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Identifying Changes in Tree Form for Harvested Ponderosa Pine in the Black Hills

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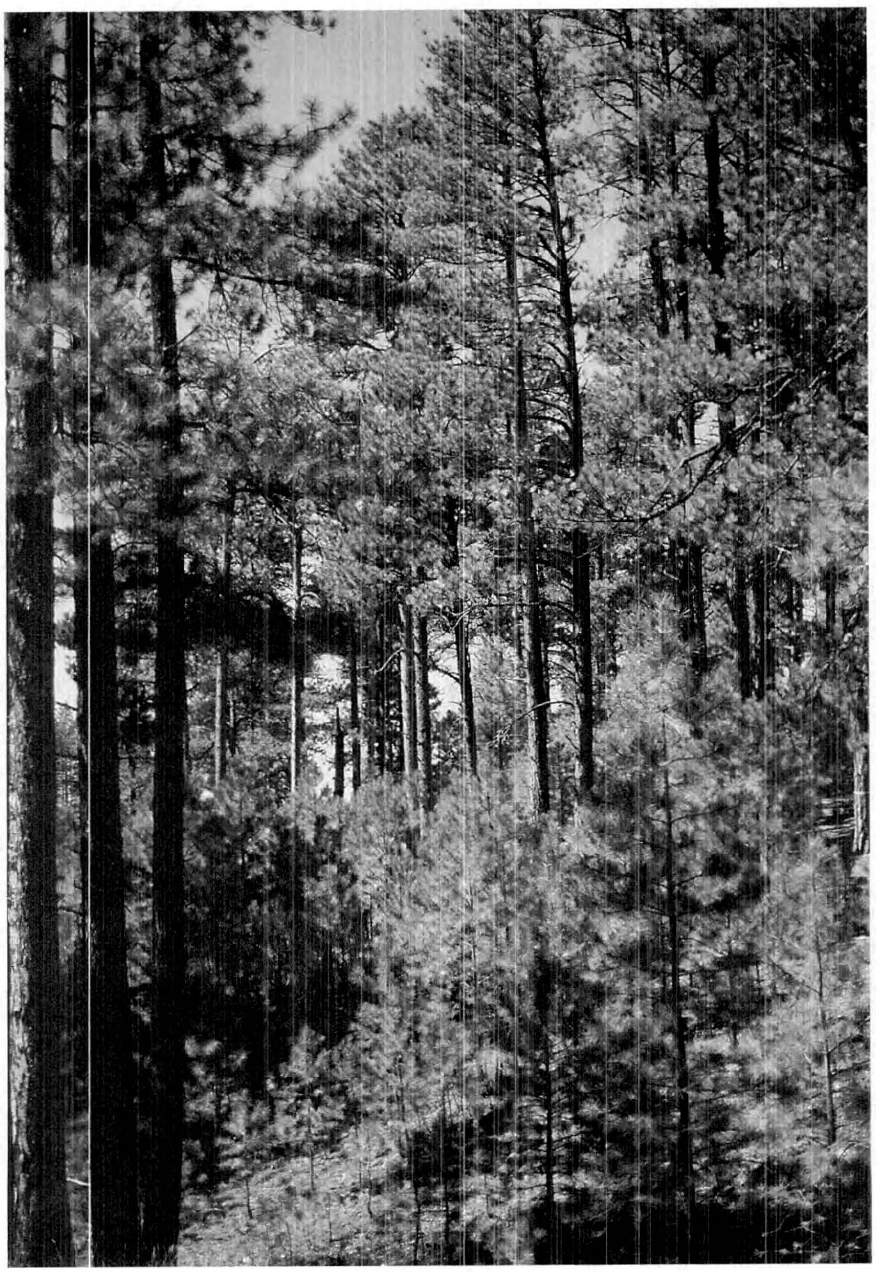

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Abstract: Recent underestimates of total volume for timber sales in the Black Hills National Forest prompted analysis of two felled ponderosa pine (Pinus ponderosa Laws.) data sets that were collected approximately 10 years apart. Though neither data set collected was a representative sample of the Black Hills, both were similar in terms of diameter at breast height and total height. We investigated several methods for assessing differences in tree form and applied them to these two data sets. Under the assumption that these two data sets were representative of harvested trees in the Black Hills (which may be incorrect), we concluded that the average tree form of harvested ponderosa pine has changed significantly in the last 10 years. This conclusion highlights the importance of using representative data in model building.

