Variation in forest inventory field measurements

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Field crews from the North Central Forest Experiment Station independently measured two forest inventory plots in Michigan's Upper Peninsula; one plot was measured by eight crews and the other was measured by nine different crews. For 61 trees, the variation in measurements of diameter at breast height (DBH), crown ratio, and site index is described. For DBH, the distribution of field crew mistakes and the distribution of measurements without mistakes are described separately. For crown ratio, the distribution of differences between individual estimates and the most frequently occurring estimate for corresponding trees is described. For site index, the distribution of differences between individual estimates and the mean of plot estimates is described. Coefficients of variation were less than 5% for DBH, approximately 73% for crown ratio, and 13% and 16% for site index for the two plots. The effects of variation in measurements on 20-year predictions of basal area and cumulative basal area growth were estimated for the two plots using STEMS, TWIGS, and Monte Carlo simulations. Coefficients of variation were 2% and 3% for basal area and 7% and 9% for cumulative basal area growth for the two plots. Variation in site index estimates had the greatest effect on variation in the output variables.

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Respectivement, huit et neuf équipes d'inventaire du North Central Forest Experiment Station ont mesuré indépendamment deux placettes dans la Péninsule Supérieure du Michigan. Les variations des mesures du diamètre à hauteur de poitrine, de la longueur du houppier et de l'indice de fertilité sont estimées sur 61 arbres. Pour le diamètre, les fautes commises par les équipes d'inventaire sont séparées de la distribution des mesures. Pour la longueur du houppier, on analyse la distribution des écarts entre les estimations individuelles et l'estimation la plus fréquemment observée. Pour l'indice de fertilité, on analyse la distribution des différences entre les estimations individuelles et la moyenne de la placette. Les coefficients de variation sont inférieurs à 5% pour le diamètre, 73% pour la longueur du houppier et respectivement 13 et 16% pour l'indice de fertilité des deux placettes. Les impacts des erreurs des mesures sur celles de la surface terrière et de son accroissement sont évalués à l'aide des logiciels de croissance STEMS et TWIGS et à l'aide de la simulation Monte Carlo sur un horizon de 20 ans. Pour les deux placettes, la surface terrière présente les coefficients de variation respectifs de 2 et 3%, son accroissement 7 et 9%. L'erreur de mesure de l'indice de fertilité excerce la plus grande influence sur l'erreur de prédiction par les logiciels de croissance.

[Traduit par la rédaction]

Introduction

Variation in forest inventory field measurements is due to measurement variation and field crew mistakes. Measurement variation can be further attributed to sampling variation, natural variation, variation in the use of instruments, and judgement variation. Sampling variation arises when a variable is estimated from a sample rather than from a complete inventory. Basal area (BA) per acre (1 acre = 0.405 ha) and site index are examples of variables subject to sampling variation. Natural variation is due to differences in the same variable among subjects that are considered similar with respect to other factors. Variation in diameter at breast height (DBH) of trees of the same species in an even-aged, unmanaged stand with uniform site characteristics is an example of natural variation. Variation in the use of instruments might occur when placing a diameter tape, while judgement variation might occur when visually estimating the crown ratio of a tree. Mistakes may be difficult to distinguish from measurements that exhibit instrument and judgement variation. However, mistakes are of greater magnitude, can frequently be attributed to errors in identifying a subject or using an instrument, and appear as outliers in the original data.

The magnitude of variation in field measurements and its effect on the precision of forest inventory estimates have not been extensively studied or documented. Myers (1961) reported that while 93% of DBH measurements by 49 forestry students on 50 ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) trees were within 0.1 in. (1 in. = 2.54 cm) of the mode, the measurements of only three students were within 0.1 in. of the mode on every tree. Omule (1980) found no significant bias in DBH measurements but a significant bias in height estimates. Nicholas et al. (1991) reported a 38% similar reclassification of dominant trees and an 81% similar reclassification of codominat trees for a second sampling visit during the same field season. Paivinen et al. (1992) found considerable variation in DBH, upper stem diameter, bole height, and height increment measurements by experienced field crew leaders at the Finnish Forest Research Institute.

Gertner and Dzialowy (1984) simulated variation in measurements of input variables to the STEMS (Belcher et al. 1982) diameter growth prediction system and examined the effects on output variables. When percent standard deviations of measurement errors exceeded 15%, bias in BA predictions became significant, and when percent standard deviation of site index increased from 0 to 30%, the standard deviation of BA predictions increased by a factor of nearly three.

