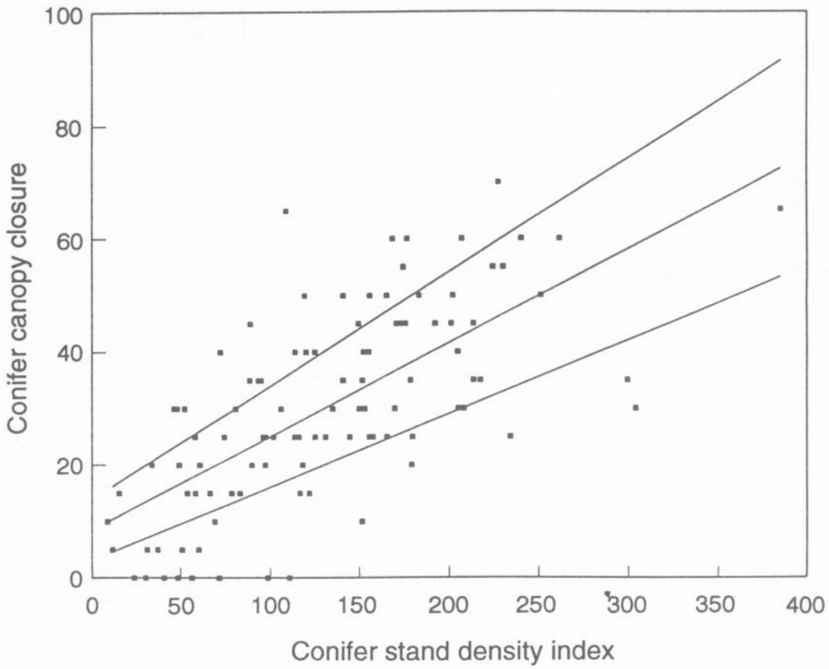

Fig. 1. Regression of measured conifer canopy closure on measured conifer stand density index, using only ponderosa pine plots (r^2 = 0.046, P = <0.0001), North Kaibab Ranger District, Arizona, 1993. Outer lines are 95% confidence limits around the regression line.

to >300%. These canopy closure estimates >100% were reassigned a maximum value of 100% for the regression mentioned above. When not so truncated the regression (estimated canopy closure on SDI) yielded an even steeper slope ($\beta = 0.559$) and a higher coefficient of determination ($r^2 = 0.51$, P <0.00001, Fig. 3).

We also observed a trend for higher canopy closure predicted by PROGNOSIS at the stand level than was observed at individual measured plots. In a recent PROGNOSIS simulation of forest conditions on our study area, Arizona Game and Fish Department (1993) reported canopy closures for various SDI values. We plotted these canopy closure values against SDI, and compared the resulting distribution with the observed canopy closure-SDI regression for ponderosa pine (Fig. 4). Most canopy closure estimates fell outside of the 95% regression confidence interval. The slope of the PROGNOSIS estimate trend was similar to the observed ponderosa pine

Table 4. Stand density index values needed to provide specified levels of canopy closure based on field data collected on the North Kaibab Ranger District, Arizona, 1993.

Data set[a]	Predictor[b]	Response[c]	Canopy closure (%)	Predicted SDI	95% confidence limits	
					Lower	Upper
All data	TSDI	TCC	40	151	88	239
			60	293	228	374
All data	TCSDI	CCC	40	182	129	242
			60	296	263	364
All data	TCSDI	TCC	40	138	111	208
			60	305	244	458
Ponderosa pine	TSDI	TCC	40	176	110	288
			60	301	241	401
Ponderosa pine	TCSDI	CCC	40	191	131	286
			60	303	258	396
Ponderosa pine	TCSDI	TCC	40	175	138	239
			60	309	243	421
Mixed conifer	TSDI	TCC	40	101	21	310
			60	242	170	424
Mixed conifer	TCSDI	CCC	40	148	75	293
			60	275	200	400
Mixed conifer	TCSDI	TCC	40	80	51	160

[a]All data includes all vegetation types, treated and untreated plots, both ponderosa pine and conifer include only untreated plots in the respective vegetation type.