Keywords: representative data, differences in tree form, Black Hills, model building, harvested pondersoa pine

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INTRODUCTION

The Rocky Mountain Region of the USDA Forest Service, National Forest System, replaced standard tree volume equations with stem profile models in 1990 in response to changing utilization standards in the Region. The profile models were intended to estimate post-harvest woody residue and improve consistency in volume estimation across Forest Service timber management, resource inventories, and land management-planning activities. Using data collected between 1981 and 1987, the models were developed and verified by Czaplewski et al. (1989). Before implementation, they were independently validated by the USDA Forest Service, Washington Office Timber Management Staff, Mensuration and Systems Development Unit in Fort Collins. Estimates from the new profile models were compared to those from the old volume equations for the 1990 timber sales in the Region. There were no major discrepancies between the two methods when utilization standards were fixed to match the underlying assumptions of the old volume estimators. The validation period lasted one year.

In 1991, a detailed analysis of the No Dollar timber sale on the Medicine Bow National Forest demonstrated that the profile models of Czaplewski et al. (1989) substantially overestimated the true volume for sample trees from this one sale. This immediately raised suspicions that the profile models were the primary cause of other undercuts in the Region. Isolating the reason for undercuts is expensive and time-consuming. Many possible causes exist and no quantitative data were available to objectively determine the portion of known undercuts across the Region that were caused by volume over-predictions computed by the profile models. However, in 1991 the number of timber sales that undercut were significantly greater than half the number of timber sales that were prepared using the profile models. This problem has increased since implementation of the profile models and, although perhaps a coincidence, the possibility of inaccurate profile models or a change in average tree form must be addressed.

The only data available to produce profile models for the Rocky Mountain Region was collected from past timber sales in the Region during the early 1980s. Some possible causes for the under prediction follow.

1. If sale locations were not selected randomly, they may not be a representative sample of Region 2 forests, and the data sets may not be representative of the area's average tree form;

2. The average form of the trees harvested in recent years is different from the average form of trees harvested in the past. This could be due to differences in management practice, stand age, environmental changes, or a combination of many different factors; and

3. There is no valid historical information that documents the quality and reliability of the data collected in the 1980s. These data were collected solely to produce volume estimates for particular sales, not for producing profile models.

Differences in tree form could be related to poor data quality; however, this is probably unlikely. An analysis of the scatter plots did not show any consistent problems that would indicate outliers or data errors influencing the results.

During the 1992 field season, new sales data were collected in the Black Hills from several locations. All trees in this data set were ponderosa pine. As a comparison, the same model-fitting procedures used on the previous sale data were applied to the new sale data. The predicted diameter values from the new model for any given height on the tree agreed with the actual tree diameters. However, when the model generated from the old data was compared to the model generated from the new data, the predictions of diameter were consistently overestimated, which would cause an overestimation of volume predictions. Preliminary estimates of volume, performed by Rocky Mountain Region of the USDA Forest Service, showed differences of 8.65 and 8.69 percent for board-foot and cubic-foot volume respectively when the model generated from the old data set was used with the new data. The lack of representative data prevented straightforward statistical comparison of the two data sets to show that the average tree form of harvested trees has changed. This paper investigates similarities and differences in the two data sets:

1. To show that they are similar enough to compare assuming that the data are representative samples of harvested trees from the Black Hills National Forest at the two different time periods;

2. To document the difference in average tree form using profile models and other methods; and

3. To determine how the average tree form has changed between time periods and at what point along the stem do the differences occur.

DATA DESCRIPTION

The oldest of the two data sets consisted of 442 trees. The measurements were collected from various timber sales using variable radius cruise plots. These trees were felled and scaled to arrive at good defect percentages, and to fill out STX cruise cards (Grosenbaugh 1964). Trees were bucked into nominal 16-foot sections. Diameters were measured at a stump height of less than 1-ft breast height (4.5 ft), and at the ends of each section up to a 4 to 6-in diameter inside bark top. Diameters were measured using the average of two cross-sectional measurements to within 0.1 in. Trees with forked or broken tops were not included in the data.