In response to the increasing emphasis being placed on quality assurance and quality control in natural resources research, we initiated a study to assess the magnitude and

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effects of variation in field measurements by inventory crews of the North Central Forest Experiment Station.

Methods

Two field crew supervisors each selected a sawtimber stand for measurement. The stands were located in the Upper Peninsula of Michigan and contained similar mixes of size classes and species, of which sugar maple (*Acer saccharum* Marsh.) was dominant. Both stands were primarily even aged, although there was substantial stocking in seedlings and small trees in some places owing to earlier selection cutting. Basal area for both plots was approximately 21 m^2/ha. A 10-point cluster plot was established for each stand in accordance with procedures specified in the *North Central Forest Inventory Analysis Field Manual* (North Central Forest Experiment Station 1991). Hereafter, the two plots are identified as L'Anse and Manistique, based on the headquarters of the field crews at the time of the inventory. The 10 subplots of the L'Anse plot were each independently measured by eight field crews, while the 10 subplots of the Manistique plot were each independently measured by nine different field crews. Subplot centers were established by the crews making the initial measurements at the subplots. Because all measurements were to be independent, no marks were made on any trees. Crews were assured of anonymity to encourage them to measure these plots as they would under usual field situations. A total of 61 trees were measured for DBH and crown ratio.

Measurements

The variables of interest were DBH, crown ratio, and site index. For each tree, DBH was measured with a diameter tape graduated to 0.1 in. and was recorded to the last 0.1 in. Crown ratio was visually estimated as the ratio of the living crown to the height of the tree to the nearest 0.1. To estimate site index, each inventory crew independently selected two or more dominant or codominant trees within the plot cluster that had not been measured on one of the subplots. Heights were measured using a clinometer and recorded to the nearest foot (1 ft = 0.305 m). Ages were estimated by counts of the rings on increment cores, adjusted for the heights at which the cores were taken, and recorded to the nearest year. The crews used these estimates of height and age to estimate site index to the nearest foot with fitted height–age curves (Carmean et al. 1989).

Analyses

The analyses focused on describing the variation in measurements and estimating their effects on predictions of BA and cumulative BA growth (CBAG). Common statistical measures of location and variation were used: mean, mode, variance, standard deviation, and coefficient of variation.

For DBH, mistakes characterized as outliers in the data were identified, their incidence was estimated, and their distribution was described. For measurements that were without mistakes, means and standard deviations for individual trees were calculated and their relationship was modeled. For crown ratio, the mode and mean were determined for each tree, and the distribution of differences between individual estimates and corresponding tree modes was determined. For site index, the distribution of differences between individual estimates and the corresponding plot means was determined.

Crews from the North Central Forest Experiment Station currently measure plots at approximately 10-year intervals. For intervening years, the status of plots and trees is predicted using TWIGS (Miner et al. 1988), a derivative of STEMS. STEMS is an individual-tree, distance-independent, model-based system of computer programs that predicts the growth of individual trees in stands (Belcher et al. 1982). A new inventory system has been proposed in which the interval between plot measurements may vary between 1 and 20 years. The effects of variation in measurements on plot and tree predictions using individual-tree prediction systems are unknown.

Simulations

Simulations were used to assess the effect of variation in measurements on 20-year predictions for the L'Anse and Manistique plots using TWIGS. At the beginning of each simulation, values for site index for each plot and values for DBH and crown ratio for each tree were selected. Site index was calculated by selecting a random number to simulate variation and then adding it to the mean of field crew estimates for the plot. The random number was selected from a normal distribution with mean zero and the same standard deviation as that calculated from field crew measurements.

Initial DBH was calculated by adding random numbers to simulate measurement variation and mistakes to the mean of field crew measurements for each tree. The random number representing measurement variation was selected from a normal distribution with mean zero and standard deviation predicted from the modeled relationship between individual tree means and standard deviations. A second random number was selected from a uniform distribution to determine if a simulated mistake should be included. The proportion of trees for which simulated mistakes were included was the same as the proportion of mistakes identified among field crew measurements. The magnitude of a mistake was determined by randomly selecting a number from a distribution that described the identified mistakes. Initial tree DBH was calculated as the sum of the mean of tree measurements without mistakes, the random number representing measurement variation, and the random number representing the magnitude of a mistake if it was to be included.

