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How do tree stand parameters affect young Scots pine biomass? – Allometric equations and biomass conversion and expansion factors

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ABSTRACT

Due to the impact of climate change and rising atmospheric carbon dioxide concentrations, assessment of forest carbon pools becomes a crucial task for forest ecology. One of the scientific gaps in this task is the assessment of young tree stands, not included in forest inventories, due to lack of merchantable volume. We aimed to provide a comprehensive set of allometric equations (AEs) and biomass conversion and expansion factors (BCEFs) for young Scots pine tree stands and to develop models of tree stand biomass based on stand features easy-measurable by remote sensing: height and density. We used data collected in 77 tree stands of Scots pine ranging in age from 3 to 20 years in Western and Central Poland, covering forest, post-agricultural and post-industrial sites. Our dataset included 423 sample trees. Our study resulted in collection of 256 site-specific AEs, 12 generalized AEs and equations allowing for dynamic BCEF calculation. Due to lack of BCEF applicability for young trees, we also provided age- and height-dependent functions allowing for precise biomass estimation at the tree-stand level. It was found that tree-stand biomass increased with tree-stand age, height and volume, and decreased with increasing density in the chronosequence. BCEFs decreased with tree-stand age, height and volume and increased with increasing density. Using these relationships we provided stand-level equations based on BCEFs and on tree height – the stand characteristic which is easily obtained from airborne data. These two models did not show a big difference in accuracy. Thus, height-based models are expected to be useful for extensive assessments of young tree stand biomass and carbon sequestration, allowing for better estimation of forest carbon pools. Moreover, our models, in comparison with IPCC guidelines, give more precise values of carbon pools and biomass of young Scots pine tree stands.

1. Introduction

Forest ecosystems act as sustainable carbon reservoirs. A number of recent studies have focused on the role of forests in mitigation of climatic change and its effects (e.g. Pan et al., 2011; Fearnside, 2012; Seidl et al., 2014; Naudts et al., 2016; Dyderski et al., 2017). The international pressure to implement comprehensive mechanisms limiting emissions of greenhouse gases to the atmosphere, also involves heightened attention to look for potential carbon sinks. Forest ecosystems are the main terrestrial carbon stock, accumulating globally ca. 2.4 ± 0.4 Pg C year^{-1} (Pan et al., 2011). Enhanced photosynthesis by forests growing under elevated CO_2 can limit processes leading to increasing atmospheric CO_2 concentration (Chmura et al., 2010; Lindner et al., 2014). Consequently, in addition to the modification of some forest management practices aimed at increasing the sequestration of carbon (Lindner et al., 2014; Sohngen and Tian, 2016), there is a need to include stands formerly omitted from consideration, especially young tree stands, which have not yet produced merchantable wood or tree stands growing on specific sites, e.g. post-industrial or peatlands. Therefore, detailed estimation of tree biomass components of a given species, as well as carbon contents, are high in importance, as generalized data is often used, according to IPCC guidelines (Eggleston et al., 2006). This in turn, could result in underestimation of total carbon sequestered in a stand. For example, IPCC assumes that coniferous species root biomass amounts to 20% of aboveground biomass, but Oleksyn et al. (1999) found higher values, depending on tree provenance. The concentration of carbon in different tissues is less variable than biomass of tree stands (Lehtonen et al., 2004; Martin and Thomas, 2011; Jagodziński et al., 2012; Uri et al., 2012). Therefore, we can estimate carbon contents based on biomass assessment. However, the

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accuracy of the method used is crucial for proper estimation.

There are two main approaches for biomass estimation: use of allometric equations (AEs) or biomass conversion and expansion factors (BCEFs) (e.g. Baskerville, 1972; Lehtonen et al., 2004; Montero et al., 2005; Zianis et al., 2005; Teobaldelli et al., 2009; Neumann et al., 2016; Jagodziński et al., 2017). These two methods differ in accuracy and labor requirement, as AEs are applied at the tree level, while BCEFs are at the tree-stand level. AEs are based on relationships between tree biomass and usually common dimensions, i.e. diameter or/and height, and allow tree-level calculations (Baskerville, 1972; Weiner, 2004; Poorter et al., 2015). Despite their relatively high accuracy, AEs have the disadvantage of requiring a high amount of labor and associated costs. In contrast, BCEFs as coefficients of tree stand merchantable volume, allow only tree-stand level calculations. Moreover, due to the lack of tree-level data in forest inventories, BCEFs are rather frequently used for large-scale estimations (Neumann et al., 2016). The largest disadvantage of BCEFs occurs when biomass estimation of young tree stands is required, as young trees have not yet reached the threshold size for merchantable wood. Data on young trees and volume of their wood are usually omitted in forest inventories (Lehtonen et al., 2004; Pajtík et al., 2008; Jagodziński et al., 2017). For example, in Poland there is no information about tree stand volume unless trees reach the merchantable volume threshold of diameter at breast height ($D_{1.3}$) of 7 cm. Analysis of ca. 550,000 records from the forest data bank revealed that information about tree stand volume appears in 4% of 15 y.o. (years old) tree stands and 65% of 20 y.o. tree stands (Forest Data Bank, 2015). In contrast, information about height is available for 57% of 3 y.o. and 82% of 5 y.o. stands. Another disadvantage is high variability of BCEFs in small individuals, in contrast to larger individuals (e.g. Konôpka et al., 2015; Jagodziński et al., 2017). Therefore, large scale analyses using BCEFs on young forests are impossible.

