SAMPLING FOR COMPLIANCE WITH USDA FOREST SERVICE GUIDELINES USING INFORMATION DERIVED FROM LIDAR

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Forest resources are traditionally assessed using field measurements. The USDA Forest Service developed a series of guidelines for planning and executing the measurements, specifically the significance level and maximum allowed sampling error. The sampling process outlined by the Forest Service includes a pre-sampling phase to supply some of the information needed for the inventory dedicated to assess the resource. The advent of remote sensing techniques, especially LIDAR, reduced the field effort while increasing estimation accuracy. The objective of this research was to determine the sample size needed for assessing forest resources using prior information derived from remote sensing sources. Remote sensing data is available at very attractive prices: LIDAR can be < $2 per acre; stereo images can reach $0.50 per acre.

Traditionally, a forest inventory is executed in two phases: first a pre-cruise with at least five plots, one being a boundary plot, is carried out in the field to determine the coefficient of variation; secondly, the actual cruise is performed using the information from the pre-cruise. The sample size, determined using sampling without replacement [the procedure recommended by the Forest Service (Robertson 2000)] is:

$$n_{pre-cruise} = \frac{1}{\left(\frac{SE}{t_{n-1;\alpha} \times CV_{plot}}\right)^{2} + \frac{1}{N_{plots}}} \tag{1}$$

where $n_{pre-cruise}$ is sample size executed as recommended by the Forest Service guidelines; SE is sampling error, which is imposed by the Forest Service guidelines; N_{plots} is the number of plots for census, computed as $N_{plots}=A_{stand}/A_{plot}$; CV_{plot} is plot level coefficient of variation; and $t_{n-1,\alpha}$ is the t value for $n-1$ degrees of freedom and significance level α [according to the Forest Service guidelines, $\alpha = 0.05$ (Robertson 2000)].

The availability of remote sensing data allows precise and accurate determination of tree height, either total or to base of crown. Height has been documented to be correlated with total volume (Zeide 1995); therefore, one could argue that the coefficient of variation for volume, when volume is the objective of the forest inventory, can be replaced by the coefficient of variation for heights. The advantage of using heights instead of volumes rests not only in an increase in accuracy and precision but also in using populations and not samples, which adds to the accuracy of the estimates. The validity of the replacement of volume with height is warranted by the linear relationship that exists between them, which allows the translation of the results obtained for height to volume. Using mild distributional assumptions and the linear equation:

$$Volume_{tree} = k \times height_{tree} \text{ (i.e., linearity)} \tag{2}$$

where k is a coefficient, the coefficient of variation, CV, for plot volume is

$$CV_{plot} = CV_{tree} / TPP^{0.5} \tag{3}$$

where TPP represents the average trees per plot. This research uses LIDAR data to compute the coefficient of variation of tree height.

Considering the relationship between the coefficient of variation for volume and for tree height (equation 2), the volume of a stand can be estimated from a sample of size:

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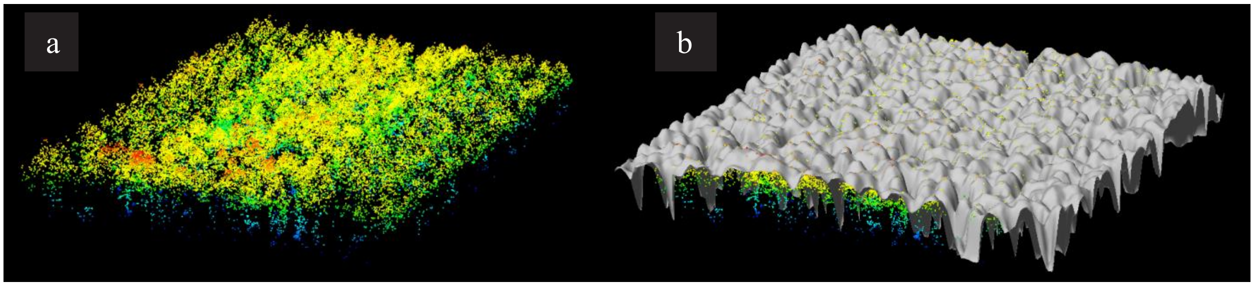

Figure 1--LIDAR point cloud (a) and identification of individual trees (b) using Fusion (McGaughey 2012).

$$n_{LIDAR} = \frac{1}{TPP \times \left(\frac{SE}{t_{n-1;\alpha} \times CV_{treeheight}}\right)^2 + \frac{1}{N_{plots}}} \qquad (4)$$

where n_{LIDAR} is sample size determined according to the Forest Service specifications but the *CV* was determined using LIDAR. CV_{tree} is the coefficient of variation of tree height (fig. 1).

The maximum sampling error is established according to the value of the resources; higher values require higher accuracy and therefore smaller sampling error, expressed as percentage from the expected volume (Robertson 2000). Considering that in the sample size formula (i.e., equations 2 and 4) the size of the inventoried stand is a variable, the computations used a fictional stand of 100 acres cruised with fixed area plots of 0.10 acre. This stand size was selected as being large enough to be feasible from the forest operations perspective and easy to adjust to stands of different sizes. The size of the plot was chosen as being widely used in estimating the volume of merchantable timber. The rest of the parameters from equation 4 were selected following a factorial design, with *CV* having three values, (10, 20, and 30 percent); trees per acre (TPA), also with three values (200, 300, and 400); and sampling error, 10 and 20 percent. The *TPP* from equation 4 can be computed as $TPP = TPA \times A_{stand} / N_{plots}$.

The largest number of plots to be ground measured using LIDAR data is at most two (table 1), when stand variability is large (i.e., CV ≥ 20 percent) and number of trees is reduced (i.e., ≤ 300 TPA); otherwise one plot suffices to obtain a forest inventory within the required limits. Alternatively, a forest inventory executed with a pre-cruise has at least one plot, but only for homogeneous stands (i.e., CV = 10 percent) and reduced values, as the sampling error should be 20 percent. For valuable stands, cruising without prior information can require 33 plots, a disproportionate field effort compared with the measurements executed using remote sensing-derived information. The main difference between the two approaches is in the computation of the expected values, with one using the entire population (i.e., the approach using LIDAR data) while the other one uses a sample (i.e., the approach using a pre-cruise) (fig. 1).

Table 1--Sample size using LIDAR data and a ground pre-cruise

CV	TPA	# plots using LIDAR	# plots using pre-cruise
10	200	1	4
10	300	1	4
10	400	1	4
20	200	1	16
20	300	1	16
20	400	1	16
30	200	2	33
30	300	2	33
30	400	1	33
10	200	1	1
10	300	1	1
10	400	1	1
20	200	1	4
20	300	1	4
20	400	1	4
30	200	1	9
30	300	1	9
30	400	1	4

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