For crown ratio, one crew from among the 17 was randomly selected and used for the entire simulation. For each tree, initial crown ratio was calculated as the sum of the mode of estimated crown ratios for that tree and a random number selected from the distribution of differences between estimates and tree modes for the selected crew.

Annual predictions of DBH growth for each tree were calculated using TWIGS. For the 1st year, the predictions were based on the simulated initial conditions; for subsequent years, the predictions were based on conditions that had been updated using the previous year's predictions. No provisions were made for variation in the use of the prism to determine plot trees or for mortality or ingrowth over the 20-year period. The sequence of establishing initial plot and tree conditions and calculating annual predictions for 20 years was repeated 500 times for each plot. For each year, means and standard deviations for BA and CBAG were calculated over the 500 Monte Carlo realizations.

Although the effects due to mistakes in measuring DBH and biases in estimating crown ratio can be greatly reduced or eliminated, the effects due to sampling variation, natural variation among subjects, and variation due to instrument use and judgement probably cannot be greatly reduced or eliminated. The effects of these remaining components of measurement variation were estimated with 500 simulations as previously described, except that simulated mistakes in DBH measurements and biases in crown ratio estimates were excluded. The probability of a DBH measurement mistake was set to zero, and a single distribution for the differences between estimated crown ratios and tree modes was used. The latter distribution was symmetric with probabilities of 5% each for differences of −0.2 and 0.2, 15% each for differences of −0.1 and 0.1, and 60% for 0.0 differences.

The separate effects of variation in measurements of DBH, crown ratio, and site index on 20-year predictions of BA and CBAG were estimated with an additional 500 simulations. In each of these three related analyses, variation (but no mistakes or biases) was included for a single variable, while the variation for the other two variables was set to zero.

Results

DBH

Measurements of DBH were typically within 0.75 cm of each other, while mistakes differed from the remaining mea-

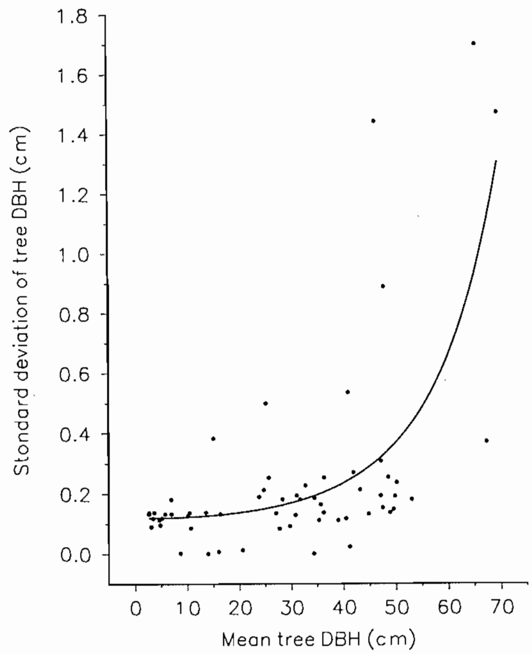

FIG. 1. Standard deviations versus means of tree DBH measurements without mistakes. The solid line represents the fitted model, $E(\hat{\sigma}) = 0.1182 \exp(0.000\ 156\ \hat{\mu}^{2.2728})$, where $E(\hat{\sigma})$ is the expectation of the calculated standard deviation based on the model and $\hat{\mu}$ is the estimated mean.

surements by at least 1.25 cm. The incidence of mistakes was 1.78%, and the magnitudes ranged from 1.78 to 38.86 cm. Because larger mistakes were associated with larger trees, the ratio of the magnitude of each mistake to the mean of the remaining measurements for each tree was calculated. The distribution of the ratios was approximately uniform with a range of −0.8 to 1.25.

For each tree, the sample mean ($\hat{\mu}$) and standard deviation ($\hat{\sigma}$) of individual DBH measurements without mistakes were calculated. The distribution of differences between individual measurements and tree means was approximately symmetric with 60% of measurements within 0.13 cm of the mean and 90% within 0.38 cm of the mean. Although distributions of differences for some field crews were asymmetrical, none was biased by more than 0.25 cm. The differences for each tree were standardized by dividing them by the corresponding sample standard deviations. The distribution of standardized differences was approximately symmetric around 0 with slightly thinner tails than would be expected for a normal distribution. The relationship between the standard deviations and means for individual trees was modeled as

[1] $E(\sigma) = 0.1182 \exp(0.000\ 156\ \hat{\mu}^{2.2728})$

where $E(\sigma)$ is the expectation of the standard deviation (Fig. 1). The model was fit using weighted least squares regression and accounted for 46% of the variation (R^2 = 0.46). Based on [1], expected coefficients of variation were less than 5% over the range of mean DBH values. Standard deviations for DBH measurements were predicted using [1] when determining initial tree conditions for the simulations.

