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The shelf-life of airborne laser scanning data for enhancing forest inventory inferences

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ABSTRACT

The term *shelf-life* is used to characterize the elapsed time beyond which a commodity loses its usefulness. The term is most often used with reference to foods and medicines, but herein it is used to characterize the elapsed time beyond which airborne laser scanning (ALS) data are no longer useful for enhancing inferences for forest inventory population parameters. National forest inventories (NFI) have a long history of using remotely sensed auxiliary information to enhance inferences. Although the combination of model-assisted estimators and ALS auxiliary data has been demonstrated to be particularly useful for this purpose, the expense associated with the acquisition of the ALS data has been an argument against their operational use. However, the longer the shelf-life of ALS data, the less the continuing acquisition costs and the greater the utility of the data.

The objective of the study was to assess the shelf-life of ALS data for enhancing inferences in the form of confidence intervals for mean aboveground, live tree, stem biomass per unit area. Confidence intervals were constructed using both model-assisted estimators and post-stratified estimators, four measurements of mostly the same forest inventory plots at 5-year intervals over a 17-year period, and a single set of ALS data acquired near the end of the 17-year period. The study area in north central Minnesota in the USA was characterized by naturally regenerated, uneven-aged, mixed species stands on both lowland and upland sites. The primary conclusions were twofold. First, the shelf-life of ALS data when used with model-assisted estimators exceeded 10 years, and second, even for 12 years elapsed time between plot measurement and ALS data acquisition, the variance of the model-assisted estimator of the mean was smaller by a factor of at least 1.75 than the variance of the stratified estimator used by the national forest inventory.

1. Introduction

National forest inventories (NFI) have a long history of using remotely sensed auxiliary information to enhance inferences in the form of confidence intervals for forest inventory parameters. Bickford (1952, 1960) in the United States of America (USA) and Poso (1972) in Finland used interpreted aerial photography to construct strata in support of stratified estimators. More recently, satellite imagery has been used as the source of auxiliary information for this purpose (Poso et al., 1984, 1987; McRoberts et al., 2002, 2006; Nilsson et al., 2005; Gormanson et al., 2017). For categorical forest attributes variables such as forest/non-forest, stratified estimators are effective for increasing precision, but they are less effective for continuous attributes such as aboveground biomass. For the latter attributes, airborne laser scanning (ALS) data are more effective as a source of stratification information. However, ALS data are even more effective when used with model-assisted estimators (McRoberts et al., 2013).

Although ALS data are more effective than satellite spectral data when used with both stratified and model-assisted estimators, ALS data are also expensive to acquire, whereas MODIS, Landsat and Sentinel 2 satellite spectral data are available without charge. Some countries including Austria (Hollaus et al., 2009), Sweden (Nilsson et al., 2017), and the USA (Chen et al., 2016) have acquired large area, wall-to-wall ALS data with small pulse densities for purposes of constructing digital terrain models (DTM). Although these data have been demonstrated to be useful for constructing inventory inferences, their utility is perishable in the sense that the data become less effective as the time between the date of ALS data acquisition and the date of ground plot measurements increases. Further, because DTMs are constant, multiple similar ALS acquisitions for this purpose are unlikely.

The term *shelf-life* is used to characterize the time beyond which a commodity loses its usefulness. The term is most often used with reference to foods and medicines, but it is also relevant for characterizing the utility of ALS data. Although a commodity loses usefulness because

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of change in the commodity, ALS data lose usefulness because of change in the environment in which they are used. The important point is that if ALS data can be demonstrated to have a long shelf-life, considerable cost savings may be realized by extending the time between their acquisitions.

The objective of the study was to assess the shelf-life of ALS data for enhancing inferences in the form of confidence intervals for mean aboveground, live tree, stem biomass per unit area. Confidence intervals were constructed using model-assisted estimators, four measurements of mostly the same forest inventory plots at 5-year intervals over a 17-year period, and a single set of ALS data. For a study area in north central Minnesota in the USA, average plot measurement dates for the four datasets ranged from 12 years before to three years following the date of the ALS acquisition. For assessing the shelf-life of the ALS data, model-assisted estimates of means and standard errors were compared to operational NFI estimates obtained using stratified estimators and Landsat-based strata.

2. Data

2.1. Study area

The 7583-km^2 study area consisted of the entirety of Itasca County in north central Minnesota in the USA (Fig. 1) and is characterized as approximately 80% forest land. Land cover includes water, wetlands and forest consisting of uplands with deciduous mixtures of pines, (*Pinus* spp.), spruce (*Picea* spp.), and balsam fir (*Abies balsamea* (L.) Mill.) and lowlands with spruce (*Picea* spp.), tamarack (*Larix laricina* (Du Roi) K. Koch), white cedar (*Thuja occidentalis* (L.)), and black ash (*Fraxinus nigra* Marsh.). Forest stands in the study area are typically naturally regenerated, uneven-aged, and mixed species.

