Remote Sensing of Environment 176 (2016) 328–340

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Simulation-based assessment of sampling strategies for large-area biomass estimation using wall-to-wall and partial coverage airborne laser scanning surveys

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A R T I C L E I N F O

Article history:
Received 25 September 2013
Received in revised form 19 January 2016
Accepted 30 January 2016
Available online 20 February 2016

Keywords:
Airborne laser scanning
Forest inventory
Variance estimation
Simulated sampling

A B S T R A C T

Airborne laser scanning (ALS) has been demonstrated to be an excellent source of auxiliary information for increasing the precision of estimating stand-level attributes in forest inventories. It has also been proposed to use ALS for estimating biomass and carbon stocks under the United Nations Collaborative Program on Reduced Emissions from Deforestation and Forest Degradation in Developing Countries (UN-REDD). The benefits of REDD depend among other facts on the cost-efficiency of the carbon accounting systems, which should be economically feasible and highly accurate. Acquiring full-coverage ALS data would provide highly accurate estimates but might be too expensive for limited inventory budgets. As an alternative, the ALS data might be collected as a sample by acquiring data from a portion of the area of interest. However, in surveys involving complex multi-phase and multi-stage systematic sampling designs, the efficiency of ALS-based estimates is hampered by the ability of estimating the sampling variability correctly. It has been demonstrated recently that the precision of such complex analytical estimators may be largely underestimated. In order to make an informed decision, simulated sampling from artificial populations generated from empirical data may provide a means for assessing the cost-efficiency of various sampling strategies when analytical approaches fail. This study presents a simulation-based assessment of sampling strategies employing ALS with focus on large-area (27,400 km^2) biomass estimation. Simulated sampling mimicking the two contrasting cases “wall-to-wall” and two-phase ALS-aided surveys is exemplified using Norwegian National Forest Inventory data for creating an artificial population. The main results indicated that (1) the gain in precision (10%) when using “wall-to-wall” ALS data may not be worth the very high inventory costs, (2) using variance estimators based on higher-order successive differences produced correct confidence intervals for two-phase systematic sampling, and (3) two-phase ALS-aided systematic surveys are cost-efficient solutions for large-area biomass estimation.

1. Introduction

During the last decades, airborne laser, used either as profiling or scanning systems, has emerged as one of the most useful remote sensing techniques for predicting the vertical distribution of vegetation (Næsset, 2004a, 2004b, Næsset et al., 2004; Hyyppä et al., 2008; Hudak et al., 2009; Wulder et al., 2012). Due to its ability to estimate the three-dimensional forest canopy structure, which is closely related to biophysical properties like timber volume and biomass, airborne laser scanning (ALS) has been used operationally for district level (~50–2000 km^2) forest management inventories (Næsset, 2002; Næsset, 2004a, 2004b) for more than a decade in temperate and boreal forests (McRoberts et al., 2010). The high level of accuracy obtained by using auxiliary variables (i.e., “*any variable about which information is available prior to sampling*”, Särndal et al., 1992, p. 219) provided by profiling and scanning lasers for biomass and carbon stock estimation in temperate and boreal forests has been also confirmed (Nelson et al., 2003; Nelson et al., 2012; Patenaude et al., 2005; Næsset & Gobakken, 2008; Andersen et al., 2009, 2011; Næsset, 2011; Stephens et al., 2012), and recently New Zealand combined ground and ALS data for country-wide estimation of carbon stocks of planted forests for reporting under the Kyoto Protocol (Beets et al., 2010, 2012; Stephens et al., 2012).

In tropical regions, promising results for estimating forest biomass using ground and ALS data have been reported (Nelson, 1997; Nelson et al., 1997; Weishampel et al., 2000; Lefsky et al., 2002; Drake et al., 2002; Drake et al., 2003; Clark, Clark, & Roberts, 2004; Lefsky et al., 2005; Dubayah et al., 2010, Asner, 2009, Asner et al., 2010, Mascaro et al., 2011, Asner et al., 2013), even in the presence of higher biomass densities (e.g., >200 Mg ha^{-1}), where visible/near-infrared vegetation indices and backscattered radar measurements saturate (Castro et al., 2003; Lu, 2006; Mitchard et al., 2009, Saatchi et al., 2011; Askne et al., 2013).

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http://dx.doi.org/10.1016/j.rse.2016.01.025
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These developments have triggered the interest of using especially scanning lasers for estimating carbon stocks under the United Nations Collaborative Program on Reduced Emissions from Deforestation and Forest Degradation in Developing Countries (UN-REDD) (http://www.un-redd.org). The potential of using the auxiliary information provided by ALS for REDD monitoring has been emphasized (Angelsen, 2008; Gibbs et al., 2007, Næsset et al., 2013), and a REDD monitoring approach combining ground based aboveground carbon density estimates, ALS metrics and other remote sensing data was considered by Asner (2009). Recent developments suggest using a general plot-aggregate allometry combining a stable ALS metric and plot estimates of basal area and basal area weighted wood density for tropical forest carbon stocks estimation (Asner & Mascaro, 2014).