[b]TSDI is total SDI with all trees ≥12.5 cm dbh regardless of tree species. TCSDI is SDI for conifer trees ≥12.5 cm dbh.

[c]TCC is total canopy closure regardless of tree species. CCC is canopy closure of conifers only.

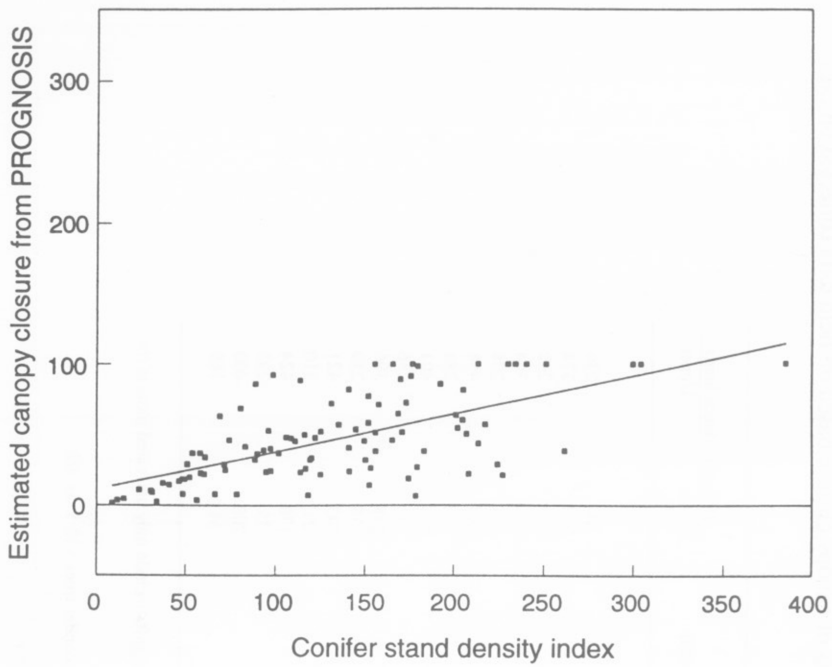

Fig. 2. Regression of conifer canopy closure estimated from PROGNOSIS equations and truncated to 100% on measured conifer stand density index, using only ponderosa pine plots ($r^2 = 0.40$, $P < 0.0001$), North Kaibab Ranger District, 1993.

relationship in our study. However the constant differed, such that lower SDI values yielded higher canopy closure estimates.

Discussion

General trends in canopy closure predictions by the PROGNOSIS model were supported by our results. However, we found an apparent upward bias in that PROGNOSIS yielded higher canopy closure estimates than we observed in the field. Data collected for any one stratum during this investigation were highly variable, indicating that factors other than SDI influence canopy closure. Uneven-aged stands increase the variability in the output from PROGNOSIS because it was designed for even-aged stands. Nevertheless, we believe that a relationship exists and that SDI can be used to manage for canopy closure if confidence interval bounds are used conservatively to predict canopy closure.