2.2. Airborne laser scanning data

Wall-to-wall ALS data were acquired in April 2012 with a nominal pulse density of 0.67 pulses/m^2 using laser scanners with pulse repetition frequency of approximately 100 kHz and wavelength of 1064 nm. The Tiffs (Toolbox for Lidar Data Filtering and Forest Studies) software was used to construct a digital terrain model using all pulse returns for all heights (Chen, 2007). For both the 168.3-m^2 plots and for the 169-m^2 square cells that tessellated the study area and served as population units, distributions of pulse return heights were constructed and used to calculate ALS metrics: mean (h_{mn}), standard deviation (h_{sd}), skewness (h_{sk}), kurtosis (h_{ku}), and quadratic mean height (h_{qm}) (Lefsky et al., 1999; Chen et al., 2012). In addition, standard height and canopy density percentiles were calculated as per (Gobakken and Næsset, 2008). In particular, heights corresponding to the 10th, 20th, …, 100th percentiles (h_{10}, h_{20}, …, h_{100}) of the distributions were calculated as were canopy densities expressed as the proportions of pulse returns with heights greater than 10%, …, 90%, 95% (d_{10}, …, d_{90}, d_{95}) of the range between a minimum ALS aboveground height threshold and the 95th height percentile.

2.3. Forest inventory data

Data were obtained for plots established by the Forest Inventory and Analysis (FIA) program of the U.S. Forest Service which conducts the NFI of the USA. The FIA program has established field plot centers in permanent locations using a systematic unaligned sampling design that is regarded as producing an equal probability sample (McRoberts et al., 2010). Each FIA plot consists of four 7.32-m (24-ft) radius circular subplots that are configured as a central subplot and three peripheral subplots with centers located at 36.58 m (120 ft) and azimuths of 0°, 120°, and 240° from the center of the central subplot. Field crews observe species and measure diameter at breast-height (dbh, 1.37 m, 4.5 ft) and height for all trees with dbh of at least 12.7 cm (5 in).

Subplot-level aboveground, live tree, stem biomass was predicted for individual measured trees using allometric models, aggregated at subplot level, scaled to a per unit area basis, designated AGB, and associated with ALS metrics for the subplot. Uncertainty associated with the allometric model predictions was ignored for this study. Data were used for only the central subplots of the 359 plots measured in 2014, 2015, and 2016 because these were the only subplots and years for which plot coordinates were obtained using survey grade GPS receivers

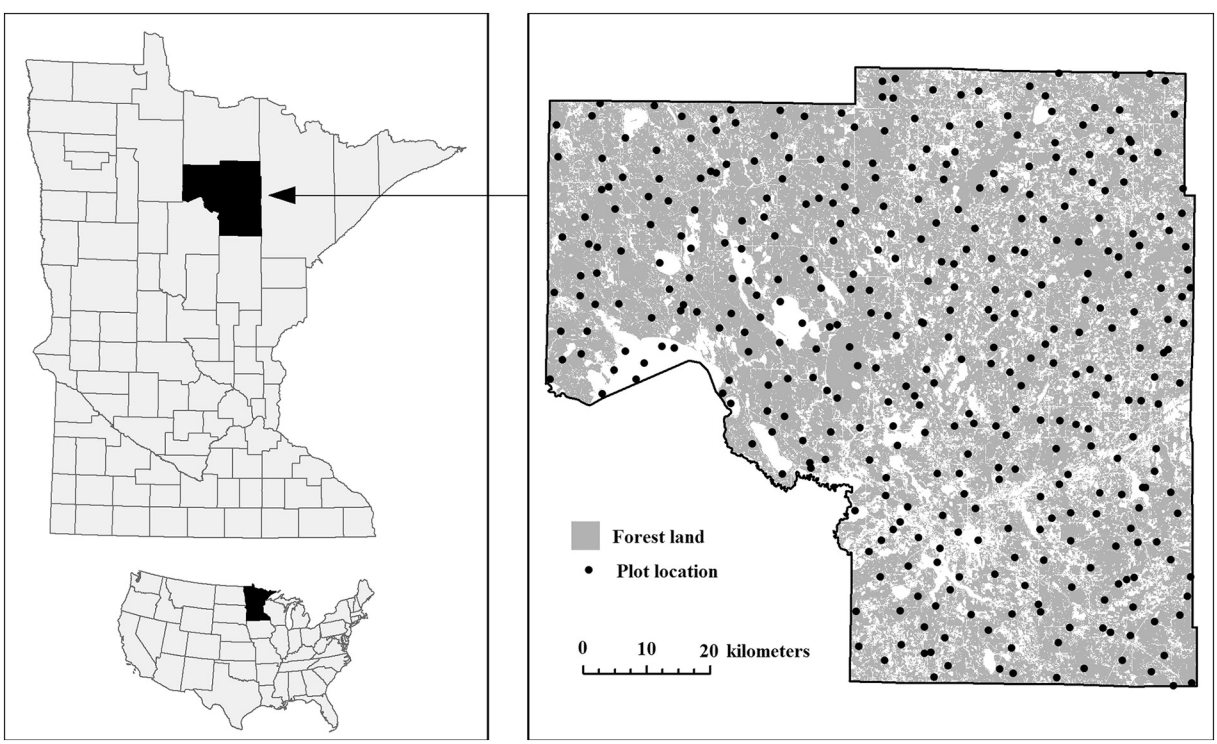

Fig. 1. Study area in Itasca County, Minnesota, USA.