The new data comprised measurements taken on 189 trees. In a half-day training session, timber sale administrators were instructed how to measure the trees and record the data. Diameters inside bark (DIB) were measured every 4 ft above the ground. Most trees had between 4 and 10 measurements taken to the top of the tree. Diameter outside bark was measured at breast height (4.5 ft) and the total height was taken from the tip to the 1-ft stump mark. All cruising was done from the 1-ft stump level to the tip of the tree, but no DIB measurements were taken at or below the 1-ft height, as was the case with the 1983 data. The trees were from a mixture of cruise plots on timber sales and opportunistic samples where logging was occurring. Because these data were collected for profile model generation and testing, great care was taken in the data collection process.

The one major difference between the two data sets is that the 1983 data contained diameter measurements at the base of the tree. The lowest diameter measurement in the 1992 data set was at 4 ft. Due to the variability at the tree base, the 1983 data was analyzed without the stump measurements.

METHODS

The objective was to compare the two data sets to check for obvious differences that could have contributed to discrepancies between the profile models. To do this, two questions were asked:

1. Is there any evidence that differences in tree form could be geographically related over the Black Hills;

2. Are the distributions of tree sizes similar in both data sets?

The first question was important because if the differences in tree form were geographically related, the lack of a simple random sample or systematic sample grid for selecting sample trees could explain difference in tree form between the two data sets. The second question was important because for most species average tree form has been shown to vary with tree size. For example, Forslund (1991) concluded that smaller aspen

(*Populus tremuloides* Michx.) trees have a paraboloid tree form and as the trees increase in size the neloidal component increases. Allen (1993) found that average relative stem profiles differed for three size classes of Caribbean pine (*Pinus caribaea* Morelet var. *hondurensis* Barrett & Golfari). If no significant geographical or size differences existed between the two data sets, the assumption that each of the data sets was a representative sample of trees in the Black Hills, even though the data were not collected in a manner that would justify this assumption, may be valid.

To answer the first question, a spatial analysis was performed to determine if geographical patterns in tree form existed. A test was performed using the geographical location of each timber sale in the 1983 data set, and the percent difference between the estimated tree form using the profile models and the actual tree volumes. The Moran's I statistic (Upton and Fingleton 1985; Cliff and Ord 1973, 1981) was used to test for nonrandom spatial patterns. No significant spatial pattern was found in the data.

To answer the second question, several descriptive statistics were compared for diameter outside bark at 4.5 ft (*DBH*) and total height *(H)*. The statistics compared for these three variables were the mean, standard error, skewness, kurtosis, and 10, 25, 50, 75, and 90 sample percentiles.

Table 1 contains the descriptive statistics. On average, the data collected in 1992 contains slightly smaller trees than the 1983 data set. A t-test for comparing the means of each descriptive statistic confirmed a significant difference in the mean for all three variables. Because the distribution of the tree sizes differed, a third data set was produced by removing trees from the 1983 data set. To match the size distributions, trees in the 1992 data set were divided into 2-in diameter classes. Trees were then deleted from the 1983 data set so that the same number of trees were in each diameter class. This data set will be referred to in the text as the 1983 trimmed data set and denoted as 1983^T in tables 1 through 6. In general, the descriptive statistics for the 1983 trimmed data were similar to those for the 1992 data set. A t-test for comparing the means for *DBH* and *H* found no significant difference. The skewness and kurtosis of the two data sets are where the largest differences occur. The distribution of data from the 1983 data set is close to being normal as indicated by the third and fourth population moments. The skewness and kurtosis for the 1992 data indicated a non-normal distribution with a consistently positive skew and high kurtosis. The trimmed 1983 data set more closely matches the descriptive statistics of the 1992 data set.

