Sampling Strategies for Efficient Estimation of Tree Foliage Biomass

Hailemariam Temesgen, Vicente Monleon, Aaron Weiskittel, and Duncan Wilson

Abstract: Conifer crowns can be highly variable both within and between trees, particularly with respect to foliage biomass and leaf area. A variety of sampling schemes have been used to estimate biomass and leaf area at the individual tree and stand scales. Rarely has the effectiveness of these sampling schemes been compared across stands or even across species. In addition, sample size estimates for achieving a certain level of precision have rarely been given. This simulation study used extensive branch and tree foliage biomass data sets for Douglas-fir (*Pseudotsuga menziesii* var. menziesii [Mirb.] Franco) and ponderosa pine (*Pinus ponderosa* Dougl ex. Laws.) to compare alternative sampling schemes and sample sizes. The use of auxiliary information at the estimation phase resulted in a more cost-efficient sampling scheme than when auxiliary information was used at the design phase. However, using auxiliary information at the design phase resulted in more precise estimates than using the same at the estimation phase for the same sample size. For both species, systematic sampling with ratio estimation provided the most efficient estimate of individual tree foliage biomass. In Douglas-fir, stratifying by branch type (i.e., whorl versus interwhorl) resulted in a marginal gain in precision. For Douglas-fir, on average, root mean square error decreased by 43.1% when sample size increased from 6 to 12 branches per tree, with a further decrease of 24.3% when sample size increased from 12 to 18 branches per tree. For ponderosa pine, on average, the root mean square error decreased by 44.4 and 23.9% when the sample size was increased from 6 to 12 and from 12 to 18 branches per tree, respectively. Additional work is needed to understand the appropriate sampling techniques for older conifer tree crowns and sampling multileader deciduous crowns. FOR. SCI. 57(2):153–163.

SAMPLING INDIVIDUAL TREE CROWNS to measure foliage biomass or leaf area index is a common approach for estimating the foliar biomass and leaf area index of the entire crown. Tree foliage biomass (mass of dry foliage) is a common response variable in analyzing the impact of silvicultural treatments such as fertilization and thinning. However, direct tree foliage biomass estimation is tedious, laborious, and costly. As a result, tree foliage biomass is typically estimated using regression or allometric relationships between foliage biomass and other easily measured attributes such as diameter outside bark at breast height (Baldwin 1989, Catchpole and Wheeler 1992, Jenkins et al. 2003), cross-sectional sapwood area at breast height (Waring et al. 1982), cross-sectional sapwood area at the base of the live crown (i.e., using the pipe model theory) (Maguire and Hann 1987), diameter at stump height (diameter outside bark at 0.3 m aboveground) (Helgerson et al. 1988), the ratio of live crown length to total tree height (Loomis et al. 1966), the distance from breast height to the base of live crown (Dean and Long 1986), or the proportion of light that passes through the canopy (Martens et al. 1993).

Models or allometric equations are developed using data collected from a specific forest population (e.g., a particular tree species at a specific location) (e.g., Temesgen et al. 2003). The underlying models need to be valid, and a strong relationship between the response variable and the predictor variable(s) should exist. The development of such regression requires measuring foliar biomass on a sample of trees. Despite numerous attempts to quantify foliage biomass, accurate and efficient estimation of biomass continues to be problematic. The high within- and between-tree crown variation has prevented the development of efficient protocols. In this article, we focused on evaluating the performance of selected sampling strategies to estimate tree foliage mass.

Estimating foliar biomass from a tree typically requires selecting a sample of branches and collecting and weighting the leaves on the branch. Many sampling designs have been used to select the sample, from very simple approaches that do not require additional measurements or only easily measured information such as counting and identifying branches to sampling protocols that require detailed auxiliary information about branch characteristics. Examples of simple designs include simple random sampling, systematic sampling, and stratified random sampling. Examples of sampling designs that require detailed auxiliary information include randomized branch sampling and probability proportional to branch size sampling. However, if auxiliary information (e.g., branch diameter or position) is available, it can be used to design an efficient sampling scheme (design phase) but can also be used to improve the efficiency of estimators after samples are drawn (estimation phase), regardless of the sampling design used. Comparing sampling strategies and, in particular, comparing strategies

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that use auxiliary information during the design or estimation phases is the primary objective of this article.

Some sampling designs use unequal probability sampling, typically selecting branches with probability proportional to a measure of their size. Larger branches are selected more often, which results in more precise estimates. However, it also means more effort to collect, handle, and measure branch biomass. Some sampling designs, such as probability proportional to branch size sampling, randomized branch sampling, and importance sampling are time-consuming and cumbersome to apply in the field, because the diameter of each branch has to be measured and recorded, which might also contribute to measurement errors. For example, Cancino and Saborowski (2005) found conventional randomized branch sampling to be imprecise because its sampling variance exceeded the population variance by almost 30% in determining the foliage biomass of three different species.

Temesgen (2003) summarized various sampling strategies that have been used to estimate crown attributes. Using Monte Carlo simulation techniques, Temesgen (2003) found that stratified random sampling resulted in the lowest mean square error values, followed by ellipsoidal, two-stage systematic, and simple random sampling, and then by two-stage unequal probability sampling for estimating total tree leaf area. Although previous studies have provided a general framework for sampling tree crowns (e.g., Gregoire et al. 1995, Temesgen 2003, Cancino and Saborowski 2005), several fundamental questions still remain. First, how robust are these sampling techniques when there are differences in branching patterns among or between tree species? For example, Temesgen (2003) based his conclusions on a limited sample of only 12 trees of hybrid spruce (*Picea engelmannii* Parry × *Picea glauca* [Moench] Voss × *Picea sitchensis* [Bong.] Carr) across three stands. Furthermore, just the four tallest trees in each stand were sampled rather than multiple crown classes. Second, are the most efficient crown sampling schemes species-specific? Finally, how many branches per tree should be sampled to estimate total foliage biomass of individual tree crowns?

