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Applicability of different non-invasive methods for tree mass estimation: A review

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ABSTRACT

Biomass estimations of trees are used at various different special scales. Along with the scale, there are diverse demands on accuracy and technical requirements. This paper reports the state of the art of different methods for non-invasive tree mass estimation technics. Different studies about biomass estimations at different spatial scales were compared on basis of three assessment criteria: accuracy, efficiency, and technical requirements. Publications were searched via Google Scholar, Web of Science and ScienceDirect including years from 1980 to 2016. References of 20 studies could be used to compare 10 methods of biomass estimation.

Allometric approaches are comparably accurate but are suitable for small area applications only. Remote sensing techniques are less accurate but more efficient. Lidar and SfM appear to be the most efficient and most accurate techniques for medium sized area applications. Especially SfM applications are promising due to lower technical requirements. Optical images are suitable for coarse but large area applications.

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1. Introduction

There are various reasons for the demand of accurate non-invasive tree mass estimations. On a larger spatial scale, accurate mass estimates are important for climate change modelling studies, greenhouse gas inventories and terrestrial carbon accounting (Muukkonen and Heiskanen, 2005). On a smaller spatial scale, accurate mass estimations are made on ecological and commercial purposes (Miller et al., 2015). Consequently, a vast number of studies presents approaches to estimate the mass of entire forests or single trees (Muukkonen, 2007; Tiwari and Singh, 1984; Véga et al., 2015). The current study reviews the most common techniques for tree mass estimation at different scales.

The exact measurement of a tree's mass requires destructive/invasive methods like felling and weighing. However, these destructive methods are expensive, time consuming and not appropriate for all objectives, like in ecological studies. Consequently, more efficient and less or non-invasive but less accurate methods are applied. These tree mass estimation procedures are always a trade-off between accuracy and efficiency. The need to find an appropriate trade-off for any specific objective appears to be the major reason for the large number of different methods.

Tree mass can be seen as commercially valid stem mass or as biomass in general which includes small branches and foliage. The majority of the reviewed studies are aiming to predict total above ground biomass (Dandois and Ellis, 2010; Popescu, 2007). Other studies like Yu et al. (2013) are aiming to estimate stem mass only and studies like Kankare et al. (2013) have estimated both.

The aim of this study is to present an overview of available techniques for non-invasive tree mass estimation. Techniques are compared based on accuracy, efficiency, and technical requirements.

2. Methods

2.1. Study selection

Publications regarding methods for tree mass estimation were searched via Google Scholar, Web of Science and ScienceDirect including years from 1980 to 2016. The following key words were used in different combinations: "tree", "forest", "biomass", "mass" and "estimation". Altogether, about 100 publications were read, but only a total of 20 publications were suitable for comparison. These studies were used to review 10 different methods for tree mass estimation.

2.2. Assessment criteria

Altogether three assessment criteria were used to compare the different methods:

- accuracy,
- efficiency, and
- technical requirements.

2.3. Accuracy

The absolute Root Mean Square Error (RMSE) or relative Root Mean Square Error (rRMSE) were the accuracy estimates used by reviewed studies throughout different methods. Consequently, the rRMSE was chosen for accuracy comparison. If no rRMSE but absolute RMSE was reported in a particular study, the rRMSE was estimated based on absolute RMSE and the approximate mean mass value $\bar{y}$ (Eq. (1)). If values of multiple publications regarding the same method could be processed a mean rRMSE was calculated.

$$rRMSE = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}}{\bar{y}} * 100 \tag{1}$$

Nevertheless, the comparison of different studies based on the rRMSE should be done with caution. Only about 30% of all reviewed studies have actually used destructive weighing to gain exact reference values. The majority of the reviewed studies have used reference values that were merely estimated. The current review outlines the way reference values were obtained when presenting a study.

2.4. Efficiency

Comparing monitored plot sizes in hectare (ha) assesses the spatial efficiency of the different methods. This assessment bases on the underlying assumption that more efficient methods and less efficient methods were used to monitor larger plot sizes and smaller plot sizes, respectively.

2.5. Technical requirements

Technical requirements are listed to get an idea about technical effort and costs for applying the reviewed methods. For final comparison, these technical requirements were broadly divided into four categories: very low, low, high and very high.

3. Results and discussion

3.1. Allometric equations

Various studies have presented allometric regressions to estimate biomass from non-invasive measurements like DBH (Diameter at Breast Height) or height (Brown et al., 1989; Ketterings et al., 2001; Nelson et al., 1999) (Table 1). However, appropriate regres-

Table 1
Studies estimating biomass using allometric equations. Studies in bold could be used for rRMSE comparison their rRMSE-values are listed in Table 6.

Author	Object	Biomass reference data
Schmitt and Grigal (1981)	Birches in US, and Canada	Meta-study using data sets of 9 original studies
Uhl et al. (1988)	Tropical forest, Brazil	Destructive sampling of 8–16 individuals per species
Brown et al. (1989)	Tropical forest, Brazil, and Venezuela	Meta-study using data sets of 9 original studies
Overman et al. (1994)	Tropical forest, Colombia	Destructive sampling of 54 trees
Telenius and Verwijst (1995)	Willow in short rotation forest, Sweden	Destructive sampling of 10 shoots per stand
Alves et al. (1997)	Tropical forest, Brazil	No reference measurements
Nelson et al. (1999)	Tropical forest, Brazil	Destructive sampling of 17–27 individuals per species
Ketterings et al. (2001)	Tropical forest, Indonesia	Destructive sampling of 29 trees
Komiyama et al. (2005)	Mangrove species, South-East Asia	Destructive sampling of 104 individuals of 10 species
Segura et al. (2006)	**Shade trees (for coffee plants), Nicaragua**	**Destructive sampling of 34 individuals of 4 species**
Wang (2006)	Temperate forest, China	Destructive sampling of 100 individuals of 10 species
Muukkonen (2007)	7 European tree species	Pseudoobservations generated by equations from literature
Annighöfer et al. (2016)	**Seedlings and saplings of European tree species**	**Weighing of 4468 individuals of 19 species**