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Use of partial-coverage UAV data in sampling for large scale forest inventories

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ABSTRACT

The use of image-based three-dimensional data from unmanned aerial vehicles (UAV) has proven effective for forest inventories. However, limitations in the range of UAV operations hinder their use in large scale applications. Use of partial-coverage UAV data in combination with field plots may increase precision of field-based estimates of forest resource parameters and may offer a cost-effective alternative to wall-to-wall acquisition. In this study, data from UAV collected in systematically distributed blocks and combined with field plots in a two-phase design with hybrid inference (UAV_{HYB}) were used to estimate mean volume and its precision (standard error) for a 7330 ha forest area in Norway. Because in UAV_{HYB} the field data do not necessarily need to come from a probability sample, the approach offers great flexibility in field data collection. The estimate of precision using UAV_{HYB} was compared to two alternative inventory approaches differing in terms of sampling design and mode of inference, i.e., (1) single-phase probabilistic sampling relying only on field samples for which the design-based approach to inference using simple random sampling estimators was adopted ($FIELD_{DB}$) and (2) a model-based approach independent from design assumptions for which wall-to-wall airborne laser scanning data were applied (ALS_{MB}). Relative efficiency (RE), calculated as the ratio between the estimated variances of two different inventory approaches, was used as measure for improvement in variance for one approach over the other. Comparison of UAV_{HYB} against $FIELD_{DB}$ revealed that the use of the former was up to four times more efficient than the latter ($RE = 4.4$). This translates to a need for 4.4 times as many field plots under simple random sampling for a $FIELD_{DB}$ estimate to be equally precise as the UAV_{HYB} estimate. For ALS_{MB} the increase in efficiency compared to UAV_{HYB} was limited ($RE = 1.6$). The study also demonstrated that the precision under UAV_{HYB} can be improved when including additional field data from other inventories to enhance the model. Cost estimates for each inventory approach were compared, revealing that UAV may be a cost-effective tool for large scale forest resource assessments.

1. Introduction

1.1. Background

Recent research efforts have shown that three-dimensional (3D) data generated from imagery collected using unmanned aerial vehicles (UAV), a combination of structure from motion and photogrammetric algorithms, is a viable data source to support forest inventories (Dandois and Ellis, 2013; Lisein et al., 2013; Puliti et al., 2015). The use of UAVs offers new opportunities for monitoring forest resources at high spatial and temporal resolution. Nevertheless, their use for forest inventory is hindered by the high costs of acquiring UAV data with full coverage (wall-to-wall) of areas larger than, say, 10 km^2 (Dandois and Ellis, 2013; Whitehead et al., 2014). However, UAVs may still be a cost-effective alternative for certain forest inventory applications. Multi-stage and multi-phase sampling applications with partial coverage of auxiliary data from remote sensing (RS) may be one such niche of applications. In recent years, partial-coverage airborne laser scanning (ALS) data, have been used in numerous studies of large scale forest inventories to improve the precision of pure field based-estimates (McRoberts et al., 2014a). Such applications have mainly applied using ALS data collected as samples (strips) with the objective of reducing the costs of ALS data acquisition while minimizing the reductions in the uncertainty of the estimates compared to a wall-to-wall coverage (McRoberts et al., 2014a). Acquisition of partial-coverage UAV data for large scale estimation of forest resources can represent an effective application of UAV to support forest inventories.

All previous studies using UAV data for forest inventory purposes (Dandois and Ellis, 2013; Lisein et al., 2013; Puliti et al., 2015) opted for wall-to-wall UAV data on small areas (1–200 ha) to provide information for forest management. Their results have been encouraging for further development of applications using UAV to map and estimate

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forest resources. In addition to reporting a high correlation between the 3D auxiliary data derived from UAV imagery and forest biophysical properties, these early experiences highlighted several advantages of UAV compared to conventional RS data acquisition platforms, like, for instance (1) wide availability of the technology, (2) very high spatial resolution, (3) cloud insensitivity, and (4) repeatability of the measurements. The availability of a variety of UAVs on the market at reasonable prices enables a wide range of actors (e.g. small private companies, NGOs, research institutions) to carry out forest UAV surveys. Puliti et al. (2015) found that the overall workflow of a forest inventory adopting UAV data was characterized by a great degree of project customization, planning flexibility, and rapidity of data delivery. Additionally, Puliti et al. (2015) noted that due to the low flight altitude used to acquire UAV data, these systems are less sensitive to cloud cover and can therefore represent a valid alternative to traditional RS data sources in areas with frequent cloud cover. Finally, as previously demonstrated (Jaakkola et al., 2010; Dandois et al., 2015), an important advantage of UAV is the repeatability of the measurements across time. By increasing the temporal resolution, UAVs offer unique opportunities for monitoring changes in forests resources over time (Whitehead et al., 2014) as required by for example international carbon reporting schemes (e.g. REDD+; Reducing Emissions from Deforestation and Forest Degradation in Developing Countries).