We used a simulation study based on extensive branch and tree foliage biomass data sets for Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* [Mirb.] Franco) (Weiskittel et al. 2006) and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) (Wilson and Maguire 2009) in Oregon to examine those questions. The Douglas-fir data set was collected across a wide gradient of crown classes, stand ages, and severity of Swiss needle cast disease, a fungal disease caused by (*Phaeocryptopus gaeumannii* [T. Rohde] Petr.). The ponderosa pine data set was collected in midrotation, pure, even-aged ponderosa pine stands across a soil productivity gradient in central Oregon. Specific objectives of this study were to examine the statistical efficiency and amount of dry biomass that needs to be measured to achieve a given precision using selected sampling alternatives and to compare the use of auxiliary information (e.g., branch diameter) at either the design or estimation phase in estimating tree foliage biomass.

Methods

Study Areas

The Douglas-fir data set included 17 plots located in the Oregon Coast Range, all within 32 km of the Pacific Ocean (44°40′N–46°7′N). The climate is humid maritime, with a distinct dry summer and a cool, wet winter. Rainfall varies from approximately 180 to 300 cm year^{-1}, and January mean minimum and July mean maximum temperatures range from −2 to 2°C and from 20 to 28°C, respectively. Variation in precipitation and temperature is strongly related to elevation and proximity to the coast. Elevation ranged from 25 to 550 m, and all aspects were represented by the study sites. The plantations in which plots were established ranged from 10 to 60 years at breast height and contained ≥75% Douglas-fir by basal area, with varying amounts of naturally regenerated western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) and hardwood species. The plots were selected to be similar in structure and composition but to vary in Swiss needle cast intensity as measured by average stand foliage retention.

The ponderosa pine data set was from 13 sites on the Deschutes National Forest near Bend, Oregon (Wilson and Maguire 2009). This region has a continental climate with long, cold winters and warm, dry summers. Average annual precipitation ranges from 38 to 114 cm and arrives mainly as rain or snow between the late fall and early spring months. The elevation of the sites ranged from 1270 to 1600 m, with average precipitation generally decreasing with declining elevation. Soils within the study region were sandy to sandy-loam Xeric Vitricriands, formed over a thick mantle of Mount Mazama volcanic pumice and ash deposited 7,000 years ago. The ash layer varied between 0.4 and 2.0 m thick at the study sites, burying material of varied origin. The terrain is flat or gently sloping. The sites were located in midrotation, pure, even-aged ponderosa pine stands, originating from natural regeneration after clearcutting, although one site was a plantation. Sampled stands ranged in age from 25 to 110 years. Sites were chosen to span the widest range of both foliage mass and productivity normally found in central Oregon. At each site, a single 20 × 20-m plot was subjectively located.

Data Description

In the Douglas-fir study, 3–12 sample trees were selected from each stand for a total of 114 trees sampled (Table 1). All sample trees were outside but adjacent to permanent monitoring plots and similar to plot trees with regard to dbh (1.3 m), foliage retention, and distance from adjacent trees. All sample trees were located away from gaps or landings and were free of any damage or obvious defect (e.g., double-tops, excessive sweep, and crooks). Before felling, dbh (to the nearest 0.1 cm) and crown width (to the nearest 0.1 m) were measured, and crown color and crown density were estimated. Each sample tree was then felled, and total height (nearest 0.01 m) from the base of the stump to the tip of the tree and height to crown base (nearest 0.01 m; lowest live branch) were measured by stretching a tape along the bole. Basal diameter (nearest 0.1 mm) and distances from

Table 1. Summary of stand-, tree-, and branch-level attributes used to create test populations for Monte Carlo simulations

Variable	Douglas-fir (n_s = 17 stands)	Ponderosa pine (n_s = 13 stands)
Individual branch	n_p = 1,200	n_p = 1,740
Branch foliage biomass (kg)	0.001–1.46 (0.09)	0.0001–3.72 (0.29)
Branch diameter (cm)	0.9–6.57 (1.12)	0.6–9.2 (1.33)
No. of first-order branches per tree	115–430 (58)	33–149 (23.3)
Individual tree	n_m = 114	n_m = 118
dbh (cm)	12.5–66.6 (10.8)	17.9–46.2 (8.1)
Tree height (m)	12.2–45.8 (8.2)	9.5–27.5 (4.7)
Tree age (years)	10–60 (9)	25–120 (15)

Data are shown as minimum–maximum (SD).

the tip of the tree (i.e., depth into the crown; nearest 0.01 m) were recorded for each live branch.

The dbh of the Douglas-fir sample trees ranged from 12 to 67 cm. Branches were selected using stratified random sampling. The crown length was divided into thirds, and a total of 3 whorl and 2 interwhorl branches were randomly selected from each third. Sample branches were cut at the base and measured for total length along the main branch axis. Sample branches ranged in basal diameter from 1 to 64 mm. Each sample branch was clipped into segments and placed in a plastic bag. The branches were dried, the foliage was separated from the woody components, and each component was weighed to the nearest 0.01 g.

In the ponderosa pine study, 7–11 trees were selected at each site. Candidate trees had good crown form, heights, and live crown lengths similar to the plot trees and were not allowed to be adjacent to each other. The final sample was randomly selected after stratification by diameter classes, so that the trees were distributed evenly across the diameter range of the site. A total of 118 trees were destructively sampled (Table 1).

Ponderosa pine biomass sampling began in mid-August 2000, after maximum foliage elongation but before the fall foliage drop. Each sample tree was measured for dbh and then felled into a clear area to minimize crown breakage. On each felled tree, a cloth tape was fixed along the length of the stem to indicate height from the ground. The crown was stratified into thirds from a visually reconstructed crown base, and heights delineating these thirds, including height to crown base and total tree height, were recorded. Within each third, branches were selected with probability proportional to the branch basal area, resulting in a stratified, probability proportional to size design. Each live branch was measured for diameter parallel to the tree bole (nearest mm) and for height at insertion into the bole (nearest 0.01 m). Branch diameter (BD) was measured approximately 1 cm from the bole. Live branches below the crown base ("full, even crown point") were assigned to the lower crown third. Branch diameters were then squared and summed within a crown third. Five branches from each crown third were then randomly selected with probability proportional to BD^2. The branches selected were cut flush with the bole and examined for missing foliage. All live foliage was collected from each sampled branch. Biomass samples were either dried in a kiln at 65°C or air-dried over several months, and air-dried branches were subsampled to verify that they had the same moisture content as the kiln-dried samples stored at ambient humidity. Total foliage biomass for the crown third was estimated from sample branch biomass estimates and sampling probabilities and summed to obtain total foliage biomass for the tree.

