Cost Considerations of Using LiDAR for Timber Inventory[1]

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Abstract

As interest in using Light Detection and Ranging (LiDAR) for forest inventory increases, the need for information comparing its cost effectiveness to conventional forest inventories is necessary. This project compared costs of a random sample ground inventory with a double sampling approach using LiDAR and fixed radius ground plots. The study examined the role of relative costs for each plot type (LiDAR and ground plots) and the similarity of plot level data (coefficient of determination) in the cost efficient mix of LiDAR and fixed radius ground plots.

Because of the high cost of acquiring LiDAR data, a double sampling approach using LiDAR technology is currently not cost effective for determining timber volumes when compared to traditional ground methods. However, LiDAR inventories can provide additional benefits such as a Digital Elevation Model (DEM), wildlife habitat characteristics, and other applications that require vertical and horizontal vegetation densities. If LiDAR data are already in place, a LiDAR inventory can be performed using a double-sample inventory to reduce cruising costs and improve the accuracy of the cruise volumes, but data must be acquired with the same time frame. Trade-offs between LiDAR and ground plots are directly related to the relative per plot costs of the two approaches and the strength of the relationship between the data derived from the two methods. In general, as LiDAR costs decrease, LiDAR plots can be substituted for ground plots to supply the same level of precision at the same total cost. As the relationship between LiDAR and ground inventory attributes increases, LiDAR plots can be substituted for a larger portion of the ground plots, while maintaining precision and total cost.

Keywords: Light Detection and Ranging, Double-sampling, Coefficient of determination

Introduction

Light Detection and Ranging (LiDAR) is a remote sensing tool that can potentially be used to conduct timber inventories. LiDAR has been used for the quantification of biomass, tree and stand height, and basal area estimation (Nelson et al. 1988, Nilsson 1996, Magnussen and Boudewyn 1998, Lefsky et al. 1999, Means et al. 1999, Means et al. 2000).

LiDAR data are collected from an aerial platform, typically an airplane but occasionally a helicopter. An airborne laser is shot to the ground below the aircraft (Dubayah and Drake 2000) and is reflected back to a sensor on the aircraft that records the time that elapsed between the shot and the reflection. Each laser shot can be reflected from more than one object allowing both tree tops and the ground to be recorded. The elevation difference between the first returns (typically the canopy) and last returns (ground) can be used to calculate tree heights. A Global Positioning Systems (GPS) and Inertial Measurement Unit (IMU) on the aircraft are used to record the exact location and time of each laser shot. Tree information obtained from the ground cruise is used to predict volume from the tree heights generated from the LiDAR data.

The only tree characteristics obtained from the LiDAR inventory are tree height and trees per acre (Dubayah and Drake 2000). Timber inventory using LiDAR requires a double-sample inventory approach because of the limited information available from a LiDAR inventory. Double sampling requires two plot types: primary plots that provide less detailed information, but typically cost less, and secondary plots that provide more information, but also cost more. Primary plots can be substituted for secondary plots to decrease cost by reducing the number of secondary plots required, if the attribute and volume information has a strong relationship with the remotely sensed data. The ground cruise provides the secondary plots and is used to collect diameter at breast height (dbh), tree height, crown class, and stem density data to determine the height-volume relationships. Tree heights from LiDAR primary plots are then used to predict timber volume.

At present, there is no consensus as to the optimal posting density for LiDAR double sampling. Parker and Evans (2004) used LiDAR data with a posting density of 0.25 postings per square meter to achieve an 11.5% sampling error at the 95% level of confidence. This study uses two posting densities to attempt to examine possible trade-off between assumed measurement accuracy (high density) verses reduced costs (low density) of LiDAR in a double sample inventory.

Objectives

The objectives of this study were to:

1) Determine if using LiDAR for timber inventory is cost effective.
2) Examine how the cost relationship changes with tract size.
3) Compare the cost and precision of two LiDAR posting densities with a conventional ground cruise.
4) Determine the breakeven point between a LiDAR double sampling cruise and a conventional timber inventory based on tract size.
5) Examine the effect of the relative cost of each plot type and the coefficient of determination between the plot types on plot allocation for double sampling.

