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Article in *Forest Ecology and Management* · January 2017

DOI: 10.1016/j.foreco.2016.10.051

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# Biomass conversion and expansion factors for a chronosequence of young naturally regenerated silver birch (*Betula pendula* Roth) stands growing on post-agricultural sites



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## ARTICLE INFO

### Article history:

Received 23 June 2016

Received in revised form 21 October 2016

Accepted 23 October 2016

### Keywords:

Stand biomass

Height

Diameter

Volume

Aboveground biomass

Belowground biomass

## ABSTRACT

Forest stand biomass or carbon storage in the biomass may be estimated by conversion of the trees volume since roughly 50% of tree biomass is carbon. There is a need to find biomass conversion and expansion factors (BCEFs) for young stands, because those established for older ones may not be relevant due to changes in biomass allocation patterns over stand age and development phases. We developed BCEFs for above- and belowground biomass components of young silver birch stands as separate functions of stand age or variables that reflect growth conditions and the biological status of trees, i.e. top height ( $H_{100}$ ), mean height ( $H_g$ ), base diameter ( $D_0$ ), quadratic mean diameter at breast height ( $D_g$ ) or stand volume ( $V$ ). Data were collected on 120 pure birch stands that regenerated naturally on post-agricultural lands in Poland. We determined BCEFs based on the stem volume and dry biomass of above- and belowground components. We applied segmented linear regression (SLR) to develop equations for BCEF determination for each of the pre-determined age classes using (a) fixed break points (FBP) found with the Ward method and (b) estimated break points (EBP) derived based on the best fit of regression models during piecewise regression estimation. We found that the use of SLR and non-linear regression (NR) approaches produced similar results in terms of quality of fit. However, non-linear parameter estimates are more efficient than linear ones, as NR seems to be more frequently used and easier to process using existing statistical tools, but at the same time the SLR provides biological interpretation of results (i.e. the point where BCEF value stabilizes and beyond which stand features do not influence BCEF). The largest difference between EBP and FBP occurs for stems, and the smallest for roots. For total biomass and all biomass components except stem, BCEFs are very high for the youngest, shortest and thinnest trees and hence stands with low volume. Their values decrease along with age, height, diameter and volume towards the EBPs. For individuals older, taller, thicker and with higher volume than EBP, there is no influence of age,  $H_{100}$ ,  $H_g$ ,  $D_0$ ,  $D_g$  and  $V$  on BCEF values. We confirmed that  $H_{100}$  might be a good biomass predictor for young birch stands, which is important because measuring tree height is not as time consuming as tree diameter measurements, particularly for young and very dense stands, and this parameter can be obtained from remote sensing technology.

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## 1. Introduction

Forest ecosystems make an important contribution to the global carbon budget and the significance of forests in mitigation of cli-

**Abbreviations:** BCEF, biomass conversion and expansion factor; BEF, biomass expansion factor; BCF, biomass conversion factor; FBP, fixed break point; EBP, estimated break point.

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<http://dx.doi.org/10.1016/j.foreco.2016.10.051>

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mate change has recently gained much attention not only in science, but also in policy discussions (Fahey et al., 2009; Rittenhouse et al., 2012). Three wide-ranging strategies leading to sustainable management of carbon in forest ecosystems exist: increasing forest area and avoiding deforestation (Woodbury et al., 2006; Zhang and Song, 2006; Whitehead, 2011; Birdsey et al., 2013), rational carbon management in existing forests (Pandey, 2002; Galik and Jackson, 2009; Malmshheimer et al., 2011) and long-lasting use of wood products (Pingoud et al., 2001; Eggers, 2002; Perez-Garcia et al., 2005; Lippke et al., 2011; Nepal et al., 2013). During the last decades of the twentieth

century the amount of abandoned agricultural land has increased remarkably (Ramankutty and Foley, 1999; Alcantara et al., 2012) and the re-vegetation of abandoned agricultural lands is now considered to be part of a long-term strategy to increase carbon sequestration (Benayas et al., 2007). For example, land-use change via increased afforestation linked to decrease of agricultural land has positively affected the net terrestrial carbon sink in Europe (Schröter et al., 2005). The conversion of arable lands abandoned for a number of socioeconomic reasons to forest lands through natural tree regeneration (secondary succession) offers a huge potential for biomass production and increasing CO<sub>2</sub> capture by newly developed forest ecosystems.

Dominance by herbaceous vegetation on abandoned agricultural lands for the first few years is usually followed by early successional tree species that gradually become more dominant and establish woodlands (Benayas et al., 2007; Ruskule et al., 2012; Tullus et al., 2013). However, the course of natural succession on abandoned farmland depends on many initial environmental conditions and socioeconomic factors, e.g. physical and chemical properties of the soil, soil moisture, topography, climate, initial cover of herbaceous vegetation, soil seed bank, proximity to forest ecosystems and previous land use (Prach et al., 2001a,b; Alard et al., 2005; Baeten et al., 2010; Buraczuk 2013). Rapid secondary succession of forest pioneer tree species, primarily birch, is relatively well described, but there is relatively poor knowledge of the dynamics of such newly established ecosystems (e.g. Johansson, 1999; Jögieste et al., 2003; Uri et al., 2012; Bijak et al., 2013; Tullus et al., 2013; Gawęda et al., 2014; Socha and Zasada, 2014; Zasada et al., 2014).

Forest stand biomass has an important role in estimating carbon sequestration because it can be readily converted into carbon storage. However, the magnitude of carbon sink by forests is still controversial, partly because of uncertainties in forest biomass and carbon content estimation (Kauppi et al., 1992; Houghton, 2003, 2005; Keith et al., 2009; Jagodziński et al., 2012, 2014; Thomas and Martin, 2012; Sileshi, 2014). Various tree biomass estimation methods, both direct and indirect, are applied on forest lands. The widely used method for tree biomass determination consists of harvesting individual trees representing the whole stand diameter at breast height (DBH) distribution to determine the oven-dried biomass of the individuals (i.e. whole tree or stem and traditionally noncommercial components such as branches, roots and foliage). Based on regression analyses linking tree variables and biomass of a particular tree component, the biomass of every tree within the stand can be estimated using such allometric equations (Ter-Mikaelian and Korzukhin, 1997; Parresol, 1999; Zianis and Mencuccini, 2004; Zianis et al., 2005, 2008; Picard et al., 2012). However, this method is time-consuming, expensive, and laborious, while the equation is considered site-specific and thus may not accurately reflect tree biomass under other site conditions (Jenkins et al., 2003; Paul et al., 2013; Jagodziński et al., 2014). Biomass equations may be replaced by stand-level volume equations and biomass expansion factors, and combined with forest inventory data. However, the conversion from stand stem volume into whole-tree stand biomass is one of the noteworthy sources of error in forest carbon inventories (e.g. Lehtonen et al., 2004; Guo et al., 2010; Wojtan et al., 2011; Luo et al., 2013).

In general, two different approaches are applied to transform easily measurable tree or stand characteristics to total stand biomass. Allometric equations for particular tree species (species-specific) or pooled by species group might be used when individual tree DBHs in the stand are available and the relationship between DBH and tree biomass (and its biomass components) is determined. In some cases, the relationship between biomass and DBH is replaced by tree height (Adegbi et al., 2002; Dutca et al., 2010). For forests where there is no data on DBH distribution, but volume

of trees was calculated, it is possible to convert merchantable timber volume to aboveground, belowground or total biomass based on expansion (biomass scaling up from a lower to a higher level, e.g. from stem to total stand biomass; BEF) and conversion factors (merchantable timber volume convergence into stem biomass; BCF) (Schroeder et al., 1997). Tobin and Nieuwenhuis (2007) indicated that more likely the best approach is an integration of biomass expansion and conversion components into one biomass factor. Such biomass conversion and expansion factors (BCEFs) convert the most widely available data on stem volume directly to whole tree or component biomass and finally into carbon storage. However, BCEFs produce only coarse biomass estimates. Moreover, the ratio of stand biomass to merchantable timber volume may not be suitable for biomass and carbon storage determination in young forest stands, because stem volume of such stands are usually omitted in conventional forest inventory procedures (Lehtonen et al., 2004; Jalkanen et al., 2005; Pajtik et al., 2008; Dutca et al., 2010). Additionally, in young stands stem volume determination is often more difficult and the BCEF values are largely age-dependent, thus changing dramatically in the first 10 years of stand development. For example, the steepest decline of BCEFs was observed in young stands of Norway spruce, European beech, sessile oak and Scots pine trees up to 1 m in height (Pajtik et al., 2008, 2011). In young stands BCEFs might be highly variable, which may be a result of a higher variance and greater heterogeneity of the structure of these stands, particularly in stands established naturally as an effect of secondary succession. Consequently, there is a need to find biomass conversion and expansion factors for young stands, because those established for older stands may not be relevant due to changes in biomass allocation patterns over stand age and stand developmental phase (Wirth et al., 2004; Jagodziński and Kałucka, 2008; Zasada et al., 2008; Jagodziński and Oleksyn, 2009a,b; Teobaldelli et al., 2009; Jagodziński et al., 2014).

Silver birch (*Betula pendula* Roth), a light-demanding, early-successional pioneer tree species, has a wide natural distribution in Eurasia and due to high production of seeds and very fast growth during the juvenile stage of development, birches quickly occupy open areas after clear-cuts and forest fires, as well as abandoned fields (Jögieste et al., 2003; Hynynen et al., 2010). In Poland, there are rough estimates that the area of silver birch secondary succession on abandoned farmlands covers around 900,000 ha (Krawczyk, 2015), which is almost 10% of contemporary Polish forest area (Central Statistical Office, 2015).

The main objective of the study was to develop biomass conversion and expansion factors for above- and belowground biomass components of young *Betula pendula* stands established during secondary succession on post-agricultural sites as separate functions of stand age. Since stand age affects biomass allocation, we hypothesized that BCEFs would be significantly different for rapidly growing young trees of various ages. For practical reasons we also developed models relating BCEFs to other stand-level predictors (top height, mean height, base diameter, basal area, quadratic mean diameter, volume) that can also be accurately measured using remote sensing techniques.

## 2. Material and methods

### 2.1. Study sites

Data for this study were collected in the years 2011–2012 in pure silver birch stands growing on post-agricultural lands in Mazowieckie province, central Poland (53°04'–51°18'N, 20°43'–21°56'E). Before we established the study sites, the approvals were obtained for each location from the private landowners or the

respective local managers of State Forests. The field studies did not involve endangered or protected species according to Polish law. All stands originated from natural regeneration that occurred after the cessation of farming. No silvicultural treatments had been performed by the time measurements were done on the sample plots.

All study sites were located in a zone of transition from the maritime to continental type within the temperate climate (Martyn, 2000). Mean annual temperatures were 6–8 °C. The lowest average temperature (slightly below –2 °C) was recorded in January. July was the warmest month with temperatures varying from 16 to 18 °C. The average annual rainfall in the region amounted to 550–600 mm and the area suffers from occasional droughts. Soils are generally poor in nutrients. They developed on glacio-fluvial melt water, sands, glacial tills, and clays as well as peats (northern sites). The potential natural vegetation in this region is mainly *Tilio-Carpinetum* and *Quercus-Pinetum* (Matuszkiewicz, 2008). Elevation of the sample plots ranged from 95 to 160 m a.s.l.