Two methods were used for tree form comparison. The first and simplest comparison was to determine if the relationship between diameter and tree height was different between the two data sets. This was done by computing the same descriptive statistics as those used earlier for the ratios of total height and 2 diameter measurements. The first diameter measurement used was *DBH*, and the second was *DIB* at 30 percent of total height (*DIB@30%*). Diameter at 30 percent of total height is important because it is the approximate center of mass for a tree. Descriptive statistics were computed for:

$$\frac{H}{DBH} \text{ and } \frac{H}{DIB@30\%}.$$

Table 2 contains these results. The results indicated no difference in the relationship between *DBH* and *H* in the two data sets. The descriptive

Table 1. Comparison of descriptive statistics for *DBH* (inches) and *H* (feet).

Data set	Variable	Mean	Std.dev.	Skew.	Kurt.	10%	25%	50%	75%	90%
1983	*DBH*	13.35	3.88	0.31	2.88	8.1	10.8	13.0	16.0	18.1
1983^T	*DBH*	12.75	3.77	1.30	4.57	9.0	10.0	11.8	14.5	17.4
1992	*DBH*	12.38	3.31	1.38	4.99	8.9	10.1	11.5	14.0	16.5
1983	*H*	61.56	14.44	-.05	2.81	42.3	52.0	62.9	70.7	79.4
1983^T	*H*	59.06	14.08	0.14	2.70	40.9	48.5	60.0	68.0	84.5
1992	*H*	58.15	13.53	2.55	15.59	44.0	50.0	56.0	63.0	73.0

^{T} *Trimmed data set*

statistics showed that all three data sets were nearly normally distributed with approximately the same mean and variance and nearly identical percentile information. The relationship between H and $DIB@30\%$ showed similar results, but the agreement was not quite as high between the 1992 and the untrimmed 1983 data sets. The largest differences occurred in the measure of kurtosis. However, nothing indicated that the relationship between total height and the 2 diameter measurements were different; therefore, differences in average tree form were probably due to a subtle difference in the taper of the trees.

The second method used to compare tree form considered the ratio of tree diameter to relative tree height, where relative diameter was defined as DIB at a given height *(H)* divided by *DBH*, i.e.,

$$\text{Relative Diameter} = \frac{DIB(h)}{DBH}.$$

The relative height was defined as the height above the ground *(h)* divided by total height *(H)*, i.e.,

$$\text{Relative Height} = \frac{h}{H}.$$

Dividing the DIB and h measurements by DBH and H transformed the diameter and height measurements to the interval [0,1], which allows the form of differently sized trees to be compared.

For evaluating the difference between average tree form, relative diameter and height were used with the profile model derived by Max and Burkhart (1976). The model was fitted for all three data sets, and was chosen over others because personal experience and detailed analyses have shown that it is one of the most flexible available as substantiated by the Alberta Forest Service (1987), Amidon (1984), Gordon (1983), Martin (1981) and Cao et al. (1980). Form of the model is:

$$\frac{DIB(h)^2}{DBH^2} = b_1(\frac{h}{H} - 1) + b_2(\frac{h^2}{H^2} - 1) + b_3(a_1 - \frac{h}{H})^2 I_1 + b_4(a_2 - \frac{h}{H})^2 I_2$$

where:

$DIB(h)$= upper stem diameter inside bark at height h

DBH = diameter at breast height outside bark

h = height at the upper stem diameter predictions

H = total tree height

b_i = model parameter

a_j = model join points;upper = 1, lower = 2

I_j = 1, if $h/H < a_i$; 0, otherwise.

We fit the model using an iterative nonlinear solution technique. The steps used were:

1. Choose initial a_1 and a_2 parameters and set I_1 and I_2.

Table 2. Comparison of descriptive statistics for the ratio of total height and diameter at breast height (*H / DBH*) and total height with diameter inside bark at 30% of total height (*H / DIB@30%*) .