Methods

The study area consisted of approximately 1200 acres of Louisiana State University's Lee Memorial Forest, located near Bogalusa in Washington Parish, Louisiana. The forest consisted of three stand types: mixed pine hardwood, mature pine, and pine plantations.

LiDAR data were collected in continuous strips along flight lines laid out to cover approximately 10% of the study area. LiDAR plots were then extracted from the continuous data. The double sample inventory was performed using 0.05 acre LiDAR and ground plots. The ground plot data were collected at every tenth LiDAR plot to establish height-volume relationships. There were 1,410 LiDAR plots and 141 ground plots collected from the 1,200 acres (Parker and Glass 2003).

LiDAR data were collected at two posting densities "high" and "low" to compare their accuracy for predicting timber volumes (Parker and Glass 2003). Posting density refers to the average spacing of the laser shots on the ground. The posting densities for high density and low density LiDAR data is four LiDAR shots per square meter and one LiDAR shot per square meters, respectively. Each posting density required a separate flight with high density LiDAR data requiring a lower flying altitude, thus taking longer and costing more to collect. It was hypothesized that low density LiDAR data would decrease collection costs, but result in decreased accuracy.

In order to compare the cost of a LiDAR based double-sample inventory to a random sample ground cruise, the cost of the ground cruise was obtained from actual field operations and was also used for the cost of the double-sample ground plots. The LiDAR inventory costs included the cost of obtaining the LiDAR data, the ground plots for determining the height volume relationship, and LiDAR data processing. If LiDAR data are already available, the cost of extracting the plots and processing the data for timber inventory is very low.

Regression models were constructed for both LiDAR posting densities to predict timber volumes from LiDAR derived tree heights. LiDAR tree heights were consistently underestimated compared to the ground heights of the same tree. A two stage method for correcting this problem was constructed (Parker and Mitchel 2004). First, the LiDAR counts of trees were corrected with a smoothing process before the regression model was computed. This was done by averaging the LiDAR canopy surface to reduce the number of false tree locations. Second, the LiDAR derived tree heights were considered to be negatively biased and were corrected within the regression model. The high and low density LiDAR models' predicted volumes were compared to determine which provided a more precision estimate.

The number of plots was a function of the cost of each plot type and coefficient of determination. In order to determine when a double sampling technique would be cost effective, examination of the relative costs of each plot type (ground vs. LiDAR) and the coefficient of determination was necessary. The plot allocation formulas for double sampling are:

$$n_1 = N_{rs}\left[\left(1-\rho^2\right)\sqrt{\left(\frac{c_2}{c_1}\right)\left(\frac{\rho^2}{1-\rho^2}\right)}+\rho^2\right] \qquad n_2 = N_{rs}\left[\left(1-\rho^2\right)\sqrt{\left(\frac{c_1}{c_2}\right)\left(\frac{1-\rho^2}{\rho^2}\right)}\right]$$

where:
N_{RS}= Number of random sample plots,
n_1= Number of primary (LiDAR) plots,

n_2= Number of secondary (ground) plots,
c_1= Cost of primary (LiDAR) plots,
c_2= Cost of secondary (ground) plots, and
ρ = Coefficient of determination
(Johnson 2000).

Changes in the relative cost of each plot type and coefficient of determination were examined to determine the impact on the cost effectiveness of double sampling. LiDAR plot costs were represented as a percentage of the ground plot costs to demonstrate how the number of each type of plot changed as relative costs changed. In order to determine the coefficient of determination and LiDAR plot cost that would be most cost effective, three coefficients of determination (0.5, 0.7, and 0.9) and LiDAR plot cost as a percentage of ground plot cost were examined. All calculations were based on a precision of ±10% at the 95% level of confidence. Total costs, based on the optimal plot allocation, were graphed to illustrate the break-even point between double sampling and single phase, conventional ground inventory for each coefficient of determination.