Crown ratio

Differences between individual crown ratio estimates and corresponding tree modes were combined into a single distribution which was close to symmetrical with 87% of estimates within 0.1 of the mode. The estimates ranged from −0.3 to 0.3. For some field crews, the distributions of differences were asymmetrical; and for some, distribution means were shifted from 0 by as much as 0.13. The coefficient of variation of differences between individual crown ratio estimates and tree means was 73%. There was no relationship between tree standard deviations for crown ratio and tree DBH means or tree crown ratio means. Differences between individual estimates of crown ratio and corresponding tree modes were not significantly (α = 0.05) correlated with differences between individual measurements of DBH and corresponding means of tree DBH.

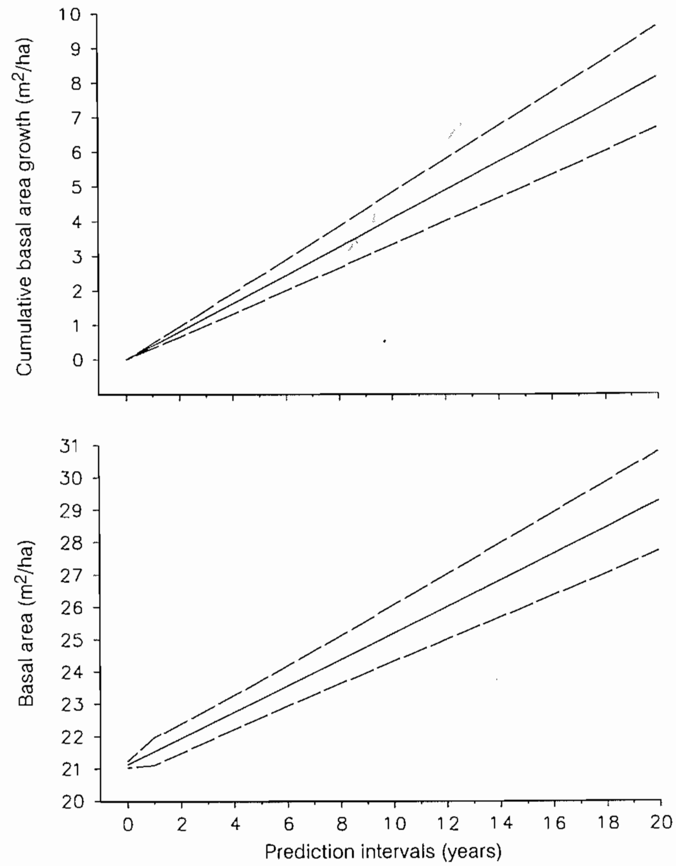

FIG. 2. Simulation mean (solid line) and 95% confidence interval (broken lines) for basal area and cumulative basal area growth for the Manistique plot.

Site index

Sources of variation for site index estimates are difficult to identify because uncertainty enters at several levels: (*i*) selection of site trees, (*ii*) species of site trees selected, (*iii*) estimation of site tree heights and ages, and (*iv*) accuracy of the fitted height–age curves. Because we were unable to determine if more than one field crew selected the same site trees, we were unable to estimate the variation of height and age measurements or to separate their effects from those of the fitted height–age curves. We assumed that site index estimates were independent and did not try to account for any correlation due to the possible selection of the same site trees by more than one field crew.

For the 16 site trees selected for the L'Anse plot, site index estimates ranged from 14.03 to 23.15 m with a mean of 17.34 m and a coefficient of variation of 16%. For the 18 site trees selected for the Manistique plot, the estimates ranged

TABLE 1. Simulation results for basal area

Plot and year	With mistakes		Without mistakes	
	Mean (m^2/ha)	CV[a]	Mean (m^2/ha)	CV
L'Anse				
0	21.27	0.01	21.27	<0.01
5	23.41	0.01	23.44	<0.01
10	25.65	0.01	25.69	0.01
15	27.96	0.02	28.04	0.01
20	30.34	0.02	30.44	0.02
Manistique				
0	21.14	0.01	21.18	<0.01
5	23.16	0.01	23.24	0.01
10	25.19	0.02	25.32	0.01
15	27.23	0.02	27.39	0.02
20	29.26	0.03	29.45	0.02

[a]CV, coefficient of variation.