Simulations

Because measuring foliage biomass is laborious and costly, data were collected on only selected first-order branches of the Douglas-fir and ponderosa pine sample trees. Therefore, the foliar biomass of every branch and the total foliage biomass per tree were not available to assess the efficiency of the selected sampling designs. Test populations were created using predicted branch foliage biomass of each first-order branch to examine the use of auxiliary information (e.g., branch diameter) at either the design phase or estimation phase and the efficiency of selected sampling designs under varying sampling intensities.

Creation of Test Populations

For each tree, branch foliage biomass was estimated using a tree-specific log-linear model fitted using branch diameter and depth into the crown as covariates. After several linear and nonlinear models were examined, the model used by Kershaw and Maguire (1995) was selected on the basis of its superior fit statistics and residual plots as the most appropriate model to predict branch foliage biomass:

$$\log(y_{ij}) = \beta_{0i} + \beta_{1i}\log(\mathrm{BD}_{ij}) + \beta_{2i}\log(\mathrm{DINC}_{ij}) + \varepsilon_{ij}, \tag{1}$$

where y_{ij}, BD_{ij}, and DINC_{ij} are the estimated foliage branch biomass (g), branch diameter (cm), and depth into the crown (m) for the jth branch on the ith tree, respectively, the β_i's are parameters to be estimated for the ith tree, and $\varepsilon_{ij} \sim \mathrm{N}(0, \sigma_i^2)$, where σ_i^2 is the tree-level residual variance on the log scale.

After estimates for β_{0i}, β_{1i}, β_{2i}, and σ_i^2 for each individual tree were obtained, the following sequence was used to create test populations simulating each tree.

1. Obtain a random draw, e_{ijs}, from a $\mathrm{N}(0, \hat{\sigma}_i^2$ distribution, where s denotes iteration number.
2. Obtain a prediction of the foliar biomass for each branch in the tree (including those that were sampled), as

$$\hat{y}_{ijs} = \exp[\hat{\beta}_{0i} + \hat{\beta}_{1i}\log(\mathrm{BD}_{ij}) + \hat{\beta}_{2i}\log(\mathrm{DINC}_{ij}) + e_{ijs}], \quad k = 1, \ldots, NB_i, \quad (2)$$

where NB_i is the number of branches (known). It is worth noting that the expression in brackets in Equation 2 is a prediction of the log foliar biomass of an individual branch, not an estimate of the expected log biomass. Therefore, back-transforming the predicted logarithmic value to obtain $\hat{y}_{ijs}$ does not result in transformation bias.

3. Sum the estimated foliage for all the branches to compute total foliar biomass for the ith tree (τ_{is}):

$$\tau_{is} = \sum_{j=1}^{\mathrm{NB}_i} \hat{y}_{ijs}. \quad \text{This is the parameter being estimated.} \quad (3)$$

4. Implement the sampling schemes described below. Compute an estimate of the total tree biomass. After this, the difference between observed (τ_{is}) and predicted ($\hat{\tau}_{is}$) values, $B_{is} = \tau_{is} - \hat{\tau}_{is}$ (kg), and the squared error of the prediction, $\mathrm{SEP}_{is} = (\tau_{is} - \hat{\tau}_{is})^2$, were calculated and later used to estimate bias and root mean square error prediction.
5. Repeat 5000 times.
6. Repeat for all trees.

Simulated Sampling Strategies

Ten sampling strategies, three samples sizes (6, 12, and 18 branches per tree), and two tree species resulted in 78 unique sampling combinations for estimating tree foliage biomass. The 10 sampling strategies were chosen using statistical and practical (i.e., ease of sampling) considerations. Several of the sampling designs used auxiliary information on branch basal area either in the design or estimation phases, as detailed below. Three sample sizes (6, 12, and 18 branches) were selected for ease of distributing samples into various strata within each stratum, because they are divisible by 3.

1. Simple random sampling (SRS). SRS was included in this study as a basis for comparing the other sampling designs. For each of the three sample sizes, branches were sampled at random with equal probability of selection, and the average biomass per branch was computed and multiplied by the number of branches in the tree to obtain an estimate of the total foliar biomass. For each selected sample, the estimated tree foliage biomass was calculated using SRS estimators.

$$\hat{\tau}_{i(\mathrm{SRS})} = \mathrm{NB}_i\left(\frac{1}{n}\sum_{j=1}^{n} y_{ij}\right), \quad (4)$$

where $\hat{\tau}_{i(\mathrm{SRS})}$ is the estimated total biomass using SRS, NB_i is the number of branches, n is the sample size, and y_{ij} is the biomass of the jth sampled branch from the ith tree.

2. Simple random sampling with ratio estimation (SRS-ratio). This strategy used the SRS sample, followed by a ratio estimator that incorporated auxiliary information (squared branch diameter) in the estimation phase. For each of the three sample sizes selected using SRS above, the ratio of average biomass and branch diameter squared for the sampled branches was multiplied by total branch diameter to obtain an estimate of the total foliar biomass.

$$\hat{\tau}_{i(\mathrm{SRS-ratio})} = \frac{\sum_{j=1}^{n} y_{ij}}{\sum_{j=1}^{n} \mathrm{BD}_{ij}^2} \sum_{j=1}^{\mathrm{NB}_i} \mathrm{BD}_{ij}^2. \quad (5)$$

3. Probability proportional to branch size (PPS). This design used auxiliary information to select samples in the design phase. In simulating PPS, sample branches were selected randomly with probability proportional to the square diameter of the first-order branch. Selection was done with replacement. For each first-order branch, the selection probability was determined as

$$\pi_{ij} = \frac{\mathrm{BD}_{ij}^2}{\sum_{j=1}^{\mathrm{NB}} \mathrm{BD}_{ij}^2}. \quad (6)$$

