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Combining UAV and Sentinel-2 auxiliary data for forest growing stock volume estimation through hierarchical model-based inference

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A B S T R A C T

Remotely sensed (RS) data are becoming increasingly important as sources of auxiliary information in forest resource assessments. Data from several satellites providing moderate image resolution are freely available (e.g. Sentinel-2). In addition, very-high-resolution three-dimensional data are available due to the advent of unmanned aerial vehicles (UAV). The increasing availability of auxiliary data offers new opportunities for large-scale forest surveys using UAVs. A recently developed hierarchical model-based mode of inference makes it possible to use hierarchically nested auxiliary data in estimating population properties, such as total or mean biomass or volume, and their corresponding uncertainties in a statistically appropriate manner. In this study, hierarchical model-based inference was used to estimate growing stock volume (GSV; $m^3\ ha^{-1}$) and its variance using a small sample of field data, a larger sample of UAV data, and wall-to-wall Sentinel-2 data in a study area in SE Norway. The main objective of the study was to compare the performance, in terms of precision, of hierarchical model-based inference (denoted Case C) against two alternative cases. These were (1) model-based inference based on field data and wall-to-wall data, collected either with airborne laser scanning (Case A.1) or Sentinel-2 data (Case A.2), and (2) hybrid inference using a small sample of field data and a larger sample of UAV data (Case B). A second objective was to assess the possibility of reducing the UAV sampling intensity when adopting Case C rather than B, without decreasing the precision of the GSV estimates. The results, calculated as standard error as percentage of the mean ($\widehat{SE}_{\%}$), indicated that in case C the precision was of similar magnitude ($\widehat{SE}_{\%}$ = 3.44%) as for Case A.1 ($\widehat{SE}_{\%}$ = 3.69%) and for Case B ($\widehat{SE}_{\%}$ = 3.58%). The standard error of Case A.2 was nearly twice as large ($\widehat{SE}_{\%}$ = 5.81%) as the rest of the cases. The results also indicated possibilities of reducing the UAV sampling intensity without losing precision in cases where wall-to-wall Sentinel-2 data are available (Case C). The same precision for Case C with only five UAV samples was achieved as for Case B with 55 UAV samples. Thus, the study highlights the cost-efficiency of applications of UAV as in Case C and also provides first insights in the use of Sentinel-2 data for GSV estimation in boreal conditions.

1. Introduction

1.1. Background

Unmanned aerial vehicles (UAVs) have been proposed as an innovative and accessible tool to support the acquisition of three dimensional (3D) remotely sensed (RS) data for forest management inventories (e.g, Dandois and Ellis, 2013; Lisein et al., 2013; Puliti et al., 2015) and for large-scale forest surveys (Puliti et al., 2017). UAV data have proven to provide detailed information on forest structures, yet their application is hampered by cost limitations when mapping large forest areas. In recent years, the availability of global coverage of RS auxiliary data has also increased rapidly, offering unique opportunities for the production of large-scale forest resource estimates and maps. Nowadays, several satellite missions exist, providing freely available imagery (i.e., Landsat 8 and Sentinel-2). However, due to the moderate resolution of these satellite products (i.e., 10–30 m) and limited correlation of spectral variables with forest structural properties, the direct use of satellite imagery in forest inventories might not be compliant with the uncertainty prerequisites of current reporting schemes (e.g., REDD +; Reducing Emissions from Deforestation and Forest Degradation in Developing Countries; UNFCC, 2010). In parallel to the increased availability of auxiliary RS data, there have been major advances in developing statistical frameworks to ensure a rigorous uncertainty assessment when increasing the sources of auxiliaries in the estimation (Gregoire et al., 2016). A relevant example is the study by

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Saarela et al. (2016), who developed estimators enabling the use of two levels of hierarchically nested RS auxiliary data. Applying this method, the combination of UAV data with satellite imagery might lead to an increase of the precision of estimators of key forest properties and also enable the production of maps. This approach may therefore benefit from the high resolution UAV data and from the large coverage of satellite imageries and, potentially, offer a cost-effective alternative to existing methods for large-area forest surveys.

1.2. UAVs in forest inventory

The use of UAVs in forest inventories has gained attention in recent years because these RS data acquisition platforms allow a large number of users to capture very detailed information on the 3D structure of forest canopy. For example, the point clouds generated from photogrammetric processing of UAV imagery were proven to produce very high quality results even when compared to state-of-the-art RS data sources like airborne laser scanning (ALS) (Wallace et al., 2016; Puliti et al., 2017). To date, most applications of UAVs to derive 3D data in forest inventories have been based on optical imagery, but application of UAV-borne lasers is also a potentially intesting, but less explored, alternative.

The use of UAVs to acquire full-coverage data is costly for large-scale forest (i.e., area > 1000 ha) inventories and for this reason, Puliti et al. (2017) proposed a method using UAV data as part of a sampling strategy for large-scale forest inventory (i.e., area = 7330 ha). Their approach resulted in an increase in precision of field based estimates while not incurring in prohibitive costs of UAV wall-to-wall data acquisition. However, the method proposed by Puliti et al. (2017) can only be used to produce point estimates over a defined area of interest and not a continuous map of forest resources. The production of maps to support decision making and for local accounting of forest resources (McRoberts, 2010) is, however, a desired property of RS based forest inventories.

