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Individual tree crown approach for predicting site index in boreal forests using airborne laser scanning and hyperspectral data

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ABSTRACT

Site productivity is essential information for sustainable forest management and site index (SI) is the most common quantitative measure of it. The SI is usually determined for individual tree species based on tree height and the age of the 100 largest trees per hectare according to stem diameter. The present study aimed to demonstrate and validate a methodology for the determination of SI using remotely sensed data, in particular fused airborne laser scanning (ALS) and airborne hyperspectral data in a forest site in Norway. The applied approach was based on individual tree crown (ITC) delineation: tree species, tree height, diameter at breast height (DBH), and age were modelled and predicted at ITC level using 10-fold cross validation. Four dominant ITCs per 400 m^2 plot were selected as input to predict SI at plot level for Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.). We applied an experimental setup with different subsets of dominant ITCs with different combinations of attributes (predicted or field-derived) for SI predictions. The results revealed that the selection of the dominant ITCs based on the largest DBH independent of tree species, predicted the SI with similar accuracy as ITCs matched with field-derived dominant trees (RMSE: 27.6% vs 23.3%). The SI accuracies were at the same level when dominant species were determined from the remotely sensed or field data (RMSE: 27.6% vs 27.8%). However, when the predicted tree age was used the SI accuracy decreased compared to field-derived age (RMSE: 27.6% vs 7.6%). In general, SI was overpredicted for both tree species in the mature forest, while there was an underprediction in the young forest. In conclusion, the proposed approach for SI determination based on ITC delineation and a combination of ALS and hyperspectral data is an efficient and stable procedure, which has the potential to predict SI in forest areas at various spatial scales and additionally to improve existing SI maps in Norway.

1. Introduction

Forest site productivity is the potential of a particular forest stand to produce aboveground wood volume (Skovsgaard and Vanclay, 2008). Information on forest site productivity is an important prerequisite for a wide range of forestry applications. Reliable site productivity measures are essential for sustainable forest management in order to estimate yields and carbon stock of forest stands to ensure a sustainable supply of timber products, and to formulate silvicultural strategies (Coops, 2015; Eid and Økseter, 1999; Splechtna, 2001). The most common quantitative measure and widely accepted method of forest site productivity characterization is site index (SI) (Skovsgaard and Vanclay, 2008). The SI of a forest stand is defined as expected height of the trees at a given base age (e.g. 40 years) for certain tree species (Skovsgaard and Vanclay, 2008). Commonly, the dendrocentric approaches for the SI determination are based on the measurements, in each forest stand, of the height and age of the largest dominant trees, in terms of diameter or height, which refer to upper social classes (Skovsgaard and Vanclay, 2008). These measurements are then averaged, usually for the 100 largest trees per hectare and referred as dominant height and age, which subsequently are used as input to calculate the SI. The dominant height of a stand reflects the productivity of a fully stocked even-aged stand as it is independent from the stem density, and it is least affected by thinning (Skovsgaard and Vanclay, 2008). However, the site productivity can also be determined with geocentric approaches based on site properties, such as edaphic (soil properties), topography

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(altitude, slope, aspect, and landform) and climate parameters (precipitation and temperature) (Clutter et al., 1983; Nothdurft et al., 2012; Paulo et al., 2014; Sharma et al., 2012), which were not considered in the current study.

Biophysical attributes such as tree species, tree height, stem diameter, and tree age are crucial for assessing the SI. In practice, the SI calculations are often based on field surveys or photo interpretations using aerial imagery. Such collection of data is expensive, time consuming, and logistically difficult (Eid et al., 2004). Furthermore, the SI changes over time due to various factors, such as atmospheric deposition of nitrogen and other nutrients, climatic changes, etc. (Boisvenue and Running, 2006; Messaoud and Chen, 2011; Sharma et al., 2011). Thus, affordable methods to retrieve the SI of a specific site and at a specific time is required.

Remote sensing technologies, such as aerial photography, airborne laser scanning (ALS), spaceborne or airborne multispectral and hyperspectral images enable observation of forest areas at different temporal and geographical scales (Coops et al., 2004; Yu et al., 2015; Zhao et al., 2011). Many studies have reported that ALS-predicted biophysical attributes may increase the accuracy of SI determination (Chen and Zhu, 2012; Holopainen et al., 2010; Tompalski et al., 2015a). In general, there are two prominent remotely sensed-based approaches to assess biophysical attributes for management purposes: area-based approach (ABA) (Næsset, 2002) and individual tree crown (ITC) approach (Hyyppä et al., 2001). In ABA, biophysical attributes are predicted for each plot or element (e.g. grid cell) of a population with the size of each element being equal to the area of the plots from which the predictive relationships are derived, while in ITC approaches biophysical attributes are determined for each detected tree, i.e. ITC level determination. In both ABA and ITC approaches, attributes can be predicted using parametric or non-parametric methods.