TABLE 2. Simulation results for cumulative basal area growth

Plot and year	With mistakes		Without mistakes	
	Mean (m^2/ha)	CV[a]	Mean (m^2/ha)	CV
L'Anse				
0	2.14	0.07	2.16	0.05
10	4.38	0.07	4.42	0.05
15	6.69	0.07	6:76	0.05
20	9.07	0.07	9.17	0.05
Manistique				
0	2.02	0.09	2.06	0.08
10	4.06	0.09	4.13	0.08
15	6.09	0.09	6.21	0.08
20	8.12	0.09	8.27	0.08

[a]CV, coefficient of variation.

from 15.22 to 23.27 m with a mean of 17.50 m and a coefficient of variation of 13%. Neither the Kolmogorov– Smirnov test (Conover 1971) nor the Anderson–Darling test (Stephens 1982) indicated that the distribution of differences between individual site index estimates and plot means significantly (α = 0.05) departed from normality. For the two plots the standard deviation of the differences was 2.80 m.

Simulations

Standard deviations and widths of the 95% confidence intervals increased with each succeeding year for both BA and CBAG (Fig. 2). Coefficients of variation for BA increased from approximately 1% for both plots to approximately 2% for L'Anse plot and 3% for the Manistique plot over the 20-year prediction interval (Tables 1 and 2). Coefficients of variation for CBAG remained at approximately 7% for the L'Anse plot and 9% for the Manistique plot over the same prediction interval.

When mistakes in measurements of DBH and biases in measurements of crown ratio were excluded from the simulations, coefficients of variation for both BA and CBAG were slightly smaller (Table 1). Nearly all the variation in the 20-year predictions for these simulations could be attributed to measurement variation for site index, confirming an earlier finding by Gertner and Dzialowy (1984). For the L'Anse plot, the separate coefficients of variation were 5% for site index, 2% for crown ratio, and less than 1% for DBH; for the Manistique plot, they were 7% for site index, 2% for crown ratio, and less than 1% for DBH. The sum of these separate coefficients of variation is slightly greater than the coefficient of variation when variation is included for the variables simultaneously. We attribute this to cancellation of some effects due to nonlinearity in the models and to correlation among effects when variation is included for all variables simulataneously.

Discussion and conclusions

Although the incidence of field crew mistakes is small, the magnitudes may be large. For DBH, which was measured with a diameter tape, there was little latitude for individual judgement, and variation among measurements without mistakes was small. For crown ratio, which required considerable judgement, measurement variation was much larger. Some crews exhibited measurement bias for both DBH and crown ratio. While measurement variation for site index contributed the most to output variation, we were unable to separately quantify the effects of its individual sources of variation. Additional research into the relative effects of individual sources of variation for site index is warranted.

The simulations showed that the effects of variation in inventory measurements should not be ignored. Mowrer and Frayer (1986) cited a general rule that coefficients of variation should not exceed 20%. while Gertner (1994) cites guidelines requiring that 95% confidence intervals be within ±20% of the mean. For sources of variation related only to variation in measurements, the 20-year predictions for BA satisfy these requirements. However, 95% confidence intervals for CBAG were ±14% and ±18% of the mean and only marginally satisfy the latter requirement.

The total variation of predictions includes not only effects due to variation in measurements, but also effects due to residual variation around estimated diameter growth, crown ratio, and site index curves, and to variation in parameter estimates for those curves. The combined effects of these sources of variation are likely to produce variance estimates that fail to satisfy either of the above requirements and may completely mask the significance of predictions. Simply eliminating measurement mistakes and biases will not appreciably improve this situation.

Uncertainty in the initial plot and tree conditions due to variation in measurements propagates through the models over time. If there had been no variation in initial values of site index, DBH, and crown ratio, there would have been no variation in BA and CBAG for this study. An effect of variation in measurements is that as time from the initial measurements increases, uncertainty increases and confidence decreases in predictions based on those measurements. These effects are studied under the general topic of propagation of variance (Mowrer 1991; Mowrer and Frayer 1986; Gertner 1989; Gertner and Dzialowy 1984) and deserve greater attention by model developers and users at all levels.

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