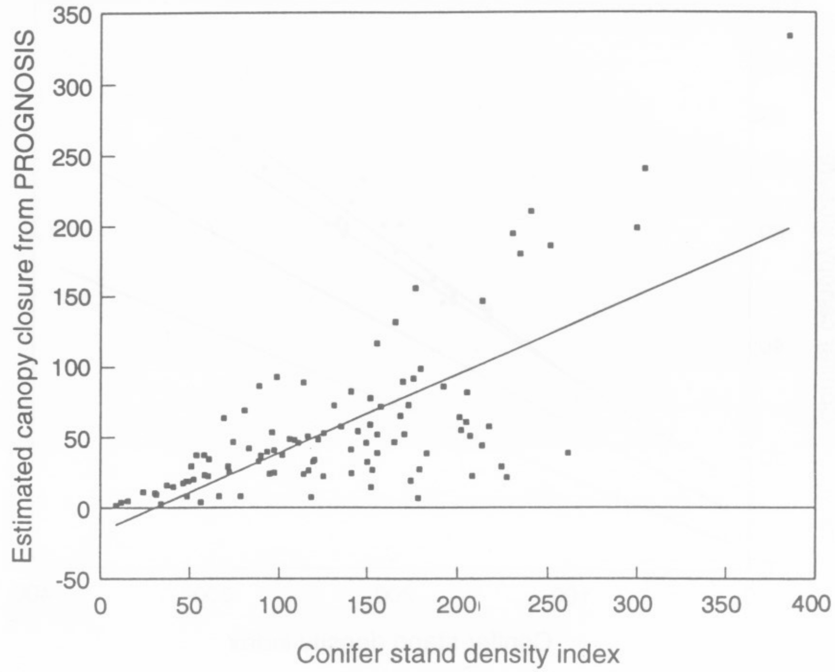

Fig. 3. Regression of conifer canopy closure estimated from PROGNOSIS equations (not truncated) on measured conifer stand density index, using only ponderosa pine plots ($r^2 = 0.51$, $P < 0.00001$), North Kaibab Ranger District, 1993.

A bias in PROGNOSIS predictions is understandable in consideration of the algorithms used to calculate canopy closure. Canopy width (and subsequently area) of a sample of individual trees is predicted, ultimately, from dbh and basal area. Basal area may be determined to represent an entire stand, and as such, applied to the computation of canopy width of each tree. We were unable to evaluate the effect of this averaging on canopy closure estimates.

Canopy closure is estimated by summing the predicted canopy area of each tree in the plot and dividing the sum by the plot area. This method cannot account for tree overlap without further site specific research and appropriate modification of coefficients. Thus, canopy closures may exceed 100%, and are by definition, biased at that point where trees begin to overlap, or canopy extends beyond the plot boundary. Additionally, we cannot evaluate the effect that aggregating tree characteristic data across plots may have on

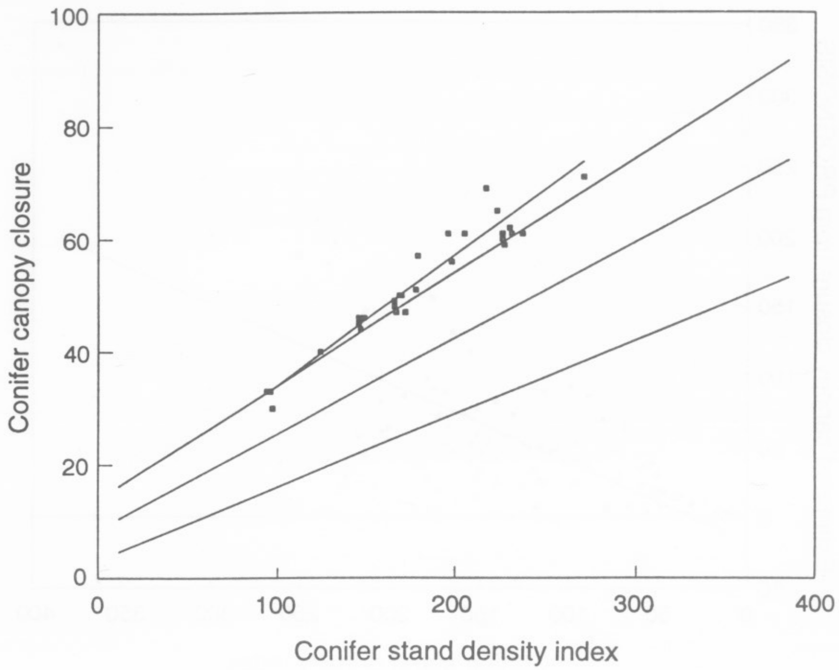

Fig. 4. Regression of conifer canopy closures, reported by Arizona Game and Fish Department (1993), estimated from PROGNOSIS equations on conifer stand density index values (short line with points) from our study area. The longer regression line and 95% confidence limits from Fig. 1 are presented for comparison.

canopy closure predictions. However, computation of one canopy closure statistic for a large stand may ignore a skewed frequency distribution of canopy areas, and as an arithmetic mean, may be biased upward by the presence of a few outliers.

A major assumption of the PROGNOSIS model is that the crown area of all trees are circular, and the total area of that circle provides cover. While the assumption may be appropriate for modeling tree growth and interaction patterns, it does not portray an accurate view of forest stand characteristics in nature. This assumption, by definition, overestimates canopy closure. Data from this study indicate that the PROGNOSIS model predictions lie at the upper edge of our observations, overestimating canopy closure for a given SDI.