## 2.2. Data and methods

At each of 30 locations (Fig. 1) we selected a chronosequence consisting of four stands growing on similar soils (120 study plots in total). The age of these stands was assessed using tree-ring analyses. To achieve relatively low error of basal area, in each stand we established a rectangular sample plot comprising a minimum of 200 trees. At each location we confirmed with local owners or managers that no treatments were performed after abandonment of agricultural activities, thus we can assume that the development of stands followed the natural self-thinning process. This was also confirmed by the high homogeneity of stocking on the plots. At each plot we measured diameters of all trees at three heights – the base (0.0 m), 0.5 m and 1.3 m (DBH). Heights were measured on a sub-sample of 50 trees and a height-diameter model was used to estimate heights of all the remaining trees with measured diameters.

At each plot within a random subset of 40 plots, we randomly chose 15–20 trees from the whole range of diameters in the stand that were felled. Felled trees were measured for their stem volume

inside and outside bark (including aboveground stump and the tree top, excluding branches) as well as for merchantable timber volume (portion of the log with outside bark diameter >7 cm). In total, we obtained volumes for 786 trees. Based on these values we developed local form factors, and stem volume and merchantable timber volume equations for all 120 plots using the following equation:

$$v = g \cdot h \cdot f \quad (1)$$

where:

$v$  – tree stem/merchantable timber volume (m<sup>3</sup>),

$g$  – basal area (m<sup>2</sup>),

$h$  – tree height based on locally parametrized Näslund's function (Näslund, 1936),

$f$  – tree form factor based on locally parametrized equations.

At every second plot out of the above mentioned 40 plots, we randomly chose 10 trees from the whole range of diameters. These trees were cut down and their root systems were excavated. Then the felled trees were divided into main components: stems, foliage, branches and coarse (>2 mm of diameter) roots. Soil and other organic materials were cleared from the dug-out roots with compressed air and brushes. All parts of the individual trees were weighed in the field using precise portable scales (accuracy 0.01 g). We took samples from each of the components investigated from every tree to determine the relationship between their fresh and dry biomass. These samples were oven-dried at 105 °C until they reached a constant weight. The dry biomass of various components was calculated for each tree on the basis of corresponding fresh to dry mass ratios (Bijak et al., 2013; Bronisz et al., 2016). Based on these biomass data, we applied the approach described by Parresol (2001) to assure the additivity of the biomass equations that were used for calculations for all sample plots. During the initial analyses, outliers were removed and for further calculations, 102 sample plots were used (Table 1). Assessment of outlier trees was carried out on the basis of their graphical behavior (Belsley et al., 1980).

Based on the dry biomass per hectare of particular components (stem, branches, foliage, roots, aboveground and total biomass)

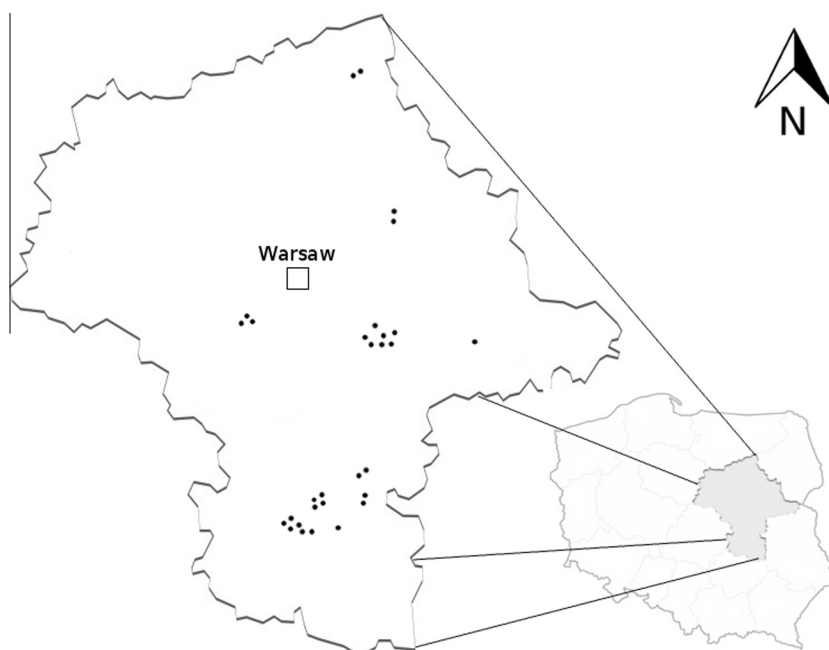


Fig. 1. Location of silver birch (*Betula pendula* Roth) chronosequences (black dots) in Mazowieckie province, central Poland.

**Table 1**

Characteristics of sample plots. Abbreviations:  $H_{100}$  – top height calculated as an average height of the 100 largest trees per hectare,  $H_g$  – mean stand height based on quadratic mean diameter,  $D_g$  – quadratic mean diameter at breast height,  $D_0$  – average stand base diameter.

Stand characteristic	Min.	Max.	Median	Mean	Std. Dev.
Age (years)	1	19	7	8	4
$H_{100}$ (m)	0.81	18.06	6.91	7.26	4.80
$H_g$ (m)	1.48	14.74	5.30	5.89	3.50
$D_g$ (cm)	0.24	9.87	2.55	3.14	2.42
$D_0$ (cm)	0.42	16.24	4.34	5.33	4.14
Basal area ( $m^2 ha^{-1}$ )	0.0133	43.5725	11.5769	11.5933	8.9803
Stem volume ( $m^3 ha^{-1}$ )	0.4400	270.6800	30.6000	50.2800	4.7200
Plot area (ha)	0.0004	0.0731	0.0079	0.0145	0.0155
Stand density (trees $ha^{-1}$ )	2926	497,500	27,680	63,193	88,966
Foliage biomass ( $Mg ha^{-1}$ )	0.0551 (3%)	6.3592 (28%)	1.9405 (7%)	2.0188 (11%)	1.0629 (8%)
Branch biomass ( $Mg ha^{-1}$ )	0.0772 (9%)	23.4893 (18%)	3.2161 (12%)	4.6699 (12%)	4.6322 (2%)
Stem biomass ( $Mg ha^{-1}$ )	0.3802 (27%)	138.3631 (73%)	17.9385 (65%)	26.4158 (58%)	27.6515 (14%)
Belowground biomass ( $Mg ha^{-1}$ )	0.1234 (12%)	27.741 (37%)	4.8354 (16%)	5.9117 (19%)	5.3031 (6%)
Aboveground biomass ( $Mg ha^{-1}$ )	0.5125 (63%)	166.4802 (88%)	23.0563 (84%)	33.1045 (81%)	33.2012 (6%)
Total biomass ( $Mg ha^{-1}$ )	0.636	193.2923	28.1553	39.0162	38.4482

and stem volume per hectare, we calculated stand-level biomass conversion and expansion factors using the following equation:

$$BCEF = \frac{B}{V} \quad (2)$$

where:

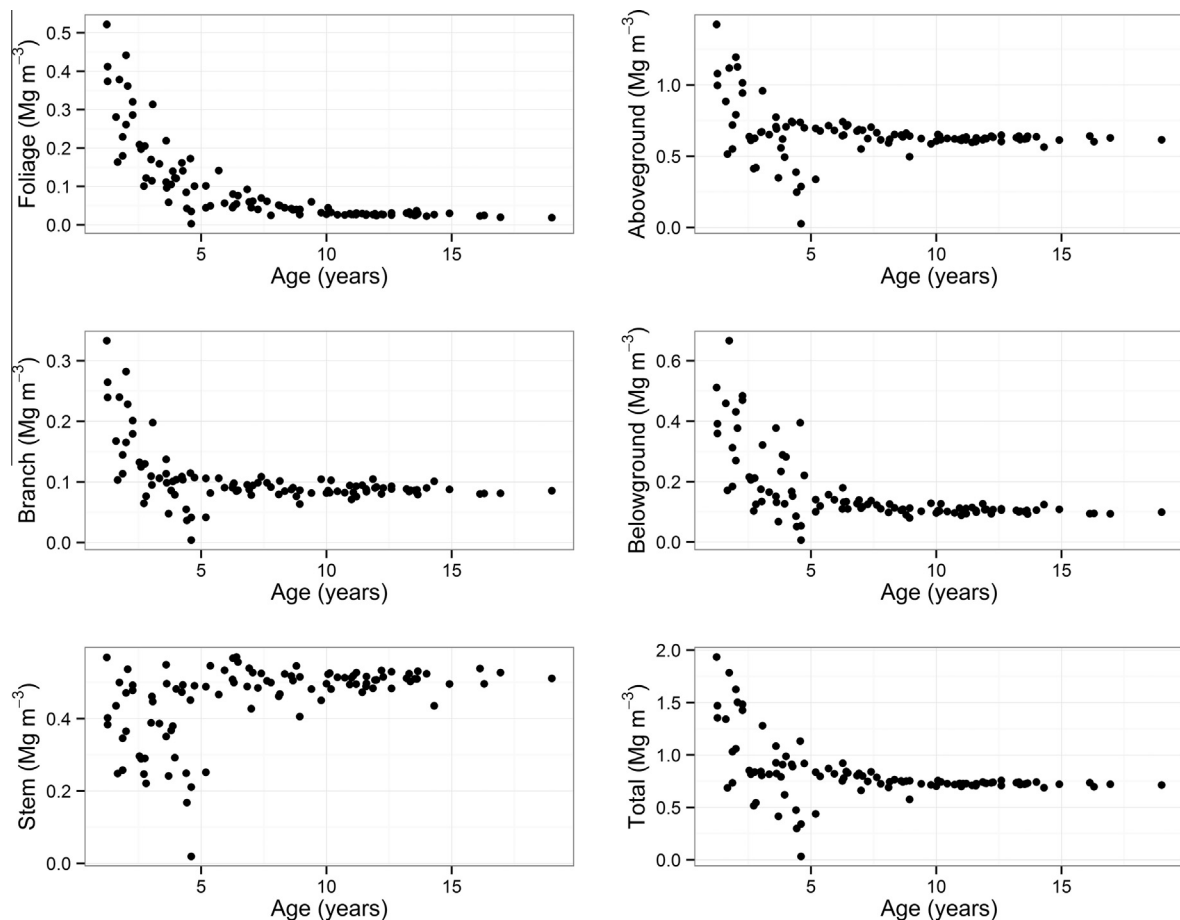
- BCEF – biomass conversion and expansion factor ( $Mg m^{-3}$ ),
- B – dry biomass ( $Mg ha^{-1}$ ),
- V – stand stem volume ( $m^3 ha^{-1}$ ).

The calculated BCEF values were plotted against age (Fig. 2). Because of the clear relationship between these variables, we

applied Ward's hierarchical clustering method (WM; Ward, 1963) to find classes of similar BCEF values. This revealed three age classes: 0–5, 5–10 and >10 years with significantly different BCEF values.

We also applied segmented (piecewise) linear regression (SLR) to elaborate the equations to determine the value of BCEF for each of the pre-determined age classes using (a) fixed break points (FBP) found earlier with the Ward method (i.e. 5 and 10 years) and (b) estimated break points (EBP) derived based on the best fit of regression models during the piecewise regression estimation.