Zianis et al. (2005) published a comprehensive review of allometric equations for European trees, which was updated by Muukkonen and Mäkipää (2006). In this database there are 205 AEs for Scots pine (*Pinus sylvestris* L.). After review of more recent papers we found 240 AEs potentially applicable for various biomass components of young Scots pines, coming from different countries, and possibly connected with different biomass allocation patterns (Oleksyn et al., 1999). The accuracy of these AEs varied across the wide range of dimensions they covered, therefore obscuring age-dependent patterns of biomass allocation (Jagodziński and Kałucka, 2008; Jagodziński and Oleksyn, 2009a,b; Teobaldelli et al., 2009; Uri et al., 2012; Jagodziński et al., 2014). There are also some AEs for young Scots pine trees (e.g. Oleksyn et al., 1999; Claesson et al., 2001; Jagodziński et al., 2014), and individual tree BCEFs (Pajtík et al., 2011). However, these studies were conducted at limited sites and it is not clear whether they are site-specific. This is especially important because the accuracy of carbon estimation strongly depends on country-specific methods (Neumann et al., 2016) and differences in biomass production and allocation between different land use forms result in site-specific allometric trajectories (Jagodziński and Kałucka, 2008; McHale et al., 2009; Jagodziński et al., 2014). For that reason there is a need for studies to include both site-specific, as well as generalized allometric equations (Muukkonen, 2007).

Collecting such data is laborious and apparently unprofitable from the point of view of forest management, especially in the youngest woodlands, which being apart from timber production, have no detailed volume information. Measurements acquired by remote sensing could be a compromise between time-consuming fieldwork and generalizations based on data obtained in older stands. Airborne Laser Scanning (ALS) may be an interesting solution, yielding data about species composition, stand height and density of tree stands that is useful for biomass estimations (White et al., 2013; Wulder et al., 2013; Zasada et al., 2013). Among tree stand characteristics, height seems to be the feature estimated with the highest accuracy by ALS (Niemi et al., 2015; Kauranne et al., 2017). As the two most frequently used methods for biomass estimation are BCEFs and AEs, there are few data about relationships between biomass and other tree stand parameters (e.g. Castedo-Dorado et al., 2012; Jagodziński et al., 2017). For that reason we aimed to provide a comprehensive set of allometric equations and biomass conversion and expansion factors for young Scots pine tree stands and to develop models of tree stand biomass based on stand features – height and density – easily measurable by remote sensing. We hypothesized that (1) generalized allometric equations would explain lower amounts of variance than those that are site-specific, but (2) also would be useful for biomass estimation due to relatively low bias, (3) despite the generalizations, generalized equations would generate lower biases and lower heteroscedasticity along a gradient of increasing observed biomass than published equations, (4) tree stand features: height, volume, age and density will influence tree stand biomass and BCEFs, and (5) biomass estimation methods based on tree stand height would not differ in accuracy from BCEF-based methods.

2. Material and methods

2.1. Study species

Scots pine (*Pinus sylvestris* L.) is a pioneer, coniferous tree species, covering over 28 million ha in Europe, constituting over 20% of total timber productivity (Houston Durrant et al., 2016). Scots pine is able to grow in a wide range of site conditions – from dry and poor arenosols to wet and fertile alluvial soils, however, it is able to reproduce naturally on poor to medium fertile podzols and brunic arenosols (Ellenberg, 1988). According to National Forest Inventory from 2011 to 2015 (Forest Data Bank, 2015), in Poland Scots pine covers an area of 5.4 million ha (58.1% of forest area in Poland) and its merchantable volume is 1519 million m^3 (60.8% of total wood resources). Thus, Scots pine stands are important carbon reservoirs, playing one of the key roles in global carbon storage accumulated in the tree components: biomass of needles, branches, stems and roots. Scots pine reaches the largest dimensions and biomass in Central Europe, due to drought-mediated limitation in southern Europe and cold-mediated limitation in the North (Oleksyn et al., 1999). However, Cienciala et al. (2006) argue that despite the high economic importance of Scots pine, little is known on this species allometry and biomass production.

Table 1
Overview of the study plots and tree stand characteristics.

Parameter	Plot area [ha]	V [m^3 ha^{-1}]	G [m^2 ha^{-1}]	N [ind. ha^{-1}]	A [years]	H_g [m]	AB [Mg ha^{-1}]	BR [Mg ha^{-1}]	FL [Mg ha^{-1}]	ST [Mg ha^{-1}]
Min	0.0080	0.06	0.00	2717.0	3.0	0.33	0.174	0.038	0.128	0.057
Mean	0.0534	31.64	8.57	6907.0	10.4	3.88	21.830	5.557	4.417	11.940
SE	0.0057	3.62	0.94	300.2	0.6	0.26	2.066	0.560	0.300	1.353
Max	0.2151	118.20	29.79	14000.0	20.0	9.10	57.590	23.860	11.870	41.170

Abbreviations: V – stem volume, G – basal area, N – tree stand density, A – tree stand age, H_g – mean height weighted by tree basal area, AB – total aboveground biomass, BR – branch biomass, FL – foliage biomass, ST – stem biomass.