The probability that a branch is included (inclusion probability) in any of the n draws is

$$\pi_{ij}^{\mathrm{HT}} = 1 - (1 - \pi_{ij})^n. \quad (7)$$

A Horvitz and Thompson (1952) unequal probability estimator was used to calculate total tree foliage biomass. The Horvitz-Thompson estimator is

$$\hat{\tau}_{i(\mathrm{PPS})} = \sum_{j \in S} \frac{y_{ij}}{\pi_{ij}^{\mathrm{HT}}}, \quad (8)$$

where $\hat{\tau}_{i(\mathrm{PPS})}$ is estimated tree foliage biomass (kg) for tree i, y_{ij} is foliage biomass from the jth sample branch on tree i, and S denotes the set of distinct indices (i.e., branches) included in the sample.

4. Systematic sampling (SYS). Branches were selected systematically along the tree crown. In general, the number of branches was not a multiple of the sample size. Murthy (1967) identified linear and fractional interval systematic sample selection procedures. When a population is not an integral multiple of sample size and sampling interval, the linear systematic sample selection procedure, unlike the fractional interval sampling selection procedure, does not ensure equal probability of inclusion in the sample for every element in the population (Murthy 1967, p. 139). Because the fractional interval systematic sample selection procedure ensures equal probability of inclusion in the sample for every first-order branch in the crown, this procedure was used to select the first sample first-order branch. After this, tree foliage biomass was estimated using SRS estimators (Equation 4).

5. Systematic sampling with ratio estimation (SYS-ratio). This design used SYS, followed by a ratio estimator that used auxiliary information in the estimation phase. For each of the three sample sizes selected using SYS above, the ratio of average biomass and branch diameter squared was computed and multiplied by total branch diameter squared. Tree foliar biomass was estimated using the SRS-ratio estimators given in Equation 5.

6. Stratified random sampling (STR). For STR, the crowns of each tree were divided into three equal strata by relative height, and the three selected sample sizes were equally allocated to each stratum. The procedure followed was to select *n*/3 branches at random with equal probability of selection within each crown stratum and compute the total biomass for each stratum. Total tree foliage biomass was calculated by summing the predicted foliage branch biomass for each stratum total,

$$\hat{\tau}_{i(\mathrm{STR})} = \sum_{h=1}^{H} \sum_{j=1}^{n_h} \frac{N_{ih}}{n_h} y_{ijh}, \tag{9}$$

where H is the number of strata, N_{ih} is the total number of branches from the ith tree in the hth stratum, n_h is the number of branches sampled in the hth stratum, and y_{ijh} is the foliage biomass from the jth sample branch in stratum h on tree i.

7. Stratified random sampling with ratio estimation (STR-ratio). The same approach as for STR was used to select branches, coupled with a ratio estimator that used the auxiliary information in the estimation phase. The combined ratio estimator (Cochran 1977, p. 165) was used to estimate tree-level foliage biomass to minimize bias and to accommodate small sample sizes in each stratum. In this approach, we assumed that the ratio of branch foliage biomass to branch diameter squared did not differ among strata. Thus, there was no need to estimate the ratio of foliage biomass to branch diameter squared for each stratum. Average sampled branch biomass and stratum level values were later used to calculate mean foliage biomass in each stratum and tree-level foliage biomass.

$$\hat{\tau}_{i(\mathrm{STR-ratio})} = \frac{\hat{\tau}_{i(\mathrm{STR})}}{\overline{\mathrm{BD}}^{2}_{i(\mathrm{STR})}} \mathrm{BD}_i^2, \tag{10}$$

where $\hat{\tau}_{i(\mathrm{STR})}$ is the estimated total foliar biomass using STR (Equation 8) and

$$\overline{\mathrm{BD}}^{2}_{i(\mathrm{STR})} = \sum_{h=1}^{H} \sum_{h=1}^{n_h} \frac{N_{ih}}{n_h} \mathrm{BD}_{ijh}^2 \quad \text{and} \quad \mathrm{BD}_i^2 = \sum_{j=1}^{N_i} \mathrm{BD}_{ij}^2. \tag{11}$$

8. Stratified sampling with probability proportional to size selection (STR-PPS). Branches were selected randomly within each stratum with probability proportional to BD^2. For each branch, the selection probability for branch j in stratum h on tree i was determined as

$$\pi_{ijh} = \frac{\mathrm{BD}_{ijh}^2}{\sum_{j=1}^{\mathrm{NB}_{ih}} \mathrm{BD}_{ijh}^2}. \tag{12}$$

The probability that a branch is included in any of the n draws is

$$\pi_{ijh}^{\mathrm{STR-HT}} = 1 - (1 - \pi_{ijh})^{n_h}. \tag{13}$$

A Horvitz and Thompson (1952) unequal probability estimator was used to calculate total tree foliage biomass for each stratum, and total tree foliage biomass was calculated by summing the predicted foliage branch biomass for each stratum total.

$$\hat{\tau}_{i(\mathrm{STR-PPS})} = \sum_{h=1}^{H} \sum_{j \in S_h} \frac{y_{ijh}}{\pi_{ijh}^{(\mathrm{STR-HT})}}, \tag{14}$$

where $\hat{\tau}_{i(\mathrm{STR\text{-}PPS})}$ is estimated tree foliage biomass (kg).

9. Stratified random sampling, by branch type ($\mathrm{STR_W}$). Branches were stratified into whorl or interwhorl types, and for each branch type a random sample (3, 6, and 9 branches per tree) was selected. Statistical approaches used in method 6 were used to estimate mean foliage biomass in each stratum and tree-level foliage biomass. Foliage mass estimation follows the STR design. This method was only used on Douglas-fir, because ponderosa pine does not have interwhorl branches.