Data set	Variable	Mean	Std.dev.	Skew.	Kurt.	10%	25%	50%	75%	90%
1983	$\frac{H}{DBH}$	4.78	1.00	0.58	3.66	3.6	4.1	4.7	5.4	6.0
1983[T]	$\frac{H}{DBH}$	4.79	1.05	0.34	3.08	3.4	4.0	4.8	5.4	6.1
1992	$\frac{H}{DBH}$	4.82	0.89	0.28	2.96	3.6	4.2	4.7	5.4	6.0
1983	$\frac{H}{DIB@30\%}$	5.99	1.28	0.86	4.75	4.5	5.2	5.8	6.7	7.6
1983[T]	$\frac{H}{DIB@30\%}$	5.96	1.44	0.75	4.38	4.2	5.0	5.8	6.8	7.7
1992	$\frac{H}{DIB@30\%}$	6.22	1.19	0.21	2.62	4.7	5.3	6.1	7.1	7.8

[T] *Trimmed data set*

2. Use a nonlinear least squares routine to estimate a_1, a_2 and $b_1 ... b_4$.

3. Update the I_1 and I_2 values using the new a_1 and a_2 estimates.

4. Repeat steps 2 and 3 until all parameters stabilize.

Final results appeared to be independent of the starting values selected.

Table 3 lists the model coefficients, R^2, and root mean square error (RMSE) values for both data sets. While the coefficients for the 1983 data vary somewhat from those given by Czaplewski et al. (1989), because of the removal of stump measurements, the predicted *DIB(h)* values are essentially identical as are R^2 and RMSE. The high R^2 values indicate a good fit of the model to the data.

Once the models were fit to the data, the predicted $DIB(h)^2$ estimates were generated using the models derived from both data sets. These predicted $DIB(h)^2$ values were compared using the 1983 data set. For the comparison, a simple linear regression model was used to test for a one-to-one correspondence between the predicted $DIB(h)^2$ values. The following models were fit to the data:

$$\hat{DIB}(h)^2_{1992} = \beta \hat{DIB}(h)^2_{1983}$$

and

$$\hat{DIB}(h)^2_{1992} = \beta \hat{DIB}(h)^2_{1983^T}$$

where

$\hat{DIB}(h)^2_{1992}$, $\hat{DIB}(h)^2_{1983}$, and $\hat{DIB}(h)^2_{1983^T}$

were the predicted squared *DIB* values generated by the Max-Burkhart models from the 1992, 1983, and 1983 trimmed data sets. The hypothesis tested was H_0: $\beta = 1$ with alternative H_1: $\beta \neq 1$.

The results in table 4 show that the predictions of $DIB(h)^2$ using the models from the 1983 data sets were substantially larger than those predicted using the 1992 model. When the models were compared, a consistent 6.0 to 8.0 percent difference in predicted $DIB(h)^2$ was found with the largest difference in prediction occurring using the 1983^T model against the 1992 model. Visual and statistical comparisons indicated no significant nonlinear trends in the comparison of predicted $DIB(h)^2$.

To verify that the difference in these models was significant, an accuracy test based on bias and precision was used (Reynolds 1984). Mean error

Table 3. Regression statistics and model coefficients for the Max-Burkhart stem profile model used for estimating inside bark diameters.

Data set	RMSE[1]	R^2	a_1	a_2	b_1	b_2	b_3	b_4
1983	0.084	0.977	0.559	0.163	-1.362	0.266	-0.855	6.500
1983^T	0.088	0.976	0.814	0.081	-3.406	1.401	-1.660	58.16
1992	0.060	0.988	0.700	0.182	-2.493	1.010	-1.334	3.08

[1] *Root mean square error*

^{T} *Trimmed data set*

Table 4. Regression coefficients for the test of one-to-one correspondence between the stem profile models used for estimating inside bark diameters.

Model	β	Std. err.	R^2
1983^T	0.9213	0.00090	0.9990
1983	0.9396	0.00066	0.9982

^{T} *Trimmed data set*

Table 5. Percent mean error and confidence intervals for accuracy test between the stem profile models used for estimating inside bark diameters.

Model	Mean error	C.I.
1983	7.388	(6.659, 8.117)
1983^T	9.056	(8.302, 9.811)

^{T} *Trimmed data set*

was used to measure bias. Confidence intervals were generated about the mean error. The bias was considered significant if the confidence interval did not contain zero. The confidence intervals were generated using:

$$\bar{e} \pm \frac{S\, t_{1-\frac{\alpha}{2},n-1}}{\sqrt{n}}$$

where:

$$\bar{e} = \sum_{i=1}^{n} \frac{\hat{DIB}(h)^2 - DIB(h)^2}{n}$$

$$S = \sqrt{\sum_{i=1}^{n} \frac{(e_i - \bar{e})^2}{n-1}}$$

$t_{1-\frac{\alpha}{2},n-1}$ = student's t distribution at $1-\alpha/2$, with $n-1$ degrees of freedom

n = number of observations.