To provide a practically useful meaning for BCEF determination, we developed a set of equations relating BCEFs for various tree



**Fig. 2.** Relationship between sample plot BCEF values ( $Mg m^{-3}$ ) and stand age for different biomass components.

biomass components with age of young birch stands as predictors. For all of the components, as well as for the total biomass, the resulting function had one or two segments, which allowed us to use Eq. (3) to calculate final BCEF in cases where age was lower than the break point:

$$BCEF = a + b \cdot z + \varepsilon \quad (3)$$

where

BCEF – biomass conversion and expansion factor of biomass component depending on age ( $\text{Mg m}^{-3}$ ),  
 a, b – equation parameters,  
 z – age (years),  
 $\varepsilon$  – error term following a normal distribution of expectation 0 and standard deviation  $\sigma$ .

For comparison we also included nonlinear regression (NR) as an alternative to the SLR method to achieve BCEF values without break points. During preliminary study we took into account five nonlinear regression models, but finally chose the one elaborated by Teobaldelli et al. (2009):

$$BCEF = a + b \cdot e^{-z^c} + \varepsilon \quad (4)$$

However, as stand age is not the most practical predictor for BCEF determination, because its precise estimation in the field is not always feasible, it does not take into account variability of stand growing conditions among sites, and does not reflect the biological state of trees, we also decided to develop equations using selected easy-to-measure stand characteristics, such as stand top

**Table 2**  
 Statistics of BCEF equation fits. Abbreviations: WM – Ward method, SLR – segmented linear regression, NR – nonlinear regression,  $H_{100}$  – top height calculated as an average height of the 100 largest trees per hectare,  $H_g$  – mean stand height based on quadratic mean diameter,  $D_g$  – quadratic mean diameter at breast height,  $D_0$  – average stand base diameter, BA – stand basal area, V – stand stem volume.

		Statistics	Foliage	Branch	Stem	Aboveground	Belowground	Total
Age (years)	WM	FBP (years)	5	5	5	–	5	–
		RSE	0.0493	0.0332	0.0966	0.15291	0.0746	0.2134
		$R^2$	0.7906	0.5542	0.1164	0.29336	0.5793	0.4373
		p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	SLR	EBP (years)	5.8000	3.6500	9.3000	–	5.5200	–
		RSE	0.0523	0.0302	0.0872	0.1537	0.0762	0.2171
		$R^2$	0.7615	0.6267	0.2723	0.2715	0.5560	0.3939
		p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	NR	RSE	0.0462	0.0302	0.0892	0.1514	0.0744	0.2159
		$R^2$	0.8170	0.6329	0.2491	0.3143	0.5835	0.4359
		p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
$H_{100}$ (m)	SLR	EBP (m)	4.6800	2.6700	7.8200	–	4.5900	–
		RSE	0.0479	0.0301	0.0872	0.1493	0.0762	0.2120
		$R^2$	0.8000	0.6299	0.2718	0.3129	0.5566	0.4220
		p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	NR	RSE	0.0424	0.0285	0.0888	0.1473	0.0765	0.2141
		$R^2$	0.8457	0.6722	0.2565	0.3505	0.5598	0.4453
		p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	SLR	EBP (m)	4.8400	2.1100	5.3000	–	3.7200	–
		RSE	0.0430	0.0261	0.0848	0.1405	0.0756	0.2026
		$R^2$	0.7327	0.4325	0.3139	0.0870	0.4662	0.2395
		p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
$H_g$ (m)	NR	RSE	0.0376	0.0267	0.0868	0.1418	0.0754	0.2093
		$R^2$	0.7989	0.4157	0.2935	0.0897	0.4773	0.2392
		p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	SLR	EBP (cm)	1.9300	0.6900	2.7300	–	1.6700	–
		RSE	0.0396	0.0235	0.0864	0.1356	0.0747	0.1968
		$R^2$	0.7738	0.5416	0.2887	0.1502	0.4781	0.2825
		p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
$D_g$ (cm)	NR	RSE	0.0349	0.0253	0.0888	0.1394	0.0732	0.2045
		$R^2$	0.8262	0.4748	0.2603	0.1137	0.5067	0.2731
		p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	SLR	EBP (cm)	2.6800	1.0200	6.1000	–	2.3200	–
		RSE	0.0497	0.0251	0.0879	0.1400	0.0718	0.1984
		$R^2$	0.7853	0.7426	0.2613	0.3955	0.6058	0.4938
		p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
$D_0$ (cm)	NR	RSE	0.0380	0.0266	0.0909	0.1448	0.0702	0.2045
		$R^2$	0.8761	0.7144	0.2207	0.3728	0.6291	0.4937
		p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	SLR	EBP (cm)	9.7200	0.8600	13.8000	–	7.4000	–
		RSE	0.0429	0.0227	0.0888	0.1341	0.0766	0.1991
		$R^2$	0.7168	0.5378	0.2641	0.1435	0.447	0.2695
		p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
BA ( $\text{m}^2 \text{ha}^{-1}$ )	NR	RSE	0.038	0.0238	0.0895	0.1359	0.0732	0.2004
		$R^2$	0.779	0.4955	0.2566	0.1205	0.4981	0.276
		p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	SLR	EBP ( $\text{m}^3 \text{ha}^{-1}$ )	26.5000	9.4000	69	–	22	–
		RSE	0.0594	0.0325	0.0912	0.1548	0.0767	0.2165
		$R^2$	0.6924	0.5700	0.2034	0.2614	0.5509	0.3973
		p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
V ( $\text{m}^3 \text{ha}^{-1}$ )	NR	RSE	0.0527	0.0335	0.0927	0.1553	0.0753	0.2205
		$R^2$	0.7615	0.5482	0.1892	0.2781	0.5677	0.4114
		p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	SLR	EBP ( $\text{m}^3 \text{ha}^{-1}$ )	26.5000	9.4000	69	–	22	–
		RSE	0.0594	0.0325	0.0912	0.1548	0.0767	0.2165
		$R^2$	0.6924	0.5700	0.2034	0.2614	0.5509	0.3973
		p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001



height ( $H_{100}$ ), mean height ( $H_g$ ), base diameter ( $D_0$ ), quadratic mean diameter at breast height ( $D_g$ ), basal area (BA) and stand volume (V) and applying two regression approaches based on the best fit during estimation. Those parameters allow calculation of BCEF using easily available variables with precise measurements, including remote sensing techniques (for example tree height). We excluded merchantable volume as a predictor, as the majority of young stands did not have any.

Goodness of fit of the resulting models and their parameters was assessed by examining pattern of residuals, residual standard errors (RSE), coefficient of determination ( $R^2$ ), and p-value (Shapiro-Wilk test) for normality of residuals. In the final step, all three analysis methods (SLR with FBP, SLR with EBP and NR) were used as a base for Seemingly Unrelated Regression (SUR). This approach enabled fulfillment of the logical assumption that the sum of the estimated biomass values of tree parts matches the estimated total biomass, assuring additivity of the biomass equations (Kozak, 1970; Chiyenda and Kozak, 1984; Cunia and Briggs, 1984; Poudel and Temesgen, 2016).

Finally, the best fitting models obtained with SLR and NR methods were subject to 10-fold cross-validation (Borra and Di Ciaccio, 2010). Such a test approach was chosen because we lacked independent empirical data for model validation.

We executed all the analyses using RStudio (RStudio Team, 2015), packages *segmented* (Muggeo, 2003, 2008) and *ggplot2* (Wickham, 2009) in R software (R Development Core Team, 2008) and PROC MODEL in SAS (SAS 9.1.3 Help and Documentation, 2002).

### 3. Results

The largest difference between FBP and EBP approaches in SLR occurred in the BCEFs for stems (5 vs 9.3 years), while the smallest difference was found for roots (5 vs 5.52 years). In general, the EBPs produced a better fit for BCEF equations than FBPs (Table 2). SLR and NR estimation methods resulted in similar accuracies for all analyzed independent variables, with higher  $R^2$  values usually obtained for the latter method. Only in the case of stem biomass did the SLR method give more precise estimates (Table 2).

During analyses of regression models it was necessary to assure homoscedasticity of the residual variance. This was done by the graphical presentation of residual distributions for SLR and NR methods (Figs. S1 and S2). For all analyzed biomass components, the majority of residuals were close to zero.

For both estimation methods (SLR and NR) values of BCEFs were very high for the youngest trees, and decreased towards the estimated break points for foliage, roots and branches (Fig. 3). In contrast, BCEF values for stem biomass initially increase towards the estimated break point (still statistically significant at the 0.01 level). Beyond the EBP, the BCEFs stabilized and their values remained constant, indicating a lack of significant effect of the given attribute. We also found no effect of predicted BCEFs on the residual values for either SLR (Fig. 4) or NR (Fig. 5) estimation methods.

In the next step of the analysis, parameters of Eq. (3) for SLR were determined based on the estimated break points for each predictor and parameters of Eq. (4) for NR (Tables 3 and 4). For the SLR

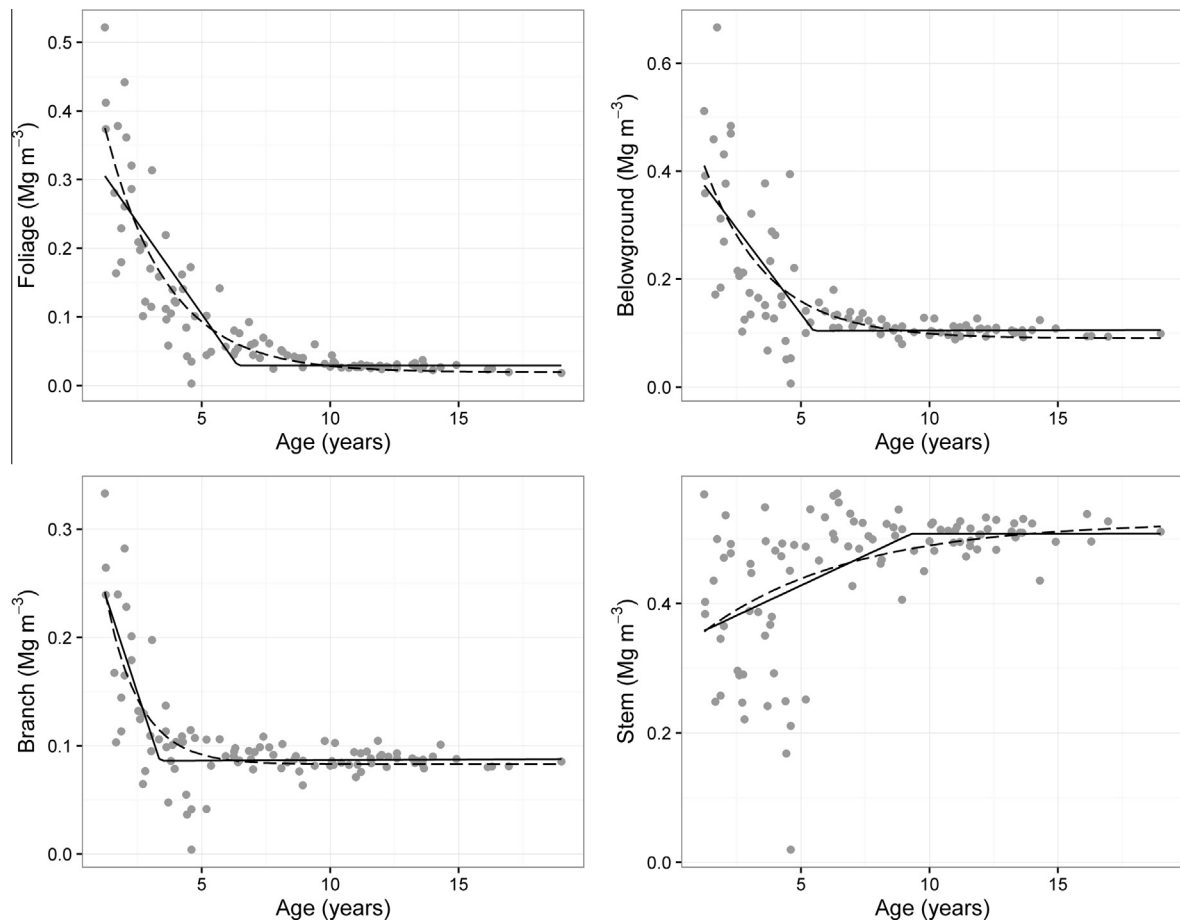


Fig. 3. Relationship between BCEF of biomass components and stand age based on SLR method (black lines) and NR method (dashed lines).