10. Stratified random sampling, by branch type with ratio estimation ($\mathrm{STR_W}$-ratio). Douglas-fir branches were randomly selected within each stratum (whorl or interwhorl branch). For each branch type 3, 6, and 9 branches per tree were selected, and auxiliary information was used in the estimation phase to estimate foliage mass. This method was only used on Douglas-fir, because ponderosa pine does not have interwhorl branches. Statistical approaches used in method 7 were used to estimate foliage biomass in each stratum and tree-level foliage biomass.

Measures Used to Assess Selected Sampling Strategies

The sampling strategies were evaluated for bias, relative bias, mean squared error, the distribution of the estimates, and sampling efficiency. Sampling efficiency was evaluated by comparing the amount of foliage collected (weighed) and the precision of foliage mass estimates for the 10 sampling strategies. For each tree, we computed the following performance measures:

1. Bias—mean difference (kg):

$$\mathrm{B}_i = \frac{1}{5000} \sum_{s=1}^{5000} (\tau_{is} - \hat{\tau}_{is}), \tag{15}$$

where τ_{is} and $\hat{\tau}_{is}$ are the estimated and known total foliage biomass for the ith tree for the sth iteration, respectively.

2. Relative bias (%):

$$\mathrm{RB}_i = \frac{1}{5000} \sum_{s=1}^{5000} \frac{(\hat{\tau}_{is} - \tau_{is})}{\tau_{is}} \tag{16}$$

3. Root mean square error (RMSE) (kg):

$$\mathrm{RMSE}_i = \sqrt{\frac{1}{5000} \sum_{s=1}^{5000} (\hat{\tau}_{is} - \tau_{is})^2}. \tag{17}$$

We also examined the width of the 95% percentiles of the RMSE values.

4. Relative RMSE (%):

$$\text{R-RMSE}_i = \sqrt{\frac{1}{5000}\sum_{s=1}^{5000}\left(\frac{\hat{\tau}_{is}-\tau_{is}}{\tau_{is}}\right)^2} \tag{18}$$

5. Foliar biomass sampled (kg): Crown sampling involves removal of foliage for dry weight sampling. As a result, sampling intensity (amount of foliage sampled and measured) was used as a criterion for comparing sampling designs and also as a surrogate for cost.

$$\text{FBS}_i = \frac{1}{5000}\sum_{s=1}^{5000}\sum_{j\in S} y_{ijs} \tag{19}$$

6. Relative foliar biomass sampled (%): proportion of foliage sampled and measured:

$$\text{RFBS}_{ij} = \frac{1}{5000}\sum_{s=1}^{5000}\sum_{j\in S}\frac{y_{ijs}}{\tau_{ijs}}. \tag{20}$$

To integrate RMSE and the amount of foliage sampled and then estimate cost efficiency of each sampling design and size, we estimated relative efficiency (precision per relative foliage biomass sampled), normalized by the total foliar biomass of the tree, and compared the overall efficiency of each sampling design and size.

$$\text{Relative\_Efficiency} = \left(\frac{1}{\text{R-RMSE}}\right)\Big/\text{RFBS}. \tag{21}$$

In general, the sampling method that requires the most amount of foliage sampled (time) will also yield the greatest precision. The greater the value of relative efficiency, the more efficient a sampling design is.

Results and Discussion

Bias and Relative Bias

Except for the designs using the ratio estimator, the estimated bias was nearly zero for all sampling designs for both Douglas-fir and ponderosa pine, as expected (Tables 2 and 3). For Douglas-fir, the biases ranged from 0.001 to 0.178 kg, whereas for ponderosa pine, the average ranged from 0.01 to 0.08 kg. For Douglas-fir, the STR-ratio resulted in 1.29% bias when six branches were sampled (only two per stratum). This result can be ascribed to the low sample size selected from highly variable Douglas-fir branch populations that included both whorl and interwhorl branches. However, the bias decreased rapidly as the sample size increased, to 0.39 and 0.27% for sample size 12 and 18 branches, respectively. This result is expected given that the ratio estimate has a bias of 1/*n* order (Cochran 1977, p. 160).

RMSE

Not surprisingly, the statistical efficiency of all sampling designs improved as sample size increased. For all sampling designs, the RMSE values decreased substantially with increasing sample sizes (Tables 4 and 5). For Douglas-fir, on average, RMSE decreased by 43.1% when sample size increased from 6 to 12 branches per tree, with a further decreased of 24.3% when sample size increased from 12 to 18 branches per tree (Table 4). For ponderosa pine, on average, RMSE decreased by 44.4% when sample size increased from 6 to 12 branches per tree, with a further decrease of 23.9% when sample size increased from 12 to 18 branches per tree (Table 5). RMSE (%) decreased as sample size increased (Tables 4 and 5).

Differences in precision of these sampling methods are due in part to variation in stratification, selection procedure, and use of auxiliary information. Five sampling strategies used stratification; two of them used PPS, and the remaining used SRS or SYS. On average, for Douglas-fir, stratified sampling was 1.11 times more efficient than SRS (Table 4). The higher relative statistical efficiency of stratified PPS over SRS is a reflection of the reduction in branch foliage biomass variability by stratifying tree crowns by relative heights. For Douglas-fir, the gain obtained by stratifying by whorl type was marginal (Table 4).

These findings are consistent with those put forth by Temesgen (2003) despite differences in the sampling methods used in each simulation study. Temesgen (2003) estimated tree leaf area by subsampling both first- and higher-order branches, whereas foliage biomass was determined in this study only by sampling first-order branches. In this study, stratifying the crown into thirds by relative height

Table 2. Median average bias and relative percent bias by sampling strategies and sample size (on the basis of 5,000 replications on each of 114 trees) for Douglas-fir