This test requires a homogeneous error structure. A visual test of the error structure did not indicate any nonhomogeneous data trends.

The 1992 data set was used for true $DIB(h)^2$ values and $\hat{DIB}(h)^2$ were generated using the 1983^T and 1983 models. The results in table 5 indicate a significant difference in average tree form for the two data sets.

The average *DBH* for the 1992 data set was 12.38 in and the average height was 58.15 ft. These values were used to generate the form of the average tree according to the three profile equations. Table 6 gives the estimated *DIB*

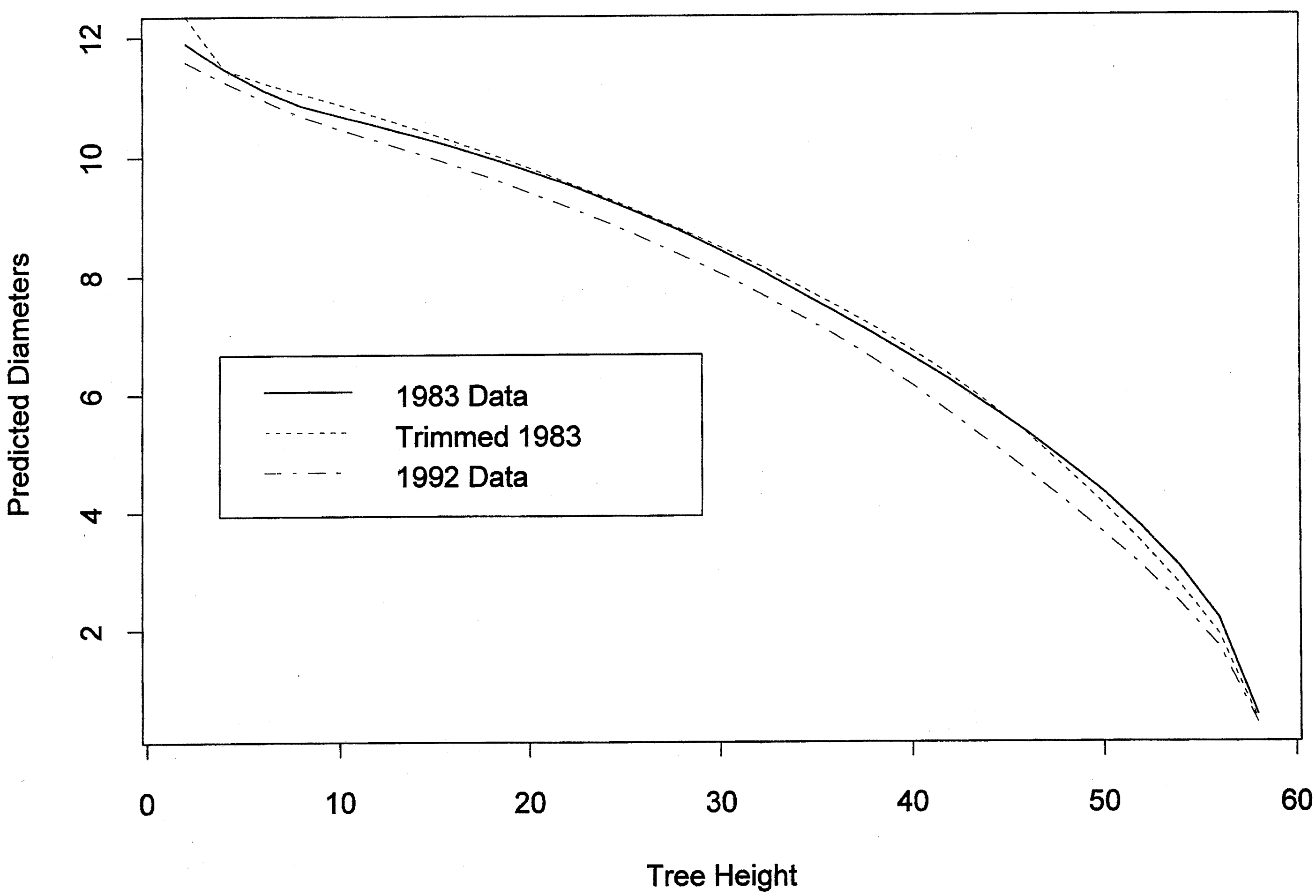

Figure 1. Estimated diameters for the three data sets.