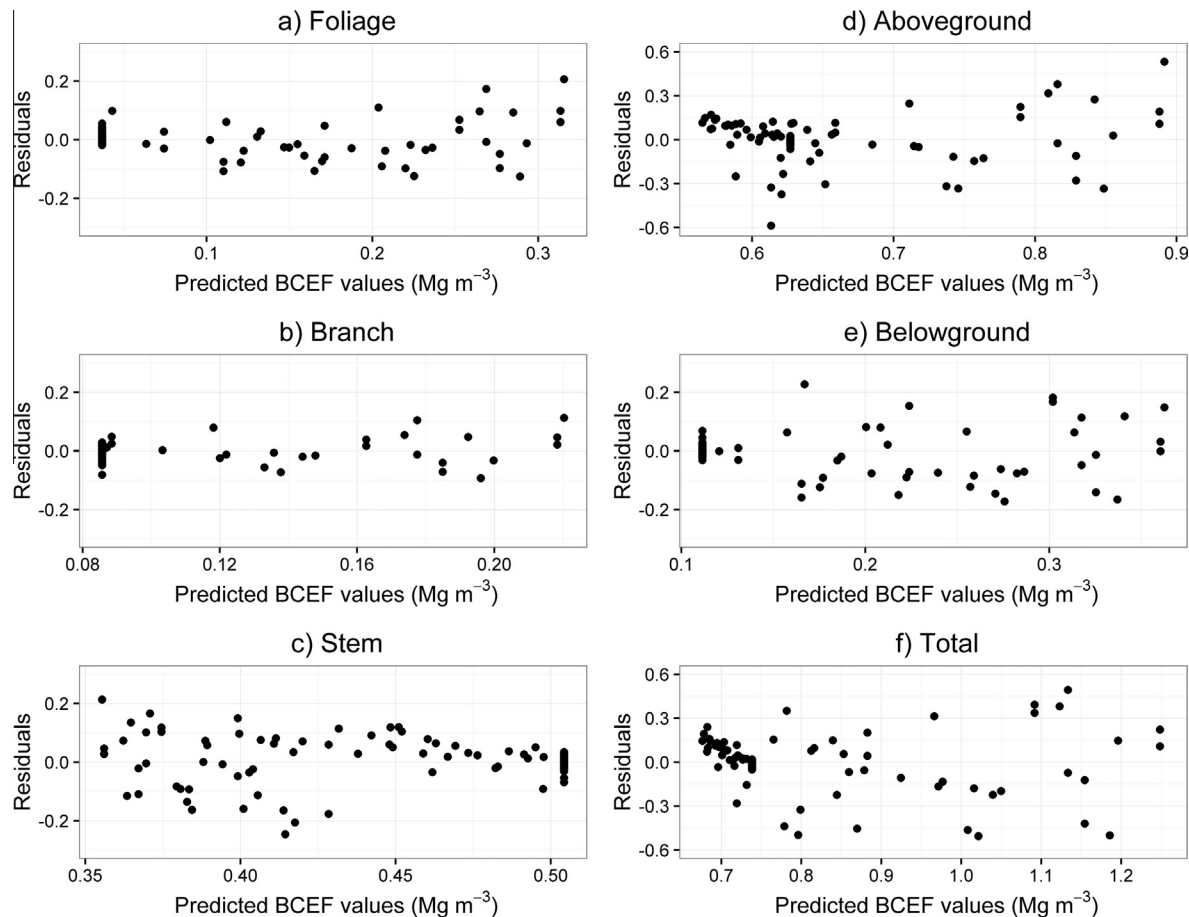


Fig. 4. Distribution of residuals against estimated biomass components for SLR method.

method the calculations of biomass conversion and expansion factors in young naturally regenerated silver birch stands can be done based on age,  $H_{100}$ ,  $H_g$ ,  $D_g$ ,  $D_0$ , BA or V with Eq. (3) and parameters shown in Table 3 for the independent attributes lower than EBP, or parameters shown in Table 4 for the independent attributes higher than EBP.

Stand age turned out to be a good predictor of standing biomass. However, it is not the most practical one, because its determination can be difficult (especially for diffuse-porous species like silver birch) and it does not reflect the influence of growth conditions on standing biomass and its allocation. Thus, other stand characteristics such as top or mean height, quadratic mean diameter, mean base diameter or stand volume might be used as more generalized predictors of BCEF, especially because all of them were significantly related to stand age (Table 5).

Results for 10-fold cross-validation (Table 6) showed that more efficient estimates of parameters can be obtained with the NR method, as mean standard error of residuals was lower than obtained for the SLR method for all the analyzed biomass components, regardless of the independent attribute applied.

#### 4. Discussion

Biomass conversion and expansion factors relate stem or merchantable timber volume to biomass stocks, and hence they are useful alternatives for allometric equations in stand biomass determination when data on individual trees is not available. However, the vast majority of BCEFs developed so far for forest tree species are relevant only to stands older than 15–20 years and do not take

into account trees with smaller dimensions. Consequently, calculation of carbon stocks for young stands, based on coefficients or equations developed for older ones, quite often leads to underestimation of the amount of sequestered carbon (Turner et al., 1995; Fang et al., 1998; Goodale et al., 2002; Zhang et al., 2012). This is a real disadvantage when carrying out accurate national inventories of forest biomass or carbon stocks according to IPCC guidelines. Thus, BCEF development should be age-dependent, otherwise biomass estimates may have significant bias (Jalkanen et al., 2005). Also, Wirth et al. (2004) pointed out the need to calculate BCEFs for young trees separately, as the values elaborated for older trees are not applicable because of differences in biomass allocation patterns that occur with stand development and tree ageing. As indicated by various research, biomass conversion and expansion factors vary with regard to tree species, biomass component, stand development phase, site index, climate, stand density, diameter distribution and forest management intensity (Brown and Lugo, 1992; Turner et al., 1995; Schroeder et al., 1997; Fang et al., 1998, 2001; Fang and Wang, 2001; Brown, 2002; Lehtonen et al., 2004; Levy et al., 2004; Jalkanen et al., 2005; Albaugh et al., 2009; Petersson et al., 2012; Luo et al., 2013; Seo et al., 2013; Enes and Fonseca, 2014; Luo et al., 2014). Among all the factors affecting BCEF values, stand age seems to be the most influential, but at the same time it alone (among those factors examined) does not reflect differences in growth conditions. The biomass of young and less productive stands is underestimated, while the biomass of older and more productive ones is overestimated, when a constant value of biomass conversion and expansion value is applied irrespectively of stand age and site conditions (Turner



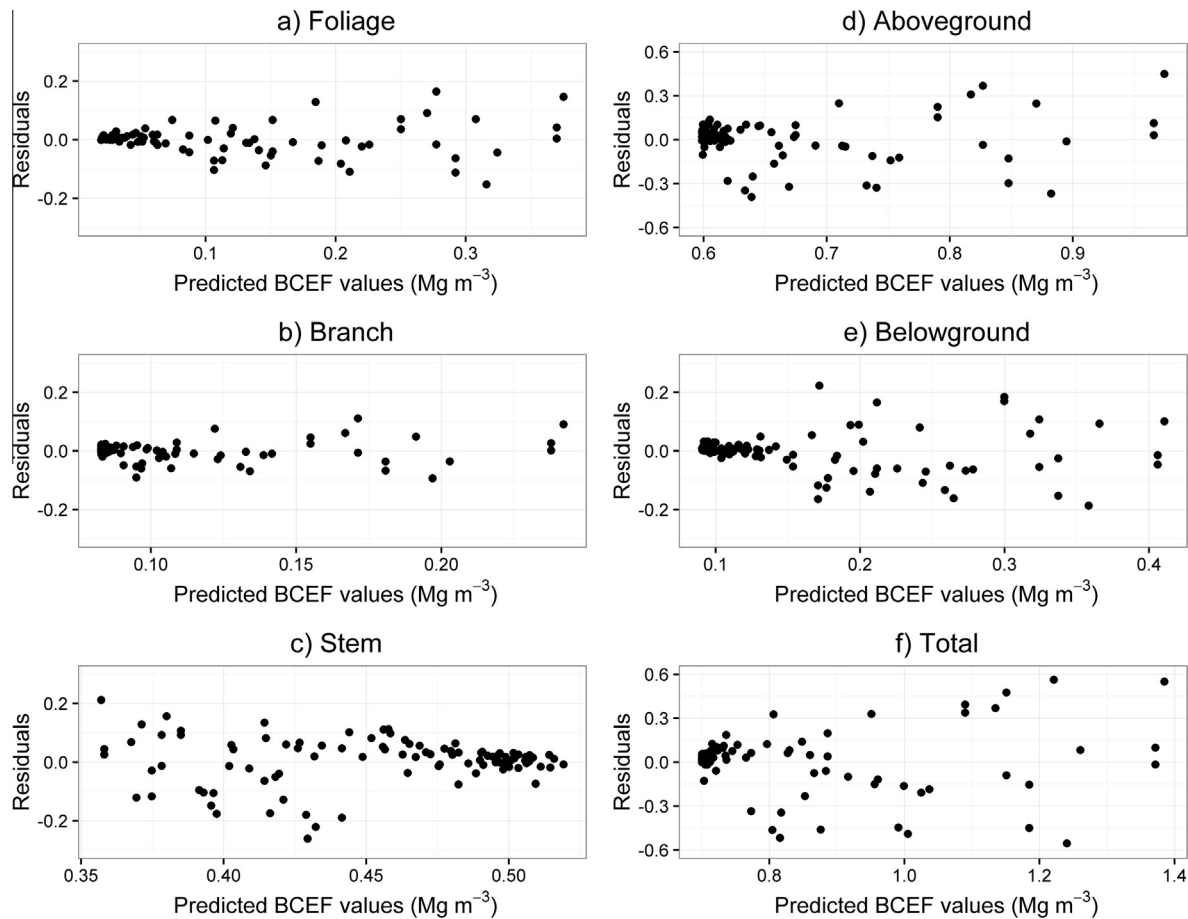


Fig. 5. Distribution of residuals against estimated biomass components for the NR method.

et al., 1995; Schroeder et al., 1997; Fang et al., 1998; Goodale et al., 2002; Teobaldelli et al., 2009; Zhang et al., 2012). However, Guo et al. (2010) stated that when BCEF is defined as a function of stem volume, it already reflects the effects of stand age, site quality and stand density (Fang et al., 2001, 2005). Our results confirmed these findings – although stand age might be a good predictor of standing biomass, other stand characteristics such as top or mean height, quadratic mean diameter, mean base diameter and stand volume demonstrate more practical meaning in biomass estimation. Significance of the parameters obtained for formulas used during BCEF determination justifies use of these attributes as the predictors.