Previous studies on an automated determination of SI assisted by remotely sensed data are few in numbers. Véga et al. (2009) generated SI and age maps based on ABA using historical aerial photographs, and ALS data. In this study, spaceborne multispectral imagery data were used to classify Jack pine trees and to extract stand boundaries. Subsequently, average dominant height was predicted from photogrammetric point clouds, and age-height models were fitted to time series of predicted dominant height values. Packalén et al. (2011) estimated SI for homogeneous Eucalyptus plantations combining ALS data and age taken from a stand register. The dominant height was expressed as a linear model using ABA with ALS explanatory variables such as height quantiles and mean height per plot. Then, the dominant height was modeled assuming a nonlinear relationship described with the Chapman-Richards equation to predict SI directly in one stage. Vehmas et al. (2011) assessed the site quality of mature boreal forests using ALS data. Five different fertility classes were correctly classified in 58% of the forest stands. Tompalski et al. (2015b) determined SI for coastal temperate rainforests using ALS data and satellite multispectral imagery, i.e. Landsat. Annual time series of Landsat were utilized to delineate stand boundaries and to determine the time since last disturbance, which was used as proxy for calculating stand age. From the ALS data, stand dominant height was predicted. Chen and Zhu (2012) used SI models to predict site quality for *Pinus radiata* plantations based on ALS data. The stand dominant height was calculated from ITCs and the age was known from the dates the plantation was established.

In the above-mentioned studies, SI is mainly determined starting from an area-based prediction of the required biophysical attributes. This is the most common approach, however recently many algorithms and methods have been developed to predict biophysical attributes at ITC level. Such ITC approaches allow for a higher spatial detail and scalable determination of biophysical attributes than the ABA. To the best of our knowledge, only few studies (Chen and Zhu, 2012; Gatziolis, 2007) partially exploited the ITC information for SI determination. However, since the SI is defined by biophysical attributes of the dominant trees which are the ones that usually are identified with the greatest accuracy applying ITC approach (Holmgren and Persson, 2004; Maltamo et al., 2004; Solberg et al., 2006), we hypothesize that using ITC framework for SI determination could be an appropriate approach for SI determination. Due to some potential advantages of ITC-based methods over the ABA (e.g. higher spatial scalability), it is highly relevant to gain more experience and evidence of the potentials and performance of SI determination based on biophysical attributes derived from remotely sensed data at ITC level. Furthermore, the dominant trees measured in the field do not always correspond to dominant ITCs, as there are different ways to select the dominant ITCs (e.g. by species and diameter at breast height, DBH). Thus, the effect of selected dominant ITCs on SI accuracy is not known. In addition, the changes in SI accuracy when ITC-based biophysical attributes are substituted with the field observations have never been analyzed and the SI determination adapted to the ITC framework should be explored more deeply.

The biophysical attributes needed for SI determination at ITC level are tree species, height, DBH, and age. The tree species information is typically obtained from aerial photographs, ALS, multispectral or hyperspectral imagery (Dalponte et al., 2015, 2014; Kim et al., 2009; Ørka et al., 2009; Yao et al., 2012). However, hyperspectral imagery seems to be the most promising data source for species classification (Dalponte et al., 2012; Ørka et al., 2013). The tree height and DBH can be predicted from ALS and aerial photographs (Hyyppä and Inkinen, 1999; Næsset and Økland, 2002). Regarding tree age, it is uncommon to determine this attribute from remotely sensed data, with the exception that this attribute traditionally has been assessed by manual photo interpretation in operational forest management inventories (e.g. Eid, 1996). However, very few studies have explored this topic based on automated methods, and in particular at the ITC level (Buddenbaum et al., 2005; Racine et al., 2014; Skoupý et al., 2012). As it is clear from these examples, each of these biophysical attributes can be predicted using more than one source of remotely sensed data – either individually or in combination. The combination of complementary remotely sensed data has shown to improve the accuracy of the prediction of the above-mentioned attributes (Dalponte et al., 2008; Tonolli et al., 2011). In particular, ALS and optical data are complementary by their nature: ALS data provide detailed information on the three-dimensional (3D) forest structure (e.g. tree heights), while optical data (in particular hyperspectral images) can provide detailed information on spectral properties of the canopy, which can be useful for prediction of qualitative attributes (e.g. tree species).

Therefore, the main goal of this study is to demonstrate and validate the potential of an ITC approach for determination of the SI from remotely sensed data. Based on predicted ITC level attributes we determined biophysical attributes at plot level in order to predict the SI. We defined an experimental setup with two subsets of dominant ITCs, inside which several experiments using different combinations of biophysical attributes for SI determination were considered. The specific objectives of this study are:

1) to make prediction models using combined ALS and airborne hyperspectral data to predict ITC level biophysical attributes (species, height, DBH, and age) and evaluate the models applying 10-fold cross validation;
2) to investigate and evaluate effects of dominant ITCs selection on the SI accuracy at plot level;
3) to evaluate differences in the SI accuracy when predicting the SI using different combinations of biophysical attributes (predicted vs field-derived) at plot level.

The uniqueness of this study is that it represents a first attempt to fully exploit the ITC information for SI determination using a combination of ALS and airborne hyperspectral data. As these data are becoming the most commonly used in the scientific, as well as the practical