Currently, the "wall-to-wall" acquisition and processing costs for ALS data are high compared to other types of remote sensing data, like, for example, Interferometric Synthetic Aperture Radar (InSAR) (Gama, dos Santos, & Mura, 2010; Solberg et al., 2010ab; Næsset et al., 2011). Although airborne interferometric canopy heights derived from X/P-band radar show promising results for biomass estimation (Neeff et al., 2005, Sambatti et al., 2012), forest attributes estimation (including AGB) using ALS measurements are still considered more accurate compared to fusing of remotely sensing data provided by other active/passive sensors (Zolkos et al., 2013, Saarela et al., 2015). Thus, for surveys covering very large areas like counties and states, countries, and sub-continents, acquiring "wall-to-wall" coverage with ALS data may easily become economically unfeasible (Næsset et al., 2009, Mitchard et al., 2012). As an alternative, sampling approaches using profiling laser from airborne or spaceborne platforms have been tested in various forest conditions. For instance, large area forest inventories were using auxiliary information provided by profiling laser systems (Nelson et al., 2003, 2012; Nelson et al., 2004; Nelson et al., 2008) used either alone or in combinations with spaceborne laser auxiliary data (Boudreau et al., 2008; Nelson et al., 2009a), as well as sampling applications based solely on spaceborne laser (Helmer et al., 2009; Nelson et al., 2009b; Lefsky, 2010). However, according to our knowledge, there is currently no operational spaceborne laser in orbit, and the next space mission (ICESat-2; employing the multi-beam, photon-counting laser) is scheduled for launch in 2016 (Nelson, 2010; Durrieu & Nelson, 2011; Anon, 2013). Two-phase and two-stage sampling for forest inventory applications using ALS auxiliary information has also been investigated (Parker & Evans, 2004, 2007; Andersen et al., 2009; Gregoire et al., 2011; Ståhl et al., 2011; Gobakken et al., 2012; Næsset et al., 2013).

The results indicated that ALS-aided sampling strategies (the combination of sample selection method and estimator, Särndal et al., 1992, p. 31) might in some cases be less precise compared to conventional field-based surveys when using an otherwise equal number of field observations to support the estimation, which is a somewhat surprising result (Næsset et al., 2013).

Complex inventories combining ALS measurements and terrestrial surveys often involve a systematic selection of the sampling units, making difficult to follow statistically rigorous uncertainty estimation. In such situations, the inference has to rely on simplifying assumptions. For instance, in the absence of design-unbiased variance estimators for systematic sampling, it is often to infer based on the assumption of having used simple random sampling. When performing systematic sampling from an ordered population (i.e., manifesting spatial trends) it is expected to obtain low variability between all possible samples. In other words, most of the population variability is captured within the systematic samples due to the regular coverage with sample units ensured by the systematic design. Under such circumstances, the overestimation of sampling variability is expected to occur when using variance estimators assuming simple random sampling, and the magnitude of this overestimation will never be known in a real application.

When complex designs are used, simulated sampling from an artificial population offers the possibility to test to what extent violating the assumptions an estimator is built upon (i.e., the requirement of independence, Särndal et al., 1992, Section 4.3.1) would influence the statistical inference on population parameters. Recent results presented by Ene et al. (2012a, 2013) indicated that ignoring these violations may cancel the advantages of using ALS as source of auxiliary data in complex inventories, as the sampling variability may be heavily overestimated.

This result has direct implications for further development of statistically rigorous inventory protocols and estimation procedures for REDD monitoring incorporating ALS auxiliary information. Estimating the uncertainties of the biomass estimates must be properly addressed using cost-efficient inventories, which would provide reliable estimates in accordance to Intergovernmental Panel on Climate Change (IPCC) principles at feasible costs such that the benefits of the REDD systems would not be diminished (Köhl et al., 2011).

When compared to the field-based sample surveys, the sampling simulation results (Ene et al., 2013) indicated that combining ALS data acquired along strips (limited element auxiliaries; Särndal et al., 1992, p. 305) with field observations would be a cost-efficient solution for large-area biomass inventories by although finding the best approach for estimating the sampling variability still remains a challenge.

Despite of even higher costs, the precision provided when using "wall-to-wall" ALS data is expected to be very high, which suggests this approach as an ideal benchmark for testing alternative sampling designs and estimation methods. Design-based inference utilizing "wall-to-wall" ALS data for forest stand volume and biomass has been addressed previously by Corona and Fattorini (2008), Næsset et al. (2011), and McRoberts et al., (2013). They reported reductions of the sampling error of a magnitude of 30–45% compared to direct estimation based solely on the field sample. However, to the very best of our knowledge, no direct comparison of precision and cost-efficiency of ALS surveys with complete and partial coverage based on the same population has so far been conducted.

Thus, the aim of this study was twofold: (1) to assess the estimation efficiency of selected design-based sampling strategies using complete and partial coverage with ALS data, and (2) to perform a cost-efficiency analysis for each of these cases. The assessments follow the approach described in Ene et al. (2012a, 2013).

2. Material

The applied datasets were acquired from Hedmark County (HC) located in south eastern Norway (Fig. 1), having a land area of 27,400 km^2 and a heterogeneous composition with regard to forest types and geomorphology. The main tree species present in HC are Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.). The material consists of field inventory data and auxiliary information (remote sensing data and digital cartographical products). For a detailed presentation of the datasets see Ene et al. (2012a, 2013) and Gobakken et al. (2012).

2.1. Field data

The field observations were provided by the Norwegian National Forest Inventory (NFI; Tomter et al., 2010), which is established as a continuous inventory system where the sampling units consist of fixed-area circular plots of 250 m^2 located on a 3×3 km grid covering the entire country, except for the areas above the coniferous tree line (>850 m above sea level) where the grid spacing is 3×9 km. The dataset from HC used for this study comprised field observations acquired on 662 plots. These were permanent NFI plots and additional plots located purposefully on the NFI sampling grid to increase sample size in developed and mountain areas in particular. All plots were used for generating an artificial population and assessing the form of the predictive biomass model, while only the plots from the probabilistic NFI sample were used for estimation (see further details below). The