The variable relationships between stem volume and biomass of particular components result in different BCEF values (Pajtić et al., 2008, 2011; Sanquetta et al., 2011). These changes in BCEFs are related to alterations in biomass allocation patterns, which are highly dynamic in young stands. In the silver birch stands investigated, biomass of all the components expressed on a stand level increased along with stand age (Zasada et al., 2014). Many recently published papers report that in older birch stands stem biomass continues to increase, while biomass of other components increases less and stabilizes in close-to-mature and mature stands (Hytönen et al., 1995; Johansson, 1999, 2007; Uri et al., 2007a,b, 2012; Aosaar and Uri, 2008; Varik et al., 2009). Biomass estimates based on our data are generally within the range of previously published results for young birch stands in neighbouring countries; however, data for young stands are very limited, particularly for belowground biomass. In our study, total biomass of birch stands averaged  $39.0 \text{ Mg ha}^{-1}$  and ranged from  $0.64 \text{ Mg ha}^{-1}$  to

$193 \text{ Mg ha}^{-1}$  in a chronosequence of stands 1–19 years old, whereas aboveground biomass averaged  $33.1 \text{ Mg ha}^{-1}$  and ranged from  $0.5 \text{ Mg ha}^{-1}$  to  $166.5 \text{ Mg ha}^{-1}$ . In Poland, so far, data on various aspects of biomass estimation in young silver birch stands was shown only in three papers based on the same research sites (Bijak et al., 2013; Zasada et al., 2014; Bronisz et al., 2016). Our estimates might be compared with data from other European countries. For example, Johansson (1999) studied silver birch stands 7–32 years old growing in Sweden and found a mean aboveground biomass of  $71.4 \text{ Mg ha}^{-1}$  with a range of  $5.7\text{--}175.3 \text{ Mg ha}^{-1}$ , and the mean annual increment of aboveground biomass was  $4.5 \text{ Mg ha}^{-1} \text{ year}^{-1}$ . Our study found mean aboveground biomass increment of ca.  $3.5 \text{ Mg ha}^{-1} \text{ year}^{-1}$  for the whole chronosequence studied. In Norway, 6-year-old silver birch stands in a provenance experiment had an average of ca.  $23.4 \text{ Mg ha}^{-1}$  aboveground biomass (Frivold and Borchgrevink, 1981), a value that was very similar to data obtained for 6-year-old stands in Poland ( $21.5 \text{ Mg ha}^{-1}$  for aboveground and  $25.5 \text{ Mg ha}^{-1}$  for total stand biomass). For 10-yr-old plantations of silver birch growing on abandoned agricultural soils in Latvia the aboveground standing biomass ranged from  $10.4$  to  $12.3 \text{ Mg ha}^{-1}$  (Daugaviete et al., 2008) and was distinctly lower than in our research. We found that aboveground biomass of 10-year-old stands ranged from  $28.3 \text{ Mg ha}^{-1}$  to  $74.8 \text{ Mg ha}^{-1}$  (mean value:  $45.6 \text{ Mg ha}^{-1}$ ) and mean aboveground biomass increment was  $4.5 \text{ Mg ha}^{-1} \text{ year}^{-1}$ . Ferm and Kaunisto (1983) reported a standing biomass for stem and branches in a 14-year-old birch stand growing on peat land in Finland as  $59 \text{ Mg ha}^{-1}$ , a value similar to what we found here. In Estonia Uri et al. (2007b) found that aboveground biomass of 8-year-old birch stands growing on

**Table 3**

Parameters (a, b, c) and their standard errors (in brackets). Abbreviations: SLR – segmented linear regression, NR – nonlinear regression  $H_{100}$  – top height calculated as an average height of the 100 largest trees per hectare,  $H_g$  – mean stand height based on quadratic mean diameter,  $D_g$  – quadratic mean diameter at breast height,  $D_0$  – average stand base diameter, BA – stand basal area, V – stand stem volume.

			Foliage	Branch	Stem	Belowground
Age (years)	SLR	a	0.39068 (0.01780)	0.28885 (0.02920)	0.33273 (0.02350)	0.43470 (0.03170)
		b	–0.06097 (0.00430)	–0.05566 (0.01280)	0.01845 (0.00412)	–0.05856 (0.00885)
	NR	a	0.01950 (0.00673)	0.08293 (0.00370)	0.52700 (0.03580)	0.09036 (0.01150)
		b	0.59540 (0.04310)	0.40775 (0.05550)	–0.21039 (0.03900)	0.53038 (0.07180)
$H_{100}$ (m)	SLR	c	0.41832 (0.03100)	0.76468 (0.07910)	0.17349 (0.09900)	0.40980 (0.06230)
		a	0.36830 (0.01700)	0.27427 (0.01830)	0.32926 (0.01980)	0.39448 (0.02580)
	NR	b	–0.07104 (0.00540)	–0.07033 (0.01060)	0.02236 (0.00394)	–0.06263 (0.00867)
		a	0.03009 (0.00600)	0.08727 (0.00475)	0.56498 (0.06940)	0.10158 (0.01100)
$H_g$ (m)	SLR	b	0.56295 (0.03950)	0.72460 (0.23990)	–0.22346 (0.05440)	0.45477 (0.06650)
		c	0.57053 (0.04760)	1.58720 (0.31210)	0.11557 (0.08300)	0.52411 (0.09390)
	NR	a	0.29871 (0.01460)	0.33940 (0.04300)	0.27938 (0.02570)	0.38868 (0.03920)
		b	–0.05925 (0.00443)	–0.11944 (0.02450)	0.04234 (0.00737)	–0.07534 (0.01610)
$D_g$ (cm)	SLR	a	0.02486 (0.00504)	0.08435 (0.00332)	0.49972 (0.01230)	0.09700 (0.01030)
		b	0.65228 (0.07580)	0.73556 (0.33570)	–0.43731 (0.17440)	0.69927 (0.19860)
	NR	c	0.70538 (0.05830)	1.53012 (0.28260)	0.66266 (0.20850)	0.76938 (0.15270)
		a	0.25231 (0.01040)	0.21528 (0.04340)	0.34299 (0.02080)	0.32455 (0.02270)
$D_0$ (cm)	SLR	b	–0.11306 (0.00780)	–0.18825 (0.13200)	0.05880 (0.01450)	–0.13049 (0.02620)
		a	0.02450 (0.00461)	0.08408 (0.00307)	0.49511 (0.01250)	0.09621 (0.0100)
	NR	b	0.30387 (0.01730)	0.14409 (0.02520)	–0.19943 (0.04630)	0.30930 (0.04060)
		c	1.13972 (0.0866)	2.56261 (0.48120)	1.13652 (0.40420)	1.25934 (0.23960)
BA ( $m^2 ha^{-1}$ )	SLR	a	0.35940 (0.01500)	0.49712 (0.04070)	0.36072 (0.02160)	0.42918 (0.02840)
		b	–0.11996 (0.00819)	–0.40518 (0.05150)	0.02303 (0.00832)	–0.13833 (0.02120)
	NR	a	0.02965 (0.00473)	0.08286 (0.00304)	0.49256 (0.01350)	0.09710 (0.00901)
		b	0.58221 (0.03720)	0.41819 (0.04690)	–0.16350 (0.04680)	0.49141 (0.06350)
V ( $m^3 ha^{-1}$ )	SLR	c	1.06488 (0.07010)	1.94960 (0.16620)	0.52688 (0.24020)	0.95565 (0.14030)
		a	0.20442 (0.00921)	0.18235 (0.01120)	0.36483 (0.01720)	0.27962 (0.01680)
	NR	b	–0.01760 (0.00132)	–0.11170 (0.03250)	0.01044 (0.00202)	–0.02413 (0.00390)
		a	0.03521 (0.00523)	0.08604 (0.00272)	0.51144 (0.01710)	0.10979 (0.00903)
	SLR	b	0.20672 (0.01160)	0.07601 (0.00758)	–0.15916 (0.02400)	0.21629 (0.02370)
		c	0.30946 (0.30946)	1.18612 (0.25160)	0.14131 (0.05130)	0.46303 (0.10920)
	NR	a	0.27458 (0.01330)	0.22350 (0.01530)	0.38537 (0.01520)	0.33694 (0.01890)
		b	–0.00905 (0.00079)	–0.01480 (0.00305)	0.00177 (0.00041)	–0.01043 (0.00169)
	SLR	a	0.02728 (0.00683)	0.08216 (0.00405)	0.49350 (0.01450)	0.09735 (0.01010)
		b	0.32357 (0.02050)	0.14844 (0.01510)	–0.12424 (0.02930)	0.29944 (0.03020)
	NR	c	0.08863 (0.00903)	0.15429 (0.02170)	0.04887 (0.02460)	0.08990 (0.01580)

**Table 4**

BCEF values for the SLR method and parameters higher than estimated break points (EBP).

	Foliage	Branch	Stem	Belowground	Total
Age (years)	0.03705	0.08569	0.50430	0.11145	0.73849
$H_{100}$ (m)	0.03584	0.08648	0.50410	0.10701	0.73343
$H_g$ (m)	0.03270	0.08739	0.50379	0.10842	0.73230
$D_g$ (cm)	0.03411	0.08539	0.50351	0.10663	0.72964
$D_0$ (cm)	0.03791	0.08384	0.50121	0.10825	0.73121
BA ( $m^2 ha^{-1}$ )	0.03335	0.08629	0.50895	0.10106	0.72965
V ( $m^3 ha^{-1}$ )	0.03476	0.08438	0.50716	0.10748	0.73377

**Table 5**

Parameters of linear models for  $H_{100}$ ,  $H_g$ ,  $D_g$ ,  $D_0$ , BA and V determination based on stand age. Prediction formula: Predictor = a + Age \* b; bold font – statistically significant parameters at the significance level  $p < 0.001$ . Abbreviations:  $H_{100}$  – top height calculated as an average height of the 100 largest trees per hectare,  $H_g$  – mean stand height based on quadratic mean diameter,  $D_g$  – quadratic mean diameter at breast height,  $D_0$  – average stand base diameter, V – stand stem volume, SE – standard error.

Predictor	a	SE	b	SE	RSE	R <sup>2</sup>
$H_{100}$ (m)	–0.32854	0.34469	<b>0.99989</b>	0.03936	1.73800	0.86590
$H_g$ (m)	–0.16900	0.25611	<b>0.76757</b>	0.02854	1.19900	0.88390
$D_g$ (cm)	<b>–0.91119</b>	0.21748	<b>0.51333</b>	0.02424	1.01800	0.82520
$D_0$ (cm)	<b>–1.23180</b>	0.32660	<b>0.86500</b>	0.03730	1.64700	0.84320
BA ( $m^2 ha^{-1}$ )	–1.80740	1.16200	<b>1.67840</b>	0.12820	5.33600	0.65080
V ( $m^3 ha^{-1}$ )	<b>–22.67450</b>	5.89220	<b>10.03330</b>	0.67280	29.71000	0.68980

abandoned agricultural land varied from 6.0 to 22.9  $Mg ha^{-1}$  (whereas in our study aboveground biomass of 8-year-old stands varied considerably and ranged from 9.8  $Mg ha^{-1}$  to 100.8  $Mg ha^{-1}$  (mean value: 41.9  $Mg ha^{-1}$ )). The differences in standing biomass

described above might be explained not only by various site conditions where the stands were growing, but also by differences in methodological approach used. Most data on standing biomass of birch stands were based on site-specific allometric equations

**Table 6**

Residual standard errors for K-fold cross validation. SLR – segmented linear regression, NR – nonlinear regression.

