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Modelling the standing timber volume of Baden-Württemberg—A large-scale approach using a fusion of Landsat, airborne LiDAR and National Forest Inventory data

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ABSTRACT

Remote sensing-based timber volume estimation is key for modelling the regional potential, accessibility and price of lignocellulosic raw material for an emerging bioeconomy. We used a unique wall-to-wall airborne LiDAR dataset and Landsat 7 satellite images in combination with terrestrial inventory data derived from the National Forest Inventory (NFI), and applied generalized additive models (GAM) to estimate spatially explicit timber distribution and volume in forested areas. Since the NFI data showed an underlying structure regarding size and ownership, we additionally constructed a socio-economic predictor to enhance the accuracy of the analysis. Furthermore, we balanced the training dataset with a bootstrap method to achieve unbiased regression weights for interpolating timber volume. Finally, we compared and discussed the model performance of the original approach ($r^2 = 0.56$, NRMSE = 9.65%), the approach with balanced training data ($r^2 = 0.69$, NRMSE = 12.43%) and the final approach with balanced training data and the additional socio-economic predictor ($r^2 = 0.72$, NRMSE = 12.17%). The results demonstrate the usefulness of remote sensing techniques for mapping timber volume for a future lignocellulose-based bioeconomy.

1. Introduction

In 2012 the European Commission adopted a strategy to support a bioeconomy based on renewable resources (European Commission, 2012). Following this strategy, one essential goal for Germany is to replace fossil fuels and materials with renewable products derived from algae, crop and wood (details see BMBF, 2010). As sources for sustainable wood production are limited, the demand for accurate, large-scale assessments of forest resources is growing (Treuhaft et al., 2003; Rudel et al., 2005). There is strong interest in estimating biomass or timber volume for different utilizations such as fuel or new products like bio-plastics. Before a bioeconomy can emerge it is important to calculate the potential supply of future resources. With this study we would like to present one example for the federal state of Baden-Württemberg (Germany). We estimated the standing timber volume using wall-to-wall remote sensing data in combination with ground truth data derived from the German National Forest Inventory (NFI). We estimated the timber volume instead of biomass since it is required for further market and price calculations.

New remote sensing platforms and sensors with higher spatial, spectral and temporal resolutions are continuously being developed. A variety of studies have estimated forest biomass with various data and methodologies (Lu, 2006; Hartig et al., 2012; Fassnacht et al., 2014). A sound procedure is combining ground truth reference data from field surveys with statistical predictors derived from remotely sensed information (Woodhouse et al., 2012). The crucial parameter for accurate estimation is tree height as it is strongly linked to timber volume (Koch, 2010). Light detection and ranging (LiDAR) systems represent one of the most accurate methods for tree height measurements on a local to regional scale (Lefsky et al., 2002; Clark et al., 2011; Næsset et al., 2011). While airborne missions are often too expensive for federal state-wide investigations, we fortunately got access to a unique wall-to-wall LiDAR dataset that covers the whole federal state of Baden-Württemberg (approximately 35742 km^2 with a resolution of 0.8 pulses per m^2). This data was originally collected by the State Agency for Spatial Information and Rural Development Baden-Württemberg for calculating a statewide Digital Terrain Model

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Fig. 1. Study area Baden-Württemberg (black) located in southwest Germany.

(DTM). The raw data allowed us to derive a DTM, a Digital Surface Model (DSM) and a Canopy Height Model (CHM).

Recent studies have shown that combining spectral or texture information with LiDAR data enhances the accuracy of biomass estimations (Fassnacht et al., 2014; Maack et al., 2015; Kattenborn et al., 2015). We combined LiDAR data with Landsat 7 images to get additional information about vegetation productivity, vitality, and species composition. Furthermore, we embrace the idea that abiotic factors like terrain characteristics that influence tree growth should be taken into consideration for estimating forest properties (Bonan et al., 1992; Sveinbjörnsson et al., 2002; Loranty and Goetz, 2012; Maack et al., 2015).

Several regression models were utilized for estimating forest characteristics such as biomass or biodiversity (Fassnacht et al., 2014). Machine learning algorithms like Classification and Regression Trees (CART) or generalized additive models (GAM) have already shown promising performance in several studies (Fassnacht et al., 2014; Kattenborn et al., 2015; Maack et al., 2015). They feature clear advantages such as reducing effects of co-linearity between predictor variables (Bright et al., 2012) and handling non-linear relationships between predictor and response variables (Guisan et al., 2002) when compared to classical linear models. We therefore used randomForest (RF), which is a very frequently utilized CART-based model (see Fassnacht et al., 2014), and generalized additive models (GAM), and checked their performance for large-scale timber volume estimations. The best performing algorithm was then used for the final modelling approach. Accordingly we evaluated the potential of satellite-based images (Landsat 7) and airborne laser scanning-derived (ALS) Canopy Height Models (CHMs) to estimate forest timber volume accurately on an extensive spatial scale in southwest Germany.

2. Study site and material

2.1. Study site Baden-Württemberg, Germany

Baden-Württemberg (center at 48° 32′ 16″N, 9° 2′ 28″E) is the third largest federal state of Germany located in the southwest corner of the country. It extends over 35,751 km^2 whereby about 14000 km^2 (39%) of the area is forested. The dominant tree species