using the 1983, 1983^T, and 1992 models and the ratios:

$$\frac{\hat{DIB}(h)_{1983}}{\hat{DIB}(h)_{1992}} \text{ and}$$

$$\frac{\hat{DIB}(h)_{1983^T}}{\hat{DIB}(h)_{1992}}.$$

Two-ft height increments were used. These results are depicted graphically in figure 1. The results in table 6 indicate that the trees in the 1983 data set had consistently larger *DIB* values than the 1992 trees. The difference ranged from 3 percent (near the base of the tree) to 75 percent at the top of the tree. Because the 1992 model never produced a *DIB* value greater than either of the 1983 models, bark thickness at breast height would have to be greater for the 1992 data than for the 1983 data.

CONCLUSIONS

This study showed that for the two data sets a significant difference in tree form exists. The data available for this study were not collected in a manner that would allow conclusive determination of what caused the difference in tree form. A single factor or a combination of factors such as prolonged drought, stand management practices, pollution, change in average tree size and age, differences in site quality, or any other less obvious factors could be involved. The discrepancies between the two data sets illustrates the need for data to be collected using some form of representative sampling. Without such data, a number of the primary goals of forest management can not be achieved such as accurately estimating total forest volume and monitoring for changes in tree form over time.

Table 6. Comparison of predicted *DIB* in two-foot intervals for a 58.15-ft tree with a *DBH* = 12.38 inches inside bark diameter.

Height	$\hat{DIB}(h)_{1983}$	$\hat{DIB}(h)_{1983^T}$	$\hat{DIB}(h)_{1992}$	$\frac{\hat{DIB}(h)_{1983}}{\hat{DIB}(h)_{1992}}$	$\frac{\hat{DIB}(h)_{1983^T}}{\hat{DIB}(h)_{1992}}$
2.0	11.89	12.36	11.58	1.05	1.14
4.0	11.46	11.46	11.24	1.04	1.04
6.0	11.11	11.23	10.94	1.03	1.05
8.0	10.84	11.05	10.67	1.03	1.07
10.0	10.67	10.86	10.45	1.04	1.08
12.0	10.51	10.66	10.26	1.05	1.08
14.0	10.34	10.46	10.06	1.06	1.08
16.0	10.16	10.25	9.85	1.06	1.08
18.0	9.96	10.03	9.63	1.07	1.08
20.0	9.75	9.80	9.39	1.08	1.09
22.0	.52	9.55	9.15	1.08	1.09
24.0	9.27	9.30	8.89	1.09	1.09
26.0	9.01	9.04	8.62	1.09	1.10
28.0	8.73	8.76	8.33	1.10	1.11
30.0	8.42	8.47	8.03	1.10	1.11
32.0	8.09	8.16	7.70	1.10	1.12
34.0	7.74	7.83	7.35	1.11	1.13
36.0	7.38	7.49	6.98	1.12	1.15
38.0	7.00	7.12	6.58	1.13	1.17
40.0	6.61	6.72	6.14	1.16	1.20
42.0	6.21	6.29	5.66	1.20	1.23
44.0	5.78	5.82	5.18	1.25	1.27
46.0	5.33	5.31	4.68	1.30	1.29
48.0	4.84	4.73	4.17	1.35	1.29
50.0	4.32	4.11	3.63	1.41	1.28
52.0	3.73	3.46	3.07	1.48	1.27
54.0	3.05	2.75	2.44	1.56	1.27
56.0	2.18	1.91	1.70	1.65	1.26
58.0	.57	.48	.43	1.75	1.25

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