			Foliage	Branch	Stem	Aboveground	Belowground	Total
Age (years)	SLR	Min.	0.03488	0.01701	0.04846	0.08484	0.04446	0.12621
		Max.	0.08826	0.05204	0.15156	0.25014	0.17428	0.40478
		Mean	0.05431	0.03179	0.08634	0.15804	0.07782	0.22516
	NR	Min.	0.02313	0.01395	0.04501	0.06200	0.03487	0.09453
		Max.	0.06724	0.04344	0.15364	0.23345	0.14174	0.29660
		Mean	0.04397	0.02864	0.08324	0.14281	0.06914	0.20097
$H_{100}$ (m)	SLR	Min.	0.02866	0.01696	0.06043	0.07647	0.03797	0.07143
		Max.	0.09244	0.05619	0.15619	0.24581	0.18064	0.41077
		Mean	0.04912	0.03081	0.08584	0.15038	0.07265	0.20968
	NR	Min.	0.02323	0.01474	0.05596	0.07933	0.03172	0.05322
		Max.	0.07229	0.04459	0.15301	0.22828	0.16464	0.35105
		Mean	0.04026	0.02685	0.08407	0.13909	0.06744	0.17909
$H_g$ (m)	SLR	Min.	0.01128	0.00546	0.05460	0.06255	0.03602	0.07796
		Max.	0.06772	0.04442	0.16497	0.25845	0.17709	0.35164
		Mean	0.04097	0.02429	0.08198	0.13399	0.06846	0.18987
	NR	Min.	0.00907	0.00511	0.03733	0.04229	0.02814	0.04744
		Max.	0.05779	0.04445	0.16976	0.25759	0.15088	0.35310
		Mean	0.03338	0.02386	0.07703	0.12659	0.06464	0.18042
$D_g$ (cm)	SLR	Min.	0.01038	0.00546	0.04666	0.05995	0.03568	0.07934
		Max.	0.05762	0.03680	0.16360	0.23879	0.15187	0.32836
		Mean	0.03678	0.02155	0.08046	0.12645	0.06643	0.18087
	NR	Min.	0.00713	0.00474	0.03942	0.04844	0.02958	0.05681
		Max.	0.05081	0.04120	0.17247	0.25287	0.14695	0.34032
		Mean	0.03211	0.02325	0.08000	0.12718	0.06429	0.17987
$D_0$ (cm)	SLR	Min.	0.03028	0.01256	0.05853	0.09826	0.04602	0.13460
		Max.	0.08848	0.06605	0.15499	0.23672	0.16530	0.36991
		Mean	0.05031	0.02651	0.08850	0.14251	0.07260	0.20193
	NR	Min.	0.01715	0.01096	0.04278	0.06430	0.04054	0.07737
		Max.	0.06564	0.04714	0.15774	0.24386	0.13248	0.32043
		Mean	0.03418	0.02438	0.08481	0.13466	0.06666	0.18619
BA ( $\text{m}^2 \text{ha}^{-1}$ )	SLR	Min.	0.06949	0.00988	0.08596	0.03452	0.07696	0.05720
		Max.	0.10288	0.03902	0.14324	0.24429	0.14096	0.36708
		Mean	0.08876	0.02322	0.11023	0.12700	0.10304	0.20432
	NR	Min.	0.01540	0.01145	0.03004	0.05191	0.01415	0.06751
		Max.	0.05091	0.03764	0.15412	0.22775	0.11249	0.31155
		Mean	0.03613	0.02227	0.07995	0.12677	0.06591	0.18366
$V$ ( $\text{m}^3 \text{ha}^{-1}$ )	SLR	Min.	0.02726	0.01694	0.05394	0.08989	0.04004	0.14425
		Max.	0.10773	0.05726	0.14850	0.25683	0.18369	0.42070
		Mean	0.05863	0.03389	0.08619	0.15537	0.07434	0.21867
	NR	Min.	0.01967	0.01813	0.04597	0.07200	0.03694	0.13217
		Max.	0.08056	0.05132	0.15242	0.25653	0.14710	0.33298
		Mean	0.05013	0.03185	0.08664	0.14537	0.06988	0.20399

where diameter at breast height was the only variable used for biomass calculations. Our previous paper (Bronisz et al., 2016) has shown that silver birch biomass estimates derived based on models from the neighbouring countries are mostly similar to the data revealed in our study (for individual trees). However, it must be pointed out that the inclusion of tree height in biomass equations may reduce potential differences in total stand biomass as a result of variability in growing conditions.

We observed fast dynamics of biomass allocation in the stands analyzed. Fraction of stem biomass in the total stand biomass was the highest among all the components analyzed and increased distinctly with increasing stand age. Biomass allocation to below-ground biomass and foliage decreased over stand age, whereas the branch biomass ratio remained rather constant for the whole chronosequence (Bijak et al., 2013; Zasada et al., 2014). Similar findings were reported by Pajtić et al. (2008) for young Norway spruce stands in Slovakia. During the first ten years of stand development, the biomass allocation to various tree components changed considerably. Pajtić et al. (2011) also noticed that in young naturally regenerated beech, oak and pine stands, biomass allocation patterns depended on tree size. The relative contribution of stem biomass to total biomass increased as trees grew larger, whereas the proportion of other biomass components decreased.

Silver birch stands in our study developed in a spontaneous way (secondary succession), and no pre-commercial thinnings were done, resulting in high-density stands, possibly leading to more rapid changes of stand biomass over age in comparison with artificially planted trees with usually lower initial stand densities (Jagodziński and Oleksyn, 2009a,b).

Biomass conversion and expansion factors for all the biomass components analyzed in our study did not change much after reaching the estimated break points (EBP), which is consistent with previous findings (Sharp et al., 1975; Turner et al., 1995). However, for all the biomass components except stem biomass, BCEFs diminished rapidly to the EBP (Fig. 3) and the particular values changed several-fold during the first years of stand development. For a Sitka spruce chronosequence ranging from 9 to 45 years, Tobin and Nieuwenhuis (2007) found that when stand age increased, all BEFs decreased exponentially and were close to constant for stands over 20 years old. Lehtonen et al. (2004) showed that BCEFs for foliage and branches decreased with increasing age of Scots pine and Norway spruce trees in stands from 10 to about 140 years old, while the opposite trend was found for the root and stem components. Similar relationships can be observed when BCEF values are related to tree size. Pajtić et al. (2008) found this for young Norway spruce stands in Slovakia. Dutca et al. (2010) reported initial decrease in

BCEF values for needles and roots of 1–12-year-old spruce plantations established on non-forest lands in the Eastern Carpathians (Romania) that was followed by a more or less stable value towards the end of the size range. The noticeable drop of BCEF values (except for the stem biomass) might be also related to canopy closure time (Bijak et al., 2014; Tomusiak et al., 2014). After canopy closure BCEFs start to stabilize and this might be related to the estimated break point.

In young stands merchantable timber volume may not exist (e.g. trees with diameter higher than 7 cm), which reduces the usefulness of BCEFs in early stages of stand development. As reported by Dutca et al. (2010), for small trees application of tree height gives better biomass estimates than using root-collar diameter. In contrast, Pajtk et al. (2008) found that stem base diameter offers slightly more precise estimates of biomass of young Norway spruce trees than their height, while Sanquetta et al. (2011) reported that for 2–24-year-old *Pinus elliptica* and *P. taeda* grown in Brazil, DBH was more closely associated with BCEF than tree height or age. Our results show that other stand parameters (e.g. top or mean height, quadratic mean diameter, mean base diameter or volume) might also be good biomass predictors for young silver birch stands. However, taking into account labour intensity of the measurements or potential use of remote sensing techniques, it seems that any variant with height as a predictor should be considered as the optimal one, especially for younger stands.

## 5. Conclusions

Biomass conversion and expansion factors (BCEFs) elaborated here may be a useful tool for assessing the biomass and carbon sequestration of naturally regenerated silver birch stands. They should, however, only be applied for young stands (1–19 years old) growing in conditions similar to those described here, because BCEFs are site specific. For total biomass and all biomass components except stem, the calculated BCEFs are very high for the youngest, shortest, thinnest trees, and hence stands with low volume. Their values decrease along with age, height, diameter and volume towards the estimated break points. For individuals older, taller, thicker and with higher volume than EBP, there is no influence of age,  $H_{100}$ ,  $H_g$ ,  $D_0$ ,  $D_g$  and  $V$  on BCEF value. Our study confirmed that top height ( $H_{100}$ ) might be a good biomass predictor for young birch stands, which is particularly important because measuring tree height is not as time consuming as tree diameter measurements, particularly for young and very dense stands, and this parameter can be obtained from remote sensing technology. The use of a constant BCEF is reliable only for stands whose parameters exceed certain thresholds expressed by estimated break points.

The use of non-linear regression produces results comparable to segmented linear regression. However, estimates of nonlinear parameters are more efficient than the linear ones. At the same time, segmented regression allows for better description and interpretation of the relationship between BCEFs and stand-level predictors, as they show the threshold beyond which the stand features analyzed no longer influence values of BCEFs.

## Acknowledgements

The research was financially supported by the research grant N N305 400238 'Ecological consequences of the silver birch (*Betula pendula* Roth) secondary succession on abandoned farmlands in central Poland' funded by the Polish National Science Center and by the General Directorate of State Forests, Warsaw, Poland, by the research grant: 'Environmental and genetic factors affecting productivity of forest ecosystems on forest and post-industrial

habitats'. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. We kindly thank Dr. Lee E. Frelich (University of Minnesota, USA) for valuable comments on the early draft of the manuscript. We also thank two anonymous reviewers for their detailed and helpful criticism on the first version of the manuscript.

## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.foreco.2016.10.051>.

