Terrestrial laser scanning for forest inventories: Tree volume and biomass estimation using extended allometric models

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1. Introduction

Forest inventories deliver information on forest area, the amount and change of forest resources, the development of the biotope forest in general and the carbon balance of a country. Single tree volume is the basis for many estimates provided by forest inventories and is not directly measurable in the field up to now. In the Swiss National Forest Inventory (NFI), wood volume and changes in wood volume are estimated based on the stem volume of individual trees using various models. For a sub-sample of tally trees, single stem volume is estimated by allometric models using three measured tree dimensions: diameter at breast height (DBH), upper diameter at 7 m height (d7) and tree height. Based on these three variables the volume of the stem, which usually is of a conical shape, can be calculated with a very high precision ($R^2 > 98.7$) (Herold et al. 2019). On the other hand, total tree volume, needed e.g., for biomass estimation, is far more complex to model, making the prediction of branch wood more prone to unexplained variation. Moreover, these allometric models for total tree volume (including branches) are based on destructively sampled trees from experimental sites and are currently not completely representative for the whole country.

Close range remote sensing technologies such as terrestrial laser scanning (TLS), present a possibility to address the need for more direct measurements. Currently, no operational application exists for TLS in forest inventories, due to open questions concerning precision and accuracy. Nevertheless, many TLS-based approaches contributing to individual tree volume or above-ground biomass estimation have been proposed and developed. A straightforward application is to retrieve simple tree structure metrics, such as stem and crown diameters, from point clouds instead of manual measurements (Holopainen et al. 2011). Tree volume can also be approximated by the voxel representation of an individual tree point cloud (Vonderach et al. 2012). The most detailed volume estimation is commonly achieved by quantitative structure models (QSM) (e.g. Raumonen et al. 2013) which estimate tree volume based on a real morphological structure model of a specific tree. However, in the context of a large-scale or national inventory, computing a QSM for every sampled tree still remains less effective than traditional inventory methods due to demands on point cloud quality and cost of data acquisition. Instead, QSMs have been proposed as non-destructive reference data for training (traditional) allometric models (Stovall et al. 2018). Another possible way of integrating TLS into forest inventories is to extend allometric models by including TLS-derived variables, such as crown diameter (Lau et al. 2019).

In order to assess these possibilities, the objectives of this study include (1) to evaluate the explanatory power of TLS-derived tree metrics regarding tree volume and biomass (total, coarse wood and fine wood), and (2) incorporating them into preliminary allometric models based on 60 sample trees. (3) Additionally, we will compare the estimated volumes to operational allometric models and to quantitative structure models.

2. Data and Methods

The study area consists of two managed mixed temperate forest sites located on the Swiss Plateau. The main tree species on site 1 are: *Fagus sylvatica, Picea abies, Acer pseudoplatanus* and *Fraxinus*

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excelsior, while the following species are present on site 2: *Fagus sylvatica, Fraxinus excelsior, Acer pseudoplatanus*, *Pinus sylvestris*, *Pinus nigra* and *Larix decidua*. From each site, approximately 30 sample trees were chosen, aiming to represent the respective species range and height distribution. DBH, d7, tree height and crown parameters were measured on the standing trees following inventory procedure. After harvesting, trees were weighed using a crane scale. The total weight was further divided into coarse wood (trunk and branches with diameter >7 cm) and fine wood (branches and twigs with diameter <7 cm). Wood disc samples were taken every 2 m along each stem to determine wood density, which was then used to convert tree weight to biomass and volume.

The TLS data were collected in winter 2020/2021 using a Leica BLK360 terrestrial laser scanner (Leica Geosystems, Heerbrugg, Switzerland), while distributing scan positions across the site so that every tree of interest was included in at least three different scans from different directions. The raw point clouds from different scan positions were co-registered using Cyclone REGISTER 360 (Leica Geosystems, Heerbrugg, Switzerland). Individual trees were segmented from the point cloud using the CompuTree software (Othmani et al. 2011), including manual filtering as the last step.

A set of tree structure metrics was then extracted from each individual tree point cloud. Besides DBH and crown diameter, multiple stem diameter values were taken between 2 m and 10 m and at 25%, 50% and 75% of tree height. To serve as metrics describing crown structure, crown projected area and volumes of different convex and concave hulls (alpha shapes) around both the crown and the whole tree were also calculated. Additionally, wood volume per compartment (diameter >7 cm and diameter ≤7 cm), was derived following the QSM approach as implemented in the TreeQSM tool (Raumonen et al. 2013).

Linear regression and correlation coefficients relating reference total, coarse and fine wood volume to the TLS-enabled tree metrics are subsequently used as a first indication of their respective explanatory power. In order to find effective combinations of the most relevant of these metrics, allometric models are then built and tested, along the lines of existing NFI stem volume models.

3. Results and Discussion

Regarding the power to predict tree volume, we observe that stem diameters up to approximately 10 m or 50% of tree height correlate well with total and coarse wood volume. TLS-based crown diameters on the other hand show lower values of correlation with total volume (R^2 = 0.25 - 0.52). We observe the various crown hulls to correlate with fine wood volume as derived by QSMs (R^2 = 0.8 - 0.92) but less so with total volume from QSMs and destructively measured volume (R^2 = 0.2 - 0.5). A possible reason for this is that TLS-based descriptors of crown shape can be heavily influenced by point cloud filtering and segmentation methods. Also, the accuracy of reference measurements needs to be considered, as some crowns were damaged during felling and weighing operations. Despite this, crown characteristics are a promising addition for allometric equations because they provide valuable information on branch volume and are also known to be sensitive to stand structure (Forrester et al. 2017).

As a next step, we will analyse interactions between the presented tree metrics as well as evaluate the feasibility of additive allometric models for coarse wood and fine wood. We expect coarse wood volume to be estimated reasonably well by a combination of “distance metrics” (tree height and various stem and crown diameters). Crown hulls in combination with echo density metrics could serve as a possible approximation for the volume of fine branches.

4. Conclusions

As the new allometric equations are fitted on a limited sample containing various species, they are not expected to be suitable for use outside the respective test sites (Duncanson et al. 2015). Rather, they provide an indication as to which parameter combinations should be further investigated and which metrics would be suitable to include in future inventories.

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