Results

The cost and sampling error for high and low posting densities were approximately \$16,200, 8.2% and approximately \$15,000, 7.6% respectively. Although the low density LiDAR data had a smaller sampling error, there was statistically no difference (α=0.05) between the sampling errors of the two posting densities. Because low density LiDAR data cost less to collect and are as accurate at predicting timber volumes as high density LiDAR data, it was the only posting density used for the break even analysis. The cost of high and low posting density LiDAR inventories exceeded the cost of a conventional ground inventory for 1,000, 10,000, and 100,000 acres, based on cost estimates obtained from the LiDAR provider (Table 1). The cost of completing the Lee Forest ground cruise was \$22/plot and was used for the per plot cost for the 1,000 acre hypothetical forest. Costs of \$31 and \$40/plot for the 10,000 and 100,000 acre hypothetical forest were used to account for additional travel time for a ±10% sampling error cruise at the 95% level of confidence.

Table 1. Total cost of two LiDAR posting density timber inventories and a conventional ground cruise providing a sampling error of ±10% @ the 95%level of confidence.

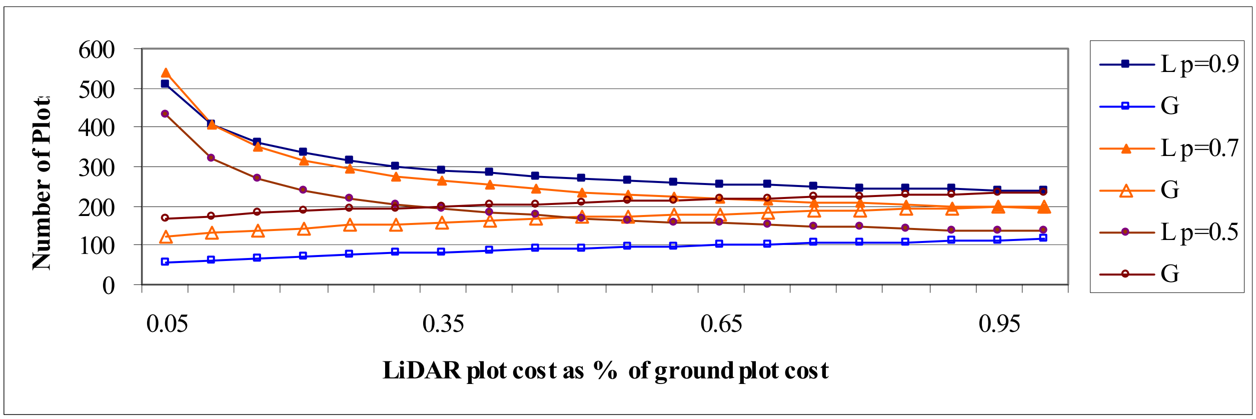
	Total Cost		
Acres	High Density	Low Density	Ground Cruise
1,000	\$15,149	\$15,049	\$4,202
10,000	\$18,424	\$17,424	\$6,107
100,000	\$40,834	\$30,834	\$7,920

Cost Comparison

A double sampling inventory approach using low density LiDAR data and ground plots was compared to the cost of a conventional ground cruise to determine the break even point as acreage changed. Low density LiDAR inventory cost approximately \$15,000 to collect and process compared to \$4,300 for a conventional inventory for the 1,200 acre study area. This indicated that using LiDAR for timber inventory was not cost effective for small tracts of land. For the Lee Forest, 195 random sample ground plots would be required to achieve the desired accuracy of ±10% (α=0.05), compared to the combination of 93 LiDAR and 304 ground plots for the double sampling. The plot allocation formula for double sampling required the cost of LiDAR plots be divided by the cost of ground plots and this combined with the coefficient of determination determined the percent of the initial random sample ground plots needed. Because the per plot cost of LiDAR plots was higher than the ground plot cost, the allocation formulas indicated that more ground plots were required than for a random sample ground cruise, demonstrating that double-sampling using LiDAR was not cost effective if LiDAR data were not already available. The marginal cost of extracting LiDAR data from an existing LiDAR data set is minor (Lefsky et al. 2002). Thus, double sampling using LiDAR may be cost effective.