	Bias (kg)			Relative bias (%)		
	6	12	18	6	12	18
SRS	−0.001	0.008	0.008	0.069	0.040	0.077
SRS-ratio	−0.111	−0.052	−0.049	−0.610	−0.387	−0.246
PPS	−0.001	0.004	−0.001	0.015	0.029	−0.002
SYS	−0.001	−0.006	−0.005	−0.007	−0.045	−0.023
SYS-ratio	−0.152	−0.067	−0.031	−0.886	−0.431	−0.241
STR by crown position						
STR	0.005	0.004	0.000	0.045	0.012	−0.012
STR-ratio	−0.178	−0.048	−0.047	−1.288	−0.391	−0.272
STR-PPS	−0.006	0.000	−0.007	−0.053	0.009	−0.045
STR by whorl						
STR_W	0.012	−0.003	0.002	0.126	−0.007	0.018
$\text{STR}_\text{W-ratio}$	−0.045	−0.026	−0.003	−0.362	−0.145	−0.021

Table 3. Median bias and relative percent bias by sampling strategies and sample size (based on 5,000 replications on each of 118 trees) for Ponderosa pine

	Bias (kg)			Relative bias (%)		
Method	6	12	18	6	12	18
SRS	−0.006	−0.006	0.006	0.003	−0.072	0.068
SRS-ratio	0.079	0.035	0.030	0.821	0.403	0.290
PPS	−0.003	0.002	0.000	−0.014	0.012	−0.001
SYS	−0.003	−0.005	0.002	−0.011	−0.067	0.013
SYS-ratio	−0.006	−0.012	0.006	−0.114	−0.143	0.060
STR by crown position						
STR	0.001	0.000	0.001	0.041	−0.005	0.013
STR-ratio	−0.034	−0.019	−0.010	−0.209	−0.227	−0.100
STR-PPS	−0.002	0.002	0.003	−0.022	0.012	0.037

Table 4. Median RMSE and relative percent RMSE estimated by sample design and sample size (based on 5,000 replications on each of 114 trees) for Douglas-fir

	RMSE (kg)			Relative RMSE (%)		
Method	6	12	18	6	12	18
SRS	12.79	8.87	7.06	71.52	49.70	40.03
SRS-ratio	8.21	5.74	4.57	50.37	35.60	28.40
PPS	5.47	3.95	3.23	32.69	23.20	19.17
SYS	11.65	7.94	6.41	66.03	48.56	37.06
SYS-ratio	7.56	5.37	4.39	47.17	33.75	26.83
STR by crown position						
STR	11.20	7.83	6.15	63.49	44.19	36.21
STR-ratio	7.30	5.30	4.35	45.49	32.23	26.23
STR-PPS	5.68	4.04	3.38	34.17	24.07	20.18
Whorl						
STR_W	10.063	6.870	5.509	56.501	39.320	31.318
$STR_{W\text{-ratio}}$	7.366	5.086	4.027	43.572	30.942	24.900

Table 5. Median RMSE and relative percent RMSE estimated by sample design and sample size (based on 5,000 replications for on each of 118 trees) for ponderosa pine

	RMSE (kg)			Relative RMSE (%)		
Method	6	12	18	6	12	18
SRS	6.42	4.38	3.50	38.2	26.3	20.7
SRS-ratio	5.29	3.45	2.66	29.9	20.2	15.3
PPS	5.27	3.95	3.32	28.7	20.8	17.2
SYS	6.01	4.10	3.33	35.7	23.9	19.4
SYS-ratio	4.32	2.90	2.36	27.0	17.4	13.9
STR by crown position						
STR	6.48	4.42	3.46	37.1	25.0	19.8
STR-ratio	4.25	2.90	2.28	25.7	17.4	13.5
STR-PPS	4.20	3.15	2.70	24.8	18.1	15.2

significantly improved the estimate compared with just selecting branches based strictly on their size. This is particularly true for fairly shade-tolerant species such as Douglas-fir because the relative vertical distribution of foliage biomass tends to become more skewed with increasing shade tolerance (Garber and Maguire 2005).

Use of ancillary information at the design stage resulted in a significant increase in statistical efficiency. However, the gain was much greater for Douglas-fir than for ponderosa pine and decreased as sample size increased. For a sample size of six branches, the RMSE of SRS was 2.34 and 1.22 times that of PPS for Douglas-fir and ponderosa pine, respectively. For a sample size of 18 branches, the equivalent RMSE ratios decreased to 2.18 and 1.05, respectively. The greater relative statistical efficiency of PPS in Douglas-fir compared with that of ponderosa pine may be a result of sampling a much greater amount of foliar biomass in the former (Table 6 and next section). It may also be related to greater variability in branch sizes within a tree because, for example, Douglas-fir grows both whorl and interwhorl branches.

Use of ancillary information at the estimation phase through a ratio estimator also resulted in gains in statistical efficiency for both species. The RMSE of SRS was approximately 1.54 times that of the SRS-ratio for Douglas-fir and between 1.21 and 1.32 times that for ponderosa pine, depending on sample size. Thus, for ponderosa pine, no sizable differences in RMSE values were observed by using

Table 6. 5 and 95% RMSE percentiles for the 114 and 118 Douglas-fir and ponderosa pine trees by sampling design, sample size, and tree species

	RMSE (kg)					
	Douglas-fir			Ponderosa pine		
Method	6	12	18	6	12	18
SRS	3.78, 39.30	2.55, 26.94	2.02, 19.93	1.30, 20.33	0.85, 13.94	0.66, 11.26
SRS-ratio	2.35, 35.00	1.66, 25.47	1.29, 21.59	0.92, 16.51	0.61, 10.94	0.46, 8.67
PPS	1.66, 24.74	1.20, 17.01	1.02, 14.27	0.92, 16.10	0.68, 11.15	0.56, 9.45
SYS	3.49, 40.01	2.42, 23.88	1.81, 20.69	1.15, 19.01	0.71, 13.12	0.60, 11.26
SYS-ratio	2.13, 33.08	1.47, 22.59	1.21, 19.06	0.86, 14.79	0.61, 10.73	0.46, 9.00
STR by crown position						
STR	3.24, 34.36	2.35, 25.67	1.83, 20.03	1.24, 19.46	0.81, 13.37	0.61, 10.76
STR-ratio	1.97, 30.79	1.40, 23.12	1.12, 18.76	0.86, 14.94	0.59, 10.43	0.44, 8.49
STR-PPS	1.52, 24.49	1.12, 16.23	0.94, 13.63	0.82, 13.40	0.61, 9.16	0.51, 7.76
STR by whorl						
STR_W	2.89, 35.76	1.99, 24.56	1.61, 18.71			
STR_W-ratio	2.10, 29.35	1.48, 21.55	1.14, 17.05			

the auxiliary information (i.e., branch diameter) during the design versus the estimation phases (Table 5). In fact, the ratio estimators showed lower RMSE for ponderosa pine than the equivalent PPS designs, with the exception that results were equivocal for the lowest sample size of 6 branches. However, for Douglas-fir, using the auxiliary information at the design phase resulted in more precise estimates than using the same information during the estimation phase (Table 4).