## References

- Adegbi, H.G., Jokela, E.J., Comerford, N.B., Barros, N.F., 2002. Biomass development for intensively managed loblolly pine plantations growing on Spodosols in the southeastern USA. *For. Ecol. Manage.* 167, 91–102.
- Alard, D., Chabrier, O., Dutoit, T., Roche, P., Langlois, E., 2005. Patterns of secondary succession in calcareous grasslands: can we distinguish the influence of former land uses from present vegetation data? *Basic Appl. Ecol.* 6, 161–173.
- Albaugh, T.J., Bergh, J., Lundmark, T., Nilsson, U., Stape, J.L., Allen, H.L., Linder, S., 2009. Do biological expansion factors adequately estimate stand-scale aboveground component biomass for Norway spruce? *For. Ecol. Manage.* 258, 2628–2637.
- Alcantara, C., Kuemmerle, T., Prishchepov, A.V., Radeloff, V.C., 2012. Mapping abandoned agriculture with multi-temporal MODIS satellite data. *Rem. Sens. Environ.* 124, 334–347.
- Aosaar, J., Uri, V., 2008. Biomass production of grey alder, hybrid alder and silver birch stands on abandoned agricultural land. *For. Stud.* 48, 53–66.
- Baeten, L., Velghe, D., Vanhellemont, M., De Frenne, P., Hermy, M., Verheyen, K., 2010. Early trajectories of spontaneous vegetation recovery after intensive agricultural land use. *Restor. Ecol.* 18, 379–386.
- Belsley, D.A., Kuh, E., Welsch, R.E., 1980. *Regression Diagnostics: Identifying Influential Data and Sources of Collinearity*. John Wiley and Sons Incorporation, Hoboken, New York, USA <http://doi.wiley.com/10.1002/0471725153>.
- Benayas, J.M.R., Martins, A., Nicolau, J.M., Schulz, J.J., 2007. Abandonment of agricultural land: an overview of drivers and consequences. *CAB Rev.: Persp. Agr., Vet. Sci., Nutr. Nat. Res.* 2, #057.
- Bijak, Sz., Bronisz, K., Szydlowska, P., Wojtan, R., 2014. Effect of site quality on self-thinning dynamics in silver birch stands on abandoned farmlands. *Sylvan* 158, 423–430.
- Bijak, Sz., Zasada, M., Bronisz, A., Bronisz, K., Czajkowski, M., Ludwisiak, L., Tomusiak, R., Wojtan, R., 2013. Estimating coarse roots biomass in young silver birch stands on post-agricultural lands in central Poland. *Silva Fenn.* 47, #963.
- Birdsey, R., Angeles-Perez, G., Kurz, W.A., Lister, A., Olguin, M., Pan, Y., Wayson, C., Wilson, B., Johnson, K., 2013. Approaches to monitoring changes in carbon stocks for REDD+. *Carbon Manage.* 4, 519–537.
- Borra, S., Di Ciccio, A., 2010. Measuring the prediction error. A comparison of cross-validation, bootstrap and covariance penalty methods. *Comput. Stat. Data Anal.* 54, 2976–2989.
- Bronisz, K., Strub, M., Cieszewski, C.J., Bijak, Sz., Bronisz, A., Tomusiak, R., Wojtan, R., Zasada, M., 2016. Empirical equations for estimating aboveground biomass of *Betula pendula* growing on former farmland in central Poland. *Silva Fenn.* 50. <http://dx.doi.org/10.14214/sf.1559>. #1559.
- Brown, S., 2002. Measuring carbon in forests: current status and future challenges. *Environ. Pollut.* 116, 363–372.
- Brown, S., Lugo, A.E., 1992. Above ground biomass estimates for tropical moist forests of the Brazilian Amazon. *Interciencia* 17, 8–18.
- Buraczek, W., 2013. *Struktura i wartość hodowlana samosiewów gatunków drzewiastych w początkowej fazie sukcesji wtórnej na gruntach porolnych niżowej części Polski*. Wydawnictwo SGGW, Warszawa.
- Central Statistical Office, 2015. *Leśnictwo – Forestry*. Główny Urząd Statystyczny, Warszawa.
- Chiyenda, S.S., Kozak, A., 1984. Additivity of component biomass regression equations when the underlying model is linear. *Can. J. For. Res.* 14, 441–446. <http://dx.doi.org/10.1139/x00-202>.
- Cunia, T., Briggs, R.D., 1984. Forcing additivity of biomass tables – some empirical results. *Can. J. For. Res.* 14, 376–384. <http://dx.doi.org/10.1139/x85-006>.
- Daugaviete, M., Gaitnieks, T., Kļaviņa, D., Teliševa, G., 2008. Carbon accumulation in the above-ground and root biomass of pine, birch and spruce cultivated in agricultural soils. *Mežzinātne* 18, 35–52 [In Latvian].
- Dutca, I., Abrudan, I.V., Stancioiu, P.T., Blujdea, V., 2010. Biomass conversion and expansion factors for young Norway spruce (*Picea abies* (L.) Karst.) trees planted on non-forest lands in Eastern Carpathians. *Not. Bot. Horti. Agrobi.* 38, 286–292.
- Eggers, T., 2002. *The Impacts of Manufacturing and Utilization of Wood Products on the European Carbon Budget*. Internal Report 9. European Forest Institute, Joensuu.



- Enes, T.D., Fonseca, T.F., 2014. Biomass conversion and expansion factors are affected by thinning. *For. Syst.* 23, 438–447.
- Fahey, T.J., Woodbury, P.B., Battles, J.J., Goodale, Ch.L., Hamburg, S., Ollinger, S., Woodall, Ch.W., 2009. Forest carbon storage: ecology, management, and policy. *Front Ecol. Environ.* 8, 245–252.
- Fang, J., Chen, A., Peng, C., Zhao, S., Ci, L., 2001. Changes in forest biomass carbon storage in China between 1949 and 1998. *Science* 292, 2320–2322.
- Fang, J., Oikawa, T., Kato, T., Mo, W., Wang, Z., 2005. Biomass carbon accumulation by Japan's forests from 1947 to 1995. *Glob. Biogeochem. Cycle* 19, #GB2004.
- Fang, J., Wang, G.G., Liu, G., Xu, S., 1998. Forest biomass of China: an estimate based on the biomass-volume relationship. *Ecol. Appl.* 8, 1084–1091.
- Fang, J.-Y., Wang, Z.M., 2001. Forest biomass estimation at regional and global levels, with special reference to China's forest biomass. *Ecol. Res.* 16, 587–592.
- Ferm, A., Kaunisto, S., 1983. Above-ground leafless biomass production of naturally generated birch stands in a peat cut-over area at Aitonneseva, Kihniö. *Folia Forestalia* 558, 1–32.
- Frivold, L.H., Borchgrevink, I., 1981. Biomass yield of silver birch (*Betula verrucosa* Ehrh.) in a 6 years old trial plantation at Ås, Norway. *Sci. Rep. Agr. Univ. Norway* 60, 1–17.
- Galik, C.S., Jackson, R.B., 2009. Risks to forest carbon offset projects in a changing climate. *For. Ecol. Manage.* 257, 2209–2216.
- Gawęda, T., Małek, S., Zasada, M., Jagodziński, A.M., 2014. Allocation of elements in a chronosequence of silver birch afforested on former agricultural lands. *Drewno* 57, 107–118.
- Goodale, Ch.L., Apps, M.J., Birdsey, R.A., Field, Ch.B., Heath, L.S., Houghton, R.A., Jenkins, J.C., Kohlmaier, G.H., Kurz, W., Liu, S., Nabuurs, G.-J., Nilsson, S., Shvidenko, A.Z., 2002. Forest carbon sinks in the Northern Hemisphere. *Ecol. Appl.* 12, 891–899.
- Guo, Z., Fang, J., Pan, Y., Birdsey, R., 2010. Inventory-based estimates of forest biomass carbon stocks in China: a comparison of three methods. *For. Ecol. Manage.* 259, 1225–1231.
- Houghton, R.A., 2003. Why are estimates of the terrestrial carbon balance so different? *Glob. Chang. Biol.* 9, 500–509.
- Houghton, R.A., 2005. Aboveground forest biomass and the global carbon balance. *Glob. Chang. Biol.* 11, 945–958.
- Hynynen, J., Niemistö, P., Viherä-Aarnio, A., Brunner, A., Hein, S., Velling, P., 2010. Silviculture of birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.) in northern Europe. *Forestry* 83, 103–119.
- Hytönen, J., Saarsalmi, A., Rossi, P., 1995. Biomass production and nutrient uptake of short-rotation plantations. *Silva Fenn.* 29, 117–139.
- Jagodziński, A.M., Jarosiewicz, G., Karolewski, P., Oleksyn, J., 2012. Carbon concentration in the biomass of common species of understory shrubs. *Sylvan* 156, 650–662.
- Jagodziński, A.M., Kałucka, I., 2008. Age-related changes in leaf area index of young Scots pine stands. *Dendrobiology* 59, 57–65.
- Jagodziński, A.M., Kałucka, I., Horodecki, P., Oleksyn, J., 2014. Aboveground biomass allocation and accumulation in a chronosequence of young *Pinus sylvestris* stands growing on a lignite mine spoil heap. *Dendrobiology* 72, 139–150.
- Jagodziński, A.M., Oleksyn, J., 2009a. Ecological consequences of silviculture at variable stand densities. I. Stand growth and development. *Sylvan* 153, 75–85.
- Jagodziński, A.M., Oleksyn, J., 2009b. Ecological consequences of silviculture at variable stand densities. II. Biomass production and allocation, nutrient retention. *Sylvan* 153, 147–157.
- Jalkanen, A., Mäkipää, R., Ståhl, G., Lehtonen, A., Petersson, H., 2005. Estimation of the biomass stock of trees in Sweden: comparison of biomass equations and age-dependent biomass expansion factors. *Ann. For. Sci.* 62, 845–851.
- Jenkins, J.C., Chojnacki, D.C., Heath, L.S., Birdsey, R.A., 2003. National-scale biomass estimators for United States tree species. *For. Sci.* 49, 12–35.
- Jögieste, K., Vares, A., Sendrós, M., 2003. Restoration of former agricultural fields in Estonia: comparative growth of planted and naturally regenerated birch. *Forestry* 76, 209–219.
- Johansson, T., 1999. Biomass equations for determining fractions of pendula and pubescent birches growing on abandoned farmland and some practical implications. *Biomass Bioenerg.* 16, 223–238.
- Johansson, T., 2007. Biomass production and allometric above- and below-ground relations for young birch stands planted at four spacings on abandoned farmland. *Forestry* 80, 41–52.
- Kauppi, P.E., Mielikäinen, K., Kuusela, K., 1992. Biomass and carbon budget of European forests, 1971 to 1990. *Science* 256, 70–74.
- Keith, H., Mackey, B.G., Lindenmayer, D.B., 2009. Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon-dense forests. *Proc. Natl. Acad. Sci. USA* 106, 11635–11640.
- Kozak, A., 1970. Methods for ensuring additivity of biomass components by regression analysis. *For. Chron.* 46, 402–405. <http://dx.doi.org/10.5558/ftc46402-5>.
- Krawczyk, R., 2015. Afforestation and secondary succession. *For. Res. Pap.* 75, 423–427. <http://dx.doi.org/10.2478/frp-2014-0039>.
- Lehtonen, A., Mäkipää, R., Heikkinen, J., Sievänen, R., Liski, J., 2004. Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests. *For. Ecol. Manage.* 188, 211–224.
- Levy, P.E., Hale, S.E., Nicoll, B.C., 2004. Biomass expansion factors and root: shoot ratios for coniferous tree species in Great Britain. *Forestry* 77, 421–430.
- Lippke, B., Oneil, E., Harrison, R., Skog, K., Gustavsson, L., Sathre, R., 2011. Life cycle impacts of forest management and wood utilization on carbon mitigation: knowns and unknowns. *Carbon Manage.* 2, 303–333.
- Luo, Y., Wang, X., Zhang, X., Ren, Y., Poorter, H., 2013. Variation in biomass expansion factors for China's forests in relation to forest type, climate, and stand development. *Ann. For. Sci.* 70, 589–599.
- Luo, Y., Zhang, X., Wang, X., Ren, Y., 2014. Dissecting variation in biomass conversion factors across China's forests: implications for biomass and carbon accounting. *PLoS ONE* 9, e94777.
- Malmheimer, R.W., Bowyer, J.L., Fried, J.S., Gee, E., Izlar, R.L., Miner, R.A., Munn, I.A., Oneil, E., Stewart, W.C., 2011. Managing forests because carbon matters: integrating energy, products, and land management policy. *J. For.* 109, S7–S51.
- Martyn, P., 2000. Klimaty kuli ziemskiej (Climates of the Earth). PWN, Warszawa.
- Matuszkiewicz, J.M., 2008. Potential Natural Vegetation of Poland. IGIPZ PAN, Warszawa.
- Muggeo, V.M.R., 2003. Estimating regression models with unknown break-points. *Stat. Med.* 22, 3055–3071.
- Muggeo, V.M.R., 2008. Segmented: an R package to fit regression models with broken-line relationships. *R News* 8, 20–25.
- Näslund, M., 1936. Skogsförsöksanstaltens gallringsförsök i tallskog. Meddelanden från Statens Skogsförsöksanstalt 29, 169 pp.
- Nepal, P., Ince, P.J., Skog, K.E., Chang, S.J., 2013. Projected US timber and primary forest product market impacts of climate change mitigation through timber set-asides. *Can. J. For. Res.* 43, 245–255.
- Pajtik, J., Konôpka, B., Lukac, M., 2008. Biomass functions and expansion factors in young Norway spruce (*Picea abies* [L.] Karst) trees. *For. Ecol. Manage.* 256, 1096–1103.
- Pajtik, J., Konôpka, B., Lukac, M., 2011. Individual biomass factors for beech, oak and pine in Slovakia: a comparative study in young naturally regenerated stands. *Trees* 25, 277–288.
- Pandey, D.N., 2002. Global climate change and carbon management in multifunctional forests. *Curr. Sci.* 83, 593–602.
- Parresol, B.R., 1999. Assessing tree and stand biomass: a review with examples and critical comparisons. *For. Sci.* 45, 573–593.
- Parresol, B.R., 2001. Additivity of nonlinear biomass equations. *Can. J. For. Res.* 31, 865–878.
- Paul, K.I., Roxburgh, S.H., England, J.R., Ritson, P., Hobbs, T., Brooksbank, K., Raison, R. J., Larmour, J.S., Murphy, S., Norris, J., Neumann, C., Lewis, T., Jonson, J., Carter, J. L., McArthur, G., Barton, C., Rose, B., 2013. Development and testing of allometric equations for estimating above-ground biomass of mixed-species environmental plantings. *For. Ecol. Manage.* 310, 483–494.
- Perez-Garcia, J., Lippke, B., Comnik, J., Manriquez, C., 2005. An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results. *Wood Fiber Sci.* 37, 140–148.
- Petersson, H., Holm, S., Ståhl, G., Alger, D., Fridman, J., Lehtonen, A., Lundström, A., Mäkipää, R., 2012. Individual tree biomass equations or biomass expansion factors for assessment of carbon stock changes in living biomass – A comparative study. *For. Ecol. Manage.* 270, 78–84.
- Picard, N., Saint-André, L., Henry, M., 2012. Manual for Building Tree Volume and Biomass Allometric Equations From Field Measurement to Prediction. FAO, Rome.
- Pingoud, K., Perälä, A.-L., Pussinen, A., 2001. Carbon dynamics in wood products. *Mitigation Adapt. Strateg. Glob. Chang.* 6, 91–111.
- Poudel, K.P., Temesgen, H., 2016. Methods for Estimating Aboveground Biomass and its Components for Douglas-fir and lodgepole pine trees. *Can. J. For. Res.* 46, 77–87.
- Prach, K., Bartha, S., Joyce, C.B., Pyšek, P., van Diggelen, R., Wiegand, G., 2001a. The role of spontaneous vegetation succession in ecosystem restoration: a perspective. *Appl. Veg. Sci.* 4, 111–114.
- Prach, K., Pyšek, P., Bastl, M., 2001b. Spontaneous vegetation succession in human-disturbed habitats: a pattern across seres. *Appl. Veg. Sci.* 4, 83–88.
- R Development Core Team, 2008. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
- Ramankutty, N., Foley, J.A., 1999. Estimating historical changes in global land cover: Croplands from 1700 to 1992. *Glob. Biogeochem. Cycle* 13, 997–1027.
- Rittenhouse, C.D., Rissman, A.R., 2012. Forest cover, carbon sequestration, and wildlife habitat: policy review and modeling of tradeoffs among land-use change scenarios. *Environ. Sci. Policy* 21, 94–105.
- Ruskule, A., Nikodemus, O., Kasparinska, Z., Kasparinskis, R., Brūmelis, G., 2012. Patterns of afforestation on abandoned agriculture land in Latvia. *Agrofor. Syst.* 85, 215–231.
- Sanquetta, C.R., Corte, A.P.D., da Silva, F., 2011. Biomass expansion factor and root-to-root ratio for *Pinus* in Brazil. *Carbon Balance Manage.* 6, #6.
- SAS 9.1.3 Help and Documentation, 2002. SAS Institute Incorporation. Cary, North Carolina.
- Schroeder, P., Brown, S., Mo, J.M., Birdsey, R., Cieszewski, C., 1997. Biomass estimation for temperate broadleaf forests of the United States using inventory data. *For. Sci.* 43, 424–434.
- Schröter, D., Cramer, W., Leemans, R., Prentice, I.C., Araújo, M.B., Arnell, N.W., Bondeau, A., Bugmann, H., Carter, T.R., Gracia, C.A., de la Vega-Leinert, A.C., Erhard, M., Ewert, F., Glendining, M., House, J.I., Kankaanpää, S., Klein, R.J.T., Lavorel, S., Lindner, M., Metzger, M.J., Meyer, J., Mitchell, T.D., Reginster, I., Rounsevell, M., Sabatés, S., Sitch, S., Smith, B., Smith, J., Smith, P., Sykes, M.T., Thonicke, K., Thuiller, W., Tuck, G., Zaehle, S., Zierl, B., 2005. Ecosystem service supply and vulnerability to global change in Europe. *Science* 310, 1333–1337.
- Seo, Y.O., Lee, Y.J., Lumbres, R.I.C., Pyo, J.K., Kim, R.H., Son, Y.M., Lee, K.H., 2013. Influence of stand age class on biomass expansion factor and allometric equations for *Pinus rigida* plantations in South Korea. *Scand. J. For. Res.* 28, 566–573.



