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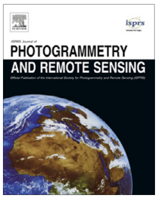

Feasibility of Terrestrial laser scanning for collecting stem volume information from single trees

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ABSTRACT

Interest in measuring forest biomass and carbon stock has increased as a result of the United Nations Framework Convention on Climate Change, and sustainable planning of forest resources is therefore essential. Biomass and carbon stock estimates are based on the large area estimates of growing stock volume provided by national forest inventories (NFIs). The estimates for growing stock volume based on the NFIs depend on stem volume estimates of individual trees. Data collection for formulating stem volume and biomass models is challenging, because the amount of data required is considerable, and the fact that the detailed destructive measurements required to provide these data are laborious. Due to natural diversity, sample size for developing allometric models should be rather large. Terrestrial laser scanning (TLS) has proved to be an efficient tool for collecting information on tree stems. Therefore, we investigated how TLS data for deriving stem volume information from single trees should be collected. The broader context of the study was to determine the feasibility of replacing destructive and laborious field measurements, which have been needed for development of empirical stem volume models, with TLS. The aim of the study was to investigate the effect of the TLS data captured at various distance (i.e. corresponding 25%, 50%, 75% and 100% of tree height) on the accuracy of the stem volume derived. In addition, we examined how multiple TLS point cloud data acquired at various distances improved the results. Analysis was carried out with two ways when multiple point clouds were used: individual tree attributes were derived from separate point clouds and the volume was estimated based on these separate values (multiple-scan A), and point clouds were georeferenced as a combined point cloud from which the stem volume was estimated (multiple-scan B). This permitted us to deal with the practical aspects of TLS data collection and data processing for development of stem volume equations in boreal forests. The results indicated that a scanning distance of approximately 25% of tree height would be optimal for stem volume estimation with TLS if a single scan was utilized in boreal forest conditions studied here and scanning resolution employed. Larger distances increased the uncertainty, especially when the scanning distance was greater than approximately 50% of tree height, because the number of successfully measured diameters from the TLS point cloud was not sufficient for estimating the stem volume. When two TLS point clouds were utilized, the accuracy of stem volume estimates was improved: RMSE decreased from 12.4% to 6.8%. When two point clouds were processed separately (i.e. tree attributes were derived from separate point clouds and then combined) more accurate results were obtained; smaller RMSE and relative error were achieved compared to processing point clouds together (i.e. tree attributes were derived from a combined point cloud). TLS data collection and processing for the optimal setup in this study required only one sixth of time that was necessary to obtain the field reference. These results helped

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to further our knowledge on TLS in estimating stem volume in boreal forests studied here and brought us one step closer in providing best practices how a phase-shift TLS can be utilized in collecting data when developing stem volume models.

1. Introduction

Stem volume information is needed for sustainable planning of forest resources (Vanclay, 1994; Kangas and Maltamo, 2006; Bettinger et al., 2009; Pretzsch, 2009). It is highly correlated with biomass and bounded forest carbon (e.g. Pretzsch, 2009; Yu et al., 2013), which makes it an important attribute to monitor in understanding the effects of climate change (Penman et al., 2003). Assessment of national forest biomass and carbon stock is, in general, based on information on forest resources, i.e. estimates of the forested area and volume of the growing stock as reported by national forest inventories (NFIs) (Liski and Kauppi, 2000). The basis of these estimates is on estimating the stem volume of individual trees. The volume estimates reported are multiplied with simple biomass expansion and/or conversion factors to obtain biomass and carbon estimates (Penman et al., 2003). Stem volume can be converted into dry weight with wood density factor and furthermore total biomass with a biomass expansion factor, but these can be combined in one value (e.g. Penman et al., 2003; Lehtonen et al., 2004; FAO, 2006). Biomass and volume equations exist to some extent (Eamus et al., 2000; Keith et al., 2000; Jenkins et al., 2003; Zianis et al., 2005) and they can directly be applied to tree level biomass estimates.

Large area inventories on forest resources such as NFIs are based on plot-level field measurements that come down to measuring individual trees, i.e. measuring easy attributes (e.g. diameter-at-breast height, 1.3 m, dbh) and modelling the attributes of interest (e.g. stem volume and/or biomass). Traditional field measurement techniques are time consuming especially if destructive measurements only are required. Therefore, for developing models for stem volume or biomass for an individual tree, flexible and effectual field measurement techniques are required.