The ranking of the sampling designs in terms of relative RMSE (precision) differed for the two species. For Douglas-fir, PPS performed the best (the lowest relative RMSE values for the three sample sizes) followed by other designs that involved sampling proportional to branch size (STR-PPS). The designs based on ratio estimators followed (STR-ratio, SYS-ratio, and SRS-ratio) and then designs that did not incorporate information on branch size at either the design or estimation phase (STR, SYS, and SRS) (Table 4). However, for ponderosa pine, there was not much of a distinction between designs that used information on branch size in the design or estimation phase, even though the latter tended to dominate as the sample size increased. In this study, using auxiliary information always improved the performance of the design in terms of RMSE. Estimators that used information on branch size at the design phase tended to be as good as or better than those that used it at the estimation phase, but the relative performance depended on the tree species. However, the improvement in RMSE when information at the design phase was used came with a cost, because a significantly larger amount of foliage had to be collected and processed.

For the three sample sizes, the SYS and SRS designs, whether stratified or not, consistently resulted in the least precise tree foliage biomass estimates. However, these are simple designs and require the least information or measurement. There was no need to measure, record, and keep track of the diameter of every branch, a task that would require an extensive effort and cost. The time spent measuring branch diameters could be used to increase the sample size and, therefore, the precision.

The distribution of RMSE from the population of trees is highly skewed. As a result, the median RMSE was used as a measure of central tendency and the 0.05 and 0.95 quantiles were reported. These quantiles indicate that strategies that used ancillary information tended to have the narrowest spread, especially PPS for Douglas-fir and both PPS and ratio estimators for ponderosa pine (Table 6). The increase in precision resulting from incorporating ancillary information tended to be greatest for the trees with the greatest sampling variability. Bean plots (Kampstram 2008) of the RMSE (%) estimated by the 10 sampling strategies for a sample size of 12 branches are displayed in Figure 1.

Amount and Proportions of Foliage Sampled

There was a substantial difference in the amount of foliage sampled between sampling strategies that incorporated ancillary information at the design phase and those that did not (Table 7). The SYS and SRS strategies resulted

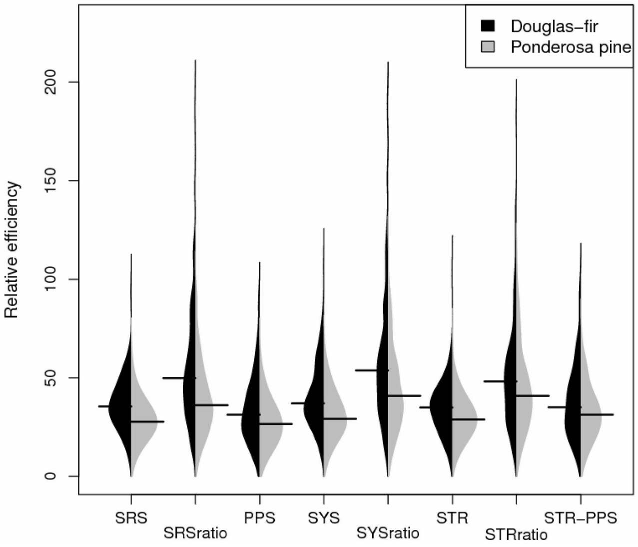

Figure 1. Beanplots of relative RMSE (%) by tree species and sampling design for a sample size of 12 branches. The black solid lines represent group medians. The sample designs were SRS, SRS-ratio, PPS, SYS, SYS-ratio, STR, STR-ratio, and STR-PPS.

Table 7. Amount of biomass sampled and relative percent biomass sampled by sampling design and sample size (5,000 replications) for Douglas-fir and ponderosa pine

	Biomass sampled (kg)			Relative biomass sampled (%)		
	6	12	18	6	12	18
SRS	0.472	0.952	1.432	2.812	5.628	8.446
PPS	1.166	2.225	3.192	6.854	13.020	18.605
SYS	0.479	0.958	1.437	2.814	5.617	8.421
STR	0.560	1.120	1.666	3.422	6.821	10.165
STR-PPS	1.043	1.968	2.856	6.019	11.604	16.711
STR$_{\mathrm{W}}$	0.600	1.197	1.806	3.476	6.995	10.454
Ponderosa pine						
SRS	1.098	2.189	3.293	6.848	13.711	20.577
PPS	1.527	2.885	4.005	9.734	18.287	25.770
SYS	1.091	2.214	3.296	6.831	13.692	20.496
STR	1.131	2.289	3.415	6.948	13.957	20.935
STR-PPS	1.457	2.769	3.967	9.435	17.770	25.118

in the lowest amount of foliage sampled. The amount of biomass sampled with use of the PPS strategy was between 2.2 and 2.4 times and between 1.2 and 1.4 times that of SRS for Douglas-fir and ponderosa pine, respectively. This difference is probably due to the greater heterogeneity of branch sizes within Douglas-fir trees. Note that the ratio estimators associated with the SRS, STR, and SYS designs also had the same amount of foliage biomass sampled.