The Lee Forest LiDAR data and ground plots had a coefficient of determination of 0.5. If this relationship, which determines the substitutability of LiDAR plots for ground plots, can be increased and/or the cost of obtaining LiDAR data decreased, LiDAR inventories may become cost effective. The combination of LiDAR and ground plots that minimizes cost for ±10% precision (α=0.05) cruise of 100,000 acres for each coefficient of determination as the percentage cost of LiDAR plots increases is shown in Figure 1.

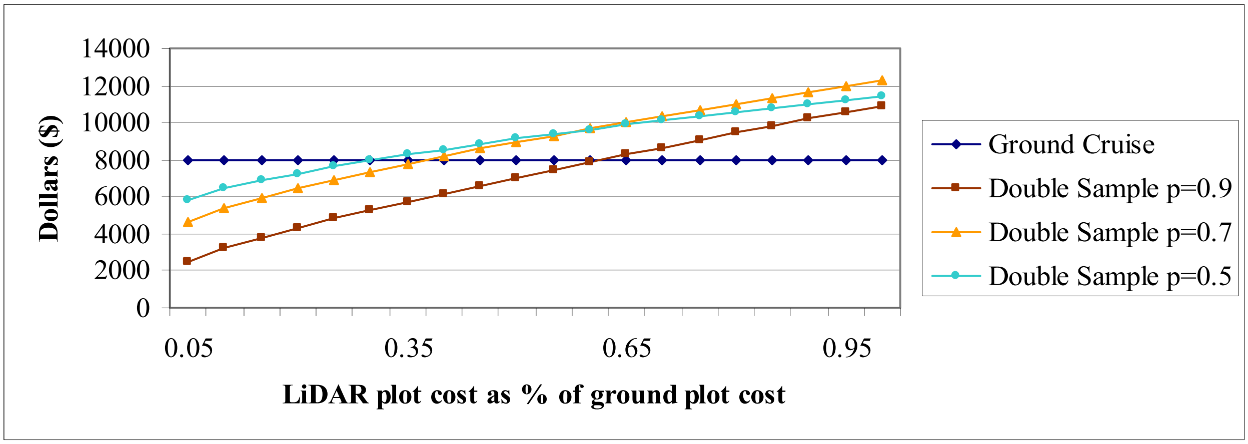
Figure 1. Allocation of LiDAR and ground plots that minimizes total inventory cost at ±10% precision at the 95% level of confidence for LiDAR (L) per plot costs expressed as a percentage of ground (G) plot costs for 100,000 acres, assuming CV%= 70 and ground plot size= 0.05 acres.



As the coefficient of determination increases, the number of ground plots required decreases and the number of LiDAR plots increases proportionately (Figure 1). As the cost of LiDAR plots approaches the cost of ground plots, the optimal number of LiDAR plots asymptotically decreases while the optimal number of ground plots increases slightly.

To illustrate the break even point for LiDAR, the total cost was graphed for three coefficients of determination levels and a range of relative costs. For a coefficient of determination equal to 0.5 (like that obtained on the Lee Forest), the break even cost of LiDAR plots was 30%. For coefficients of determination equal to 0.7 or 0.9, the breakeven cost for LiDAR was 35% and 61%, respectively, for a 100,000 acre tract.

Figure 2. Total cost of a double sampling LiDAR cruise and a fixed plot ground cruise for the three coefficients of determination and a range of relative plot costs for a 100,000 acre tract.



Discussion

Currently, timber inventory using LiDAR is not cost effective on most acreage due to the high fixed cost associated with data collection. For large, remote tracts with limited accessibility where the cost of conducting a ground cruise would be higher, LiDAR could be cost effective. As LiDAR plot costs fall below 35% of ground plot costs, double-sampling with LiDAR becomes cost effective for coefficient of determination 0.7 or greater. As the use of LiDAR for forestry and other applications increases, costs should decrease. This, combined with additional research applying LiDAR to timber inventory, may improve coefficients of determination between LiDAR and ground plots allowing LiDAR to become a cost effective inventory method. If LiDAR data are already in place or obtained for a Digital Elevation Model, wildlife habitat management, or other applications for which three-dimensional vegetation structure is required, the marginal cost of extracting plots from the data is very low (Lefsky et al. 2002). In this case, LiDAR plots can be used to increase precision or reduce total costs of a forest inventory.

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