1.3. Sentinel-2

The need to further assess the contribution of regional/local forest ecosystems to the global carbon cycle has been one of the motivation behind the development of earth observation missions (e.g., Landsat, SPOT, Sentinel-2) devoted to providing users with free RS optical multispectral data acquired at regular intervals in time. The newly operational Sentinel-2 multispectral mission represents one of the most innovative and promising thus far, as it is the first to offer an unpreceded combination of high spectral, spatial, and temporal resolution (Drusch et al., 2012). Given the large focus of the Sentinel-2 mission on vegetation classification and forest monitoring, a key factor in designing the multispectral instrument (MSI) was the spectral resolution in the red-edge region of the spectrum. The result was the incorporation of three narrow bands (15–20 nm wide) centered at 705, 740, and 783 nm, in the red-edge region of the spectrum characterized by a high correlation with vegetation biophysical properties like chlorophyll content and leaf area index (Danson and Plummer, 1995; Delegido et al., 2011; Clevers and Gitelson, 2013). In addition to the spectral component, the increased spatial resolution of Sentinel-2 (10–20 m for the bands of interest for vegetation mapping) offers an increased level of detail compared to Landsat data (30 m resolution), which could contribute to improve the correlation between growing stock volume (GSV) and RS data. The frequent revisit time planned for the Sentinel-2 mission (3–5 days) also presents new opportunities to obtain cloud free imagery at regular intervals and to make use of dense time series of imagery. Previous experiences using Landsat data revealed that moderate resolution satellite optical data can be used for precise estimation and mapping of forest area (McRoberts, 2006). However, the drawback of multispectral satellite imagery is the difficulty of describing forest biophysical properties characterized by a strong vertical component like tree height or growing stock volume (Næsset et al., 2016; Saarela et al., 2016).

Sentinel-2 data have been available since June 2015 and to the very best of our knowledge such data have to date been used in only one forestry related study on tree species classification (Immitzer et al., 2016) and there are no experiences so far on estimation of GSV. In this study, Sentinel-2 data were used as they are expected to represent an important data source for future forest monitoring schemes. It is therefore highly relevant to understand the level of uncertainty that can be expected when using Sentinel-2 to enhance the estimation.

1.4. Combining multiple levels of RS auxiliary

Traditionally, RS based forest inventories have relied upon models linking field plot information with RS data. The estimation in these cases has often been done in a model-based framework (Ståhl et al., 2016), where the precision of the estimators is based on the uncertainty of the model parameter estimates (Gregoire, 1998; McRoberts, 2006, 2010). With the increased availability of RS auxiliary data, there is an increased need for rigorous statistical frameworks that enable a clear reporting of the uncertainty of the estimators (Gregoire et al., 2016). Due to the large costs of acquiring expensive RS auxiliary data (i.e., ALS or UAV data) over large areas, statistical frameworks that enable the use of two-phase or two-stage sampling designs have recently been developed (Gregoire et al., 2011; Ståhl et al., 2011; Ringvall et al., 2016). Ståhl et al. (2011) proposed an inferential framework drawing partly on design-based inference and partly on model-based inference, which has later been referred to as hybrid inference, a notion introduced by Corona et al. (2014). With hybrid inference, a probabilistic sample of RS data is acquired (first phase) and then a second sample of field plots (second phase) is acquired where RS data are also available. The hybrid variance estimator includes two sources of uncertainty, namely: (1) the sampling error in the first phase and (2) the uncertainty due to model parameter estimates.

In response to the wide availability of RS data from various sources, there have been increased efforts to combine multiple RS data types at different resolution for increasing the precision of estimators in large-area forest surveys. Some of the first examples of the use of multiple RS data in forest inventories used space-borne lidar samples in combination with samples of ALS and field plots (Boudreau et al., 2008; Nelson et al., 2009; Neigh et al., 2013; Margolis et al., 2015; Nelson et al., 2016). All these studies relied on a nested structure of the models linking biomass with ALS data and then ALS predicted above ground biomass or carbon with space-borne Lidar, but they admitted that they estimated the variance by accounting only for uncertainty associated with the second model. However, given the increase in complexity due to the nested structure of the models, it is crucial to account for every source of uncertainty in the estimation. A recent study by Saarela et al. (2016) aimed at filling this gap by developing hierarchical model-based estimators to estimate GSV and its uncertainty when using a combination of field, ALS, and Landsat data. The merit of the work by Saarela et al. (2016) lies in the development of variance estimators accounting for the uncertainties of all the models linking the different levels of information. In their work, Saarela et al. (2016) demonstrated that ignoring the uncertainty related to the field-to-RS model can lead to an underestimation of the variance by approximately 70%. Overall, the hierarchical model-based estimators also proved to be more precise than an hybrid estimator. In light of these results, the proposed inferential approach opens up many opportunities to develop new techniques for large-scale forest surveys using multiple RS data sources.

When using UAVs as part of sampling strategies (e.g., Puliti et al., 2017) the estimators by Saarela et al. (2016) do offer opportunities for augmenting samples of UAV data with wall-to-wall satellite imagery (i.e. Sentinel-2). Such an approach could increase the precision of the estimates at no additional cost. Additionally, the availability of wall-to-wall coverage of RS auxiliary data enables the production of continuous