Given that implementing a PPS strategy requires measuring a much greater amount of foliar biomass, a better measure of sampling efficiency may be the precision gain relative to the biomass sampled. For a given sample size, it was observed that the higher the relative precision, the better the performance of a sampling design. According to this metric, ratio estimators were by far the most efficient sampling designs for both species, and those that incorporated the ancillary information at the design phase were the worst (Table 8). For example, for Douglas-fir, the precision attained per kg of foliage sampled using the SRS-ratio strategy was between 1.11 and 1.15 times that of the SRS and between 1.61 and 1.73 times that of the PPS strategies, with the lowest figures corresponding to the greatest sampling sizes. For ponderosa pine, the relative sampling efficiency of the different strategies did not change very much with sample size. For this species, the precision attained per kg of foliage sampled using the SRS-ratio strategy was approximately 1.14 times that of the SRS and 1.39 times that of the PPS strategy.

Compared with other strategies, the use of auxiliary information at the design phase led to the selection and measurement of a higher proportion of larger branches with higher amounts of foliage, whereas use of auxiliary information at the estimation phase did not favor the selection of larger branches. Use of BD^2 only at the estimation phase immensely reduced the amount of foliage required to be weighed and processed to achieve a given precision (Figure 2). This reduced workload saves time and offers a cost-effective alternative for tree crown sampling. Conversely, use of BD^2 at the design phase can be time-consuming and costly.

In practical terms, the effort is directly related to the amount of biomass collected and processed and less so to the number of branches sampled. Therefore, the effort may be allocated to either increase the sample size or to collect larger branches. From this point of view, for Douglas-fir, the precision attained per kg sampled was approximately the same for SRS-ratio and 18 branches sampled as for sampling only 6 branches using a PPS design. As noted earlier, this metric does not include the additional effort needed to measure and record the diameter of all the branches in a tree. This observation implies that if the cost of drying and measuring foliage biomass is higher, then sampling a higher

Table 8. Median relative efficiency by sampling design, sample size, and tree species

	Douglas-fir			Ponderosa pine		
Method	6	12	18	6	12	18
SRS	50.35	35.54	29.91	37.83	27.71	23.75
SRS-ratio	72.79	49.87	41.21	49.22	36.12	30.96
PPS	43.49	31.30	26.85	36.66	26.62	22.56
SYS	53.40	37.04	33.18	40.41	29.28	25.40
SYS-ratio	75.48	53.79	43.49	55.58	40.86	33.35
STR by crown position						
STR	48.31	34.95	28.36	38.99	28.90	24.97
STR-ratio	67.52	48.15	39.82	54.35	40.86	34.49
STR-PPS	49.15	35.13	29.46	43.63	31.34	25.80
STR by whorl						
STR$_{\mathrm{W}}$	48.72	35.29	30.07			
STR$_{\mathrm{W}}$-ratio	63.04	46.00	39.08			

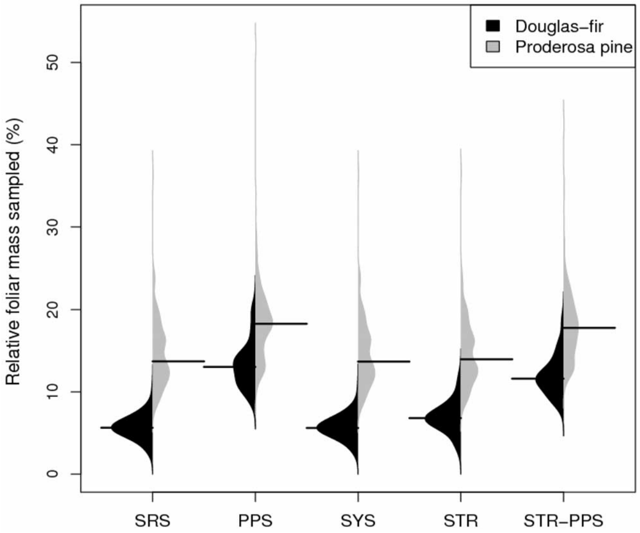

Figure 2. Beanplots of relative amount of foliage sampled by tree species and sampling design for a sample size of 12 branches. The black solid lines represent group medians The sample designs were SRS, PPS, SYS, STR, and STR-PPS.

number of branches using SRS-ratio or SYS-ratio is a viable option.

For all sampling designs, the range of the estimated foliage biomass for the 232 samples trees decreased as the sampling intensity increased, as expected (Table 7). The narrowest and widest ranges were obtained by the STR and the STR-PPS method, respectively. For all sampling designs, the distributions of the estimates of the 5,000 iterations were nearly normal.

For the 10 sampling strategies examined, the RMSE values did not show any trend over tree size attributes (e.g., dbh and tree height). The RMSE differences among these sampling strategies were more pronounced for Douglas-fir than for ponderosa pine. This result might be due to the inclusion of interwhorl branches of Douglas-fir trees. In addition, Douglas-fir also had a much higher within-tree variability of foliage biomass than ponderosa pine, in part created by the Swiss needle cast defoliation gradient in the crown.

Summary and Conclusions

When only RMSE is considered, the use of auxiliary information at the design phase resulted in lower RMSE values than those obtained when auxiliary information was used at the estimation phase for Douglas-fir, whereas the results were equivocal for ponderosa pine. For both species, the auxiliary information proved to be very useful in reducing sampling error. Based on our simulation results, SYS-ratio (using auxiliary information at the estimation phase) provided the highest relative efficiency. It was followed by SRS-ratio for Douglas-fir and by STR-ratio for ponderosa pine. Use of auxiliary information at the estimation phase (i.e., the ratio estimators) was always more efficient in terms of precision gain for unit of effort than use of the auxiliary information at the design phase (i.e., PPS and STR).

The efficiency of the SRS-ratio may be hindered by operational difficulty and detailed measurement of branch diameter. However, this sampling design is effective for describing foliage biomass distribution within tree crowns. Cost factors and the availability of suitable variance estimators are two fundamental concerns in designing methods for estimating foliage biomass. On the basis of the Monte Carlo simulations using extensive Douglas-fir and ponderosa pine data, SYS-ratio provided the highest relative precision (precision per relative foliage biomass sampled) followed by STR-ratio for ponderosa pine and SRS-ratio for Douglas fir.

The ranking of the 10 sampling strategies based on relative efficiency will help identify lower cost sampling strategies for a given precision of foliage biomass. These findings also may guide researchers in identifying other approaches to improve the estimation of foliage biomass.

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