Our data suggest that nearly all groups of trees sampled will meet the desired canopy closure of 40% if that stand is managed to the highest SDI in the confidence interval. Canopy closure predictions by PROGNOSIS, in its present form, should not be used to evaluate wildlife habitat. Such values will ensure that most tree groups will possess canopy closure values less than the standard described by Reynolds et al. (1992).

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Literature Cited

Arizona Game and Fish Department. 1993. Review of U.S. Forest Service strategy for managing northern goshawk habitat in the southwestern United States. Arizona Game and Fish Department, Phoenix. 198 pp.

Austin, K. 1991. Habitat use by breeding goshawks in the southern Cascades. Paper presented at annual meeting of the Raptor Research Foundation, Inc., Tulsa, Okla.

Brown, R. L. 1991. Effects of timber management practices on elk. Arizona Game and Fish Department Technical Report 10, Phoenix. 70 pp.

Hoffman, R. W., H. G. Shaw, M. A. Rumble, B. F. Wakeling, C. M. Mollohan, S. D. Schemnitz, R. Engel-Wilson, and D. A. Hengel. 1993. Management guidelines for Merriam's wild turkeys. Colorado Division of Wildlife Report 18, Fort Collins. 24 pp.

Hoover, R. L., and D. L. Willis. 1987. Managing forested lands for wildlife. Developed in cooperation with U.S. Forest Service, Rocky Mountain Region. Colorado Division of Wildlife.

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

Kennedy, P. L. 1989. The nesting ecology of Cooper's hawks and Northern goshawks in the Jemez Mountains, New Mexico: a summary of results, 1984–1988. Report to the U.S. Forest Service, Santa Fe National Forest. Purchase Order No. 43-8379-8-346. New Mexico.

LeCount, A. L., and J. C. Yarchin. 1990. Black bear habitat use in east-central Arizona. Arizona Game and Fish Department Technical Report 4, Phoenix. 42 pp.

Leopold, A. 1949. A sand county almanac. Oxford University Press, New York.

McTague, J. P., and D. R. Patton. 1989. Stand density index and its application in describing wildlife habitat. Wildlife Society Bulletin 17:58–62.

Moeur, M. 1981. Crown width and foliage weight of Northern Rocky Mountain conifers. U.S. Forest Service Research Paper INT-283. Intermountain Forest and Range Experiment Station, Ogden, Utah. 14 pp.

Moeur, M. 1985. COVER: a user's guide to the CANOPY and SHRUBS extension of the Stand Prognosis Model. General Technical Report INT-190. Intermountain Research Station, Ogden, Utah. 49 pp.

Mollohan, C. M., D. R. Patton, and B. F. Wakeling. 1995. Habitat selection and use by Merriam's turkeys in north-central Arizona. Arizona Game and Fish Department Technical Report 9, Phoenix. 48 pp.

Patton, D. R., and J. R. Vahle. 1986. Cache and nest characteristics of the red squirrel in an Arizona mixed-conifer forest. Western Journal of Applied Forestry 1:48–51.

Reineke, L. H. 1933. Perfecting a stand density index for even-aged forests. Journal of Agricultural Research 46:627–638.

Reynolds, R. T., R. T. Graham, M. H. Reiser, R. L. Bassett, P. L. Kennedy, D. A. Boyce, Jr., G. Goodwin, R. Smith, and E. L. Fisher. 1992. Management recommendations for the northern Goshawk in the Southwestern United States. U.S. Forest Service, Southwestern Region, Albuquerque, N. Mex. 185 pp.

Thomas, J. W., H. Black, Jr., R. H. Scherzinager, and R. J. Pederson. 1979. J. W. Thomas, editor. Wildlife habitats in managed forests the Blue Mountains of Oregon and Washington. U.S. Forest Service, Agriculture Handbook No. 553. 512 pp.

Wykoff, W. R., N. L. Crookston, and A. R. Stage. 1982. User's guide to the Stand Prognosis Model. U.S. Forest Service, General Technical Report INT-133. Intermountain Research Station, Ogden, Utah. 112 pp.