As already mentioned, the most serious limitation to the practical use of UAVs in forestry is the difficulty of covering forests fully on a large scale. One of the main constraints is national aviation regulations. Regardless of the large differences among national legislations, current aviation regulations in general play a main role in defining the area-range for which UAVs can be operated and the size of the aircrafts used. The requirement of conducing UAV operations within a visual line of sight (VLOS) often limits the area that can be covered by each flight as the UAV must be visible at all times with the naked eye. As an example, in Norway the VLOS is defined by a maximum flight altitude of 125 m above ground level and to a maximum horizontal distance from the UAV operator of 600 m. Flight altitude limitations can vary substantially between countries and an increase in area coverage is expected when operating at higher altitudes. Limitations of the allowable weights of UAVs also indirectly affect the range of operation of these systems by hindering the use of large, heavy, and long-lasting batteries. It is important to mention that modifications to the current UAV regulatory frameworks are strictly related to the development of technologies to ensure safe operations (Floreano and Wood, 2015).

Given the mentioned limitations and in order to benefit from the use of UAVs in operational forest inventories, it would be useful to identify the niches that UAVs may fill by providing superior performance in terms of costs and precision of resource estimates compared to alternative technologies. One potentially interesting application for which UAVs may offer advantages, is large scale inventory where extensive field data collection can be costly or where field locations can be inaccessible, and where the use of RS to complement the field sampling is advisable. Yet, UAVs cannot provide wall-to-wall data on such large scale in a cost-effective manner, but UAVs used as part of a sampling strategy over large landscapes (i.e., partial cover) is indeed a viable option.

To clearly understand how UAVs can be used as sampling tools in large scale inventories, it is crucial to clarify some of the main underlying statistical frameworks enabling such application. For this purpose, the following sub-chapters introduce the inferential frameworks applied.

1.2. Design-based inference

Large scale forest inventories aiming at estimating total or mean values for variables of interest (e.g. volume or biomass) and their uncertainty have traditionally been carried out in a design-based (DB) sampling framework. Such a framework requires a probability sample of field plots distributed in the study area when the intention is to provide estimates of the population parameters under DB inference. Under DB, the reliability of the estimation is based on the probabilistic nature of the sampling design (McRoberts, 2010). DB approaches have been widely applied because the estimators are familiar, generally unbiased, and their estimation is not computationally intensive. Nevertheless, with small sample sizes the precision of the DB estimates can be insufficient for many uses of the estimates. Additionally, the strict requirements for DB approaches may limit the applicability in cases where probability samples are not available. In the current study, the DB approach was applied only to characterize the uncertainty of pure field-based estimates, although DB inference also may draw on auxiliary RS data, such as ALS data (Gregoire et al., 2011), to enhance precision of estimates.

1.3. Model-based inference

Because RS technologies can be used to provide wall-to-wall auxiliary data for the entire population subject to analysis, RS data have been used extensively to assist large scale forest inventories – even when there is no probability sample of ground plots at hand, by adopting the model-based (MB) framework. In MB, auxiliary RS data are used to develop models linking field plots to variables extracted from the RS data. The constructed models are subsequently used to predict the variable of interest across the entire study area. These predictions are then used to estimate the population parameters. The variance of the point estimates under MB inference is usually quantified in terms of uncertainty associated with the model parameters estimates, at least in large scale applications (Ståhl et al., 2016). For smaller areas, other sources of uncertainty associated with the use of a model for prediction may need to be accounted for (Breidenbach and Astrup, 2012). A potential disadvantage in MB inference is that unbiasness of the estimator relies on a correctly specified model, which sometimes can be hard to justify – and especially if the sample used to obtain the model is not a probability sample or the model is developed from data external to the area under analysis (Särndal et al., 1992, p. 411). Nevertheless, MB inference has the advantage over DB of producing maps that are consistent with the estimates (McRoberts, 2010) and often more precise estimates, especially when sample sizes are small. Additionally, since the field sample for MB is used only to obtain a model that is suitable for the population of interest, the field plots can be selected using non-probabilistic sampling or even by including external data collected outside of the study area, but it is important for reasons given above that measures are taken to assure – as far as is possible – that the model is correctly specified (McRoberts et al., 2014b). In the current study, MB inference was adopted for estimation when a wall-to-wall dataset of auxiliary ALS data was available.

1.4. Hybrid inference

Sometimes acquisition of wall-to-wall RS auxiliary data can be prohibitively costly for large scale inventories. That can often be the case for ALS. An alternative could be to collect the auxiliary data as a sample of the entire study area. Such samples may be acquired according to probabilistic principles. The recent increased need for reliable, robust, and repeatable estimates of forest resources at regional to national scales (Andersen et al., 2011; Gobakken et al., 2012) has led to the development of multi-phase and multi-stage sampling approaches based on samples of RS data combined with samples of field data. Most of the studies published over the past five years have relied on two-phase designs. In a first-phase, partial-coverage ALS data are acquired according to probabilistic sampling designs along individual ALS strips. In the second phase, a sample of field plots is collected according to probabilistic principles within the ALS strips or opportunistically in areas where both ALS and field data are available. The second-phase sample is typically used to develop a regression model that relates the