Terrestrial laser scanning (TLS) provides three dimensional (3D) data that can be used in measuring a tree stem. However, additional models and/or assumptions are required to obtain the full 3D reconstruction of the stem from TLS data. TLS has been widely studied related to forest inventory with various focus (Liang et al., 2016). TLS has been employed in estimating stem volume (Thies et al., 2004; Moskal and Zheng (2012); Pueschel et al., 2013; Astrup et al., 2014) and biomass (Holopainen et al., 2011; Yu et al., 2013) but also measuring stem form (i.e. diameters along the stem or stem curve) (see Pfeifer and Winterhalder, 2004; Henning and Radtke, 2006; Maas et al., 2008; Liang et al., 2014) of individual trees. TLS has thus proved to have potential for inventorying single-tree level attributes. The relative root-mean-square error (RMSE) of TLS-based dbh estimates has varied between 5.8% and 13.1% (Tansey et al., 2009; Lindberg et al., 2012; Kankare et al., 2014, 2015). However, measuring diameters to the tip of a tree can be challenging (Watt and Donoghue, 2005; Hackenberg et al., 2015; Xia et al., 2015). Thies et al. (2004) reconstructed 30% of the stem of a European beech and 22% of the stem of a Wild cherry automatically. In Liang et al. (2014), the highest diameters measured automatically, was possible to a relative height of 68.5% for Scots pine (*Pinus sylvestris* L.) and 61.0% for Norway spruce (*Picea abies* (L.) H. Karst.). However, e.g. Raumonen et al. (2013) were able to reconstruct the entire stem profile of one Scots pine using a 3D structural model. In addition, the tree height has been reported as an underestimate, varying from 0.64 m to 2 m (Hopkinson et al., 2004; Maas et al., 2008; Kankare et al., 2014), although differing results have been obtained. Liang and Hyyppä (2013) reported a mean overestimate of 1.3 m, and Calders et al. (2015) attained a RMSE of 0.55 m for TLS-based tree height when compared with destructively measured height. Tansey et al. (2009) were completely unable to measure the tree height, due to occlusion. Furthermore, wind conditions can affect the reliability of determining diameter and canopy size due to swaying of trees during scanning (Vaaja et al., 2016).

Forest conditions play a major role in collecting TLS data (see Kankare et al., 2015) ensuring that individual tree characteristics are visible and distinguishable to the scanner. TLS has widely been studied in forestry, related to detecting tree species (Othmani et al., 2013), estimating leaf area (Béland et al., 2014), and modelling small trees (Bienert et al., 2014; Hess et al., 2015). In addition to stem volume and profile, extensive research on stem and crown modelling in geometrical manner exist (Xu et al., 2007; Côté et al., 2011; Côté et al., 2012; Dassot et al., 2012; Eysn et al., 2013; Raumonen et al., 2013; Aiteanu and Klein, 2014; Delagrange et al., 2014; Hackenberg et al., 2014; Calders et al., 2015; Hackenberg et al., 2015; Raumonen et al., 2015). TLS data acquisition depends on the question addressed and best practices, i.e. a standard way of collecting and processing TLS data, for utilizing TLS operationally in various forested areas would be beneficial. The context of this paper is in developing stem volume equations at individual tree level with TLS data, but other TLS-based forestry applications have also been studied (Liang et al., 2016) and TLS has the potential to automatize and expand field measurements for forest inventory (Newnham et al., 2015).

Martins Neto et al. (2013) used four TLS scanning distances (5 m, 10 m, 15 m, and 20 m) for measuring diameters from sample trees, and concluded that the optimal scanning distance is related to tree height. Delagrange and Rochon (2011) also used several scan locations, but all of them were at same distance, i.e. 12 m, because their main interest was to estimate crown volume. Henning and Radtke (2006), on the other hand, had nine sample trees that were scanned at various positions at distances between 2 m and 7 m, but their emphasis was in registration of multiple point clouds without artificial reference targets. Dassot et al. (2012) and Schilling (2014) used TLS for volume estimates and scanned their sample trees from several locations and combined the point clouds (i.e. multiple-scan method) to obtained better results. They did not, however, take a stand on the optimal scan location or distance. To our best knowledge there are no studies related to establishing on optimal scan distance for estimating stem volume of an individual tree with TLS. In addition, the above-mentioned studies have all combined data sets from several scan locations into one point cloud, but we wanted to test whether it improves the results if the point clouds are processed separately (to minimize the effect of swaying caused by the wind).

A growing interest in utilizing TLS data as basis for developing stem volume equations exist. There are, however, many questions related to data acquisition and processing and should be answered before TLS can be utilized for this task. This study is our first investigation towards our goal of TLS-based stem volume equations; therefore the aim of this paper is to provide insight how TLS data should be acquired with the scanner used to provide accurate stem volumes for stem volume model development in boreal