- Sharp, D.D., Lieth, H., Whigham, D., 1975. Assessment of regional productivity in North Carolina. In: Lieth, H., Whittaker, R.H. (Eds.), *Primary Productivity of the Biosphere*. Ecological Studies, vol. 14. Springer-Verlag, Berlin-Heidelberg-New York, pp. 131–146.
- Sileshi, G.W., 2014. A critical review of forest biomass estimation models, common mistakes and corrective measures. *For. Ecol. Manage.* 329, 237–254.
- Socha, J., Zasada, M., 2014. Stand density and self-thinning dynamics in young birch stands on post-agricultural lands. *Sylvan* 158, 340–351.
- Studio Team, 2015. *RStudio: Integrated Development for R*. RStudio Inc, Boston, MA URL: <http://www.rstudio.com/>.
- Teobaldelli, M., Somogyi, Z., Migliavacca, M., Usoltsev, V.A., 2009. Generalized functions of biomass expansion factors for conifers and broadleaved by stand age, growing stock and site index. *For. Ecol. Manage.* 257, 1004–1013.
- Ter-Mikaelian, M.T., Korzukhin, M.D., 1997. Biomass equations for sixty-five North American tree species. *For. Ecol. Manage.* 97, 1–24.
- Thomas, S.C., Martin, A.R., 2012. Carbon content of tree tissues: a synthesis. *Forests* 3, 332–352.
- Tobin, B., Nieuwenhuis, M., 2007. Biomass expansion factors for Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Ireland. *Eur. J. For. Res.* 126, 189–196.
- Tomusiak, R., Ludwisiak, Ł., Bronisz, K., Baran, E., Bronisz, A., Wojtan, R., Bijak, Sz., Czajkowski, M., Zasada, M., 2014. Age tables for silver birch (*Betula pendula* Roth) trees for early succession stands on abandoned agricultural lands. *Sylvan* 158, 579–589.
- Tullus, T., Tullus, A., Roosaluuste, E., Kaasik, A., Lutter, R., Tullus, H., 2013. Understorey vegetation in young naturally regenerated and planted birch (*Betula* spp.) stands on abandoned agricultural land. *New For.* 44, 591–611.
- Turner, D.P., Koerper, G.J., Harmon, M.E., Lee, J.J., 1995. A carbon budget for forests of the conterminous United States. *Ecol. Appl.* 5, 421–436.
- Uri, V., Lohmus, K., Ostonen, I., Tullus, H., Lastik, R., Vildo, M., 2007a. Biomass production, foliar and root characteristics and nutrient accumulation in young silver birch (*Betula pendula* Roth.) stand growing on abandoned agricultural land. *Eur. J. For. Res.* 126, 495–506.
- Uri, V., Vares, A., Tullus, H., Kanal, A., 2007b. Above-ground biomass production and nutrient accumulation in young stands of silver birch on abandoned agricultural land. *Biomass Bioenerg.* 31, 195–204.
- Uri, V., Varik, M., Aosaar, J., Kanal, A., Kukumägi, M., Lohmus, K., 2012. Biomass production and carbon sequestration in a fertile silver birch (*Betula pendula* Roth) forest chronosequence. *For. Ecol. Manage.* 267, 117–126.
- Varik, M., Aosaar, J., Uri, V., 2009. Biomass production in silver birch stands in Oxalis site type. *For. Stud.* 51, 5–16.
- Ward Jr., J.H., 1963. Hierarchical Grouping to Optimize an Objective Function. *J. Am. Stat. Ass.* 58, 236–244.
- Whitehead, D., 2011. Forests as carbon sinks – benefits and consequences. *Tree Physiol.* 31, 893–902.
- Wickham, H., 2009. *Ggplot2: Elegant Graphics for Data Analysis*. Springer, New York. Available online at: <http://had.co.nz/ggplot2/book>.
- Wirth, C., Schumacher, J., Schulze, E.-D., 2004. Generic biomass functions for Norway spruce in Central Europe – a meta-analysis approach toward prediction and uncertainty estimation. *Tree Physiol.* 24, 121–139.
- Wojtan, R., Tomusiak, R., Zasada, M., Dudek, A., Michalak, K., Bijak, Sz., Bronisz, K., 2011. Trees and their components biomass expansion factors for Scots pine (*Pinus sylvestris* L.) of western Poland. *Sylvan* 155, 236–243.
- Woodbury, P.B., Heath, L.S., Smith, J.E., 2006. Land use change effects on forest carbon cycling throughout the southern United States. *J. Environ. Qual.* 35, 1348–1363.
- Zasada, M., Bijak, Sz., Bronisz, K., Bronisz, A., Gawęda, T., 2014. Biomass dynamics in young silver birch stands on post-agricultural lands in central Poland. *Drewno* 57, 29–39.
- Zasada, M., Bronisz, K., Bijak, Sz., Wojtan, R., Tomusiak, R., Dudek, A., Michalak, K., Wróblewski, L., 2008. Empirical formulae for determination of the dry biomass of aboveground parts of tree. *Sylvan* 152, 27–39.
- Zhang, H., Guan, D., Song, M., 2012. Biomass and carbon storage of *Eucalyptus* and *Acacia* plantations in the Pearl River Delta, South China. *For. Ecol. Manage.* 277, 90–97.
- Zhang, Y., Song, C., 2006. Impacts of afforestation, deforestation, and reforestation on forest cover in China from 1949 to 2003. *J. For.* 104, 383–387.
- Zianis, D., Mencuccini, M., 2004. On simplifying allometric analyses of forest biomass. *For. Ecol. Manage.* 187, 311–332.
- Zianis, D., Muukkonen, P., Mäkipää, R., Mencuccini, M., 2005. Biomass and stem volume equations for tree species in Europe. *Silva Fenn. Monogr.* 4.