Drewno 2014, Vol. 57, No. 192
DOI: 10.12841/wood.1644-3985.S07.02

Michał Zasada, Szymon Bijak, Karol Bronisz, Agnieszka Bronisz, Tomasz Gawęda

BIOMASS DYNAMICS IN YOUNG SILVER BIRCH STANDS ON POST-AGRICULTURAL LANDS IN CENTRAL POLAND

The paper analyses the production and allocation of biomass in young, spontaneous silver birch afforestation occurring on post-agricultural lands in the Mazowsze region (central Poland). We investigated 114 sample plots of age varying from 1 to 19 years. During the first 15 years after their establishment on abandoned farmland, the naturally regenerated silver birch stands produced on average approximately 75 tons of dry biomass per hectare. The major (50–70%) part of this biomass was stored in the tree stems and this share increased with age. The fractions of biomass in the foliage and roots decreased over time, while the share of biomass in the branches remained rather constant. The significant age-dependency of the allometric relationships suggested the need to use age-sensitive biomass expansion factors to estimate the biomass from the stem volume.

Keywords: secondary succession, afforestation, biomass allocation, silver birch

Introduction

Carbon accumulation in different ecosystems has recently become a topic of great interest. Forest biomass is considered as having a large potential for the temporary and long-term storage of carbon [Lorentz, Lal 2010; Carroll et al. 2012; Hodgman et al. 2012] and estimates of the biomass that sequesters carbon have been pre-

---

Michał Zasada, Warsaw University of Life Sciences – SGGW, Warsaw, Poland
e-mail: michal.zasada@wl.sggw.pl
Szymon Bijak, Warsaw University of Life Sciences – SGGW, Warsaw, Poland
e-mail: szymon.bijak@wl.sggw.pl
Karol Bronisz, Warsaw University of Life Sciences – SGGW, Warsaw, Poland
e-mail: karol.bronisz@wl.sggw.pl
Agnieszka Bronisz, Warsaw University of Life Sciences – SGGW, Warsaw, Poland
e-mail: agnieszka.bronisz@wl.sggw.pl
Tomasz Gawęda, State Forests National Forest Holding, Bielsko Forest District, Bielsko-Biała, Poland
e-mail: tomasz.gaweda@katowice.lasy.gov.pl

sented in numerous studies [Orzeł et al. 2006; Bijak, Zasada 2007; Zasada et al. 2008, 2009; Bronisz et al. 2009; Alves et al. 2010; Ribeiro et al. 2011; Wojtan et al. 2011; Jagodziński et al. 2012; Skovsgaard, Nord-Larsen 2012; Suchanek et al. 2012; Ochał et al. 2013]. Knowledge of the carbon stocks in forests is crucial for assessing the role of these biomes in global carbon budgets. In the case of many tree species, their potential for carbon sequestration and the dynamic of this process over time is still poorly understood and misquantified.

Spontaneous natural reforestation of abandoned farmland has recently been observed in Poland as well as in other central and eastern European countries on a large scale. Fast-growing pioneer species, especially silver birch (*Betula pendula* Roth.), have appeared extensively on lands, where agricultural activity had ceased [Bernadzki, Kowalski 1983; Karlsson et al. 1998; Johansson 2007; Uri et al. 2007a, b; Hynynen et al. 2010]. The phenomenon has become more and more important as the area of such lands increased as a result of socio-economic changes that took place in these regions. Moreover, the expected high-productivity of such stands seems to be a promising source of bioenergy as far as the dwindling of non-renewable natural resources is concerned. Also their potential role in the mitigation of greenhouse gas emissions should be considered, especially considering that the European Union plans to increase the share of energy generated from renewable sources to 20% by the year 2020. The production of energy from the wood of fast-growing deciduous species is one means of achieving this goal [Hodgman et al. 2012]. However, despite the ecological and economic importance of these newly-established ecosystems, our knowledge of their dynamics is relatively limited.

The majority of studies on silver birch biomass deal with the calculation of aboveground fractions of trees [Mälkönen 1977; Johanson 1999; Claesson et al. 2001; Repola 2008; Varik et al. 2009; Strub et al. 2014]. In recent years, the scope of research has broadened and belowground biomass, as well as the allocation of carbon and nutrients in the various components, have been included in analyses [Uri et al. 2007a, b, 2012; Kuznetsova et al. 2011; Bijak et al. 2013; Varik et al. 2013]. Thus far studies on silver birch biomass in Poland have been limited and have not dealt with the dynamics of biomass fractions. The main objective of the presented study was (i) to assess the biomass of various pools (stem, branch, foliage and roots) in young silver birch stands growing on abandoned farmlands in central Poland and (ii) to model the dynamics of biomass allocation over time.

Materials and methods

Measurements were carried out in pure silver birch stands on 114 sample plots located in the Mazowsze region (central Poland) (table 1). The plots were established on former arable lands that had been abandoned. Age was determined using tree-ring analyses, and the investigated stands were classified into one of the following age classes: I – trees 1–4 years of age, II – 5–8 years of age, III – 9–12 years of age and IV – trees older than 12 years of age. Each plot was more or less rectangular in shape and located in a randomly chosen position within a given area. The plots consisted of approximately 200 trees each. Because of the very diverse spacing, a single plot area varied from 2 to 731 m^2. All the trees on the plot were measured for their diameter at 0.0, 0.5 and 1.3 m above ground level, and a sample of 50 individual trees was measured for total tree height. Height-diameter curves were elaborated based on breast height diameter (DBH), or other diameters in cases where DBH was not present. Such curves were determined for each plot and used to calculate the height of each tree.

Table 1. Basic characteristics of sample plots

Age class		Plot area [m^2]	Stocking [trees/ha]	DBH [cm]	Height [m]
I n = 46	min.	2	27297	0.22	0.15
	m	18	194078	0.57	1.14
	max.	74	1555556	1.40	3.02
	SD	14	249641	0.34	0.64
II n = 30	min.	16	4680	0.20	0.34
	m	83	45695	2.02	3.50
	max.	359	165000	4.60	6.06
	SD	78	36849	0.95	1.43
III n = 22	min.	53	2926	2.01	3.81
	m	239	12047	4.72	7.65
	max.	731	31746	8.35	10.65
	SD	147	7976	1.64	1.81
IV n = 16	min.	173	3200	3.61	6.59
	m	315	7910	5.70	9.18
	max.	645	12644	7.99	12.39
	SD	151	2926	1.34	1.72

min. – minimum, m – mean, max. – maximum, SD – standard deviation, n – number of plots

We used allometric equations elaborated by Strub et al. [2014] to calculate the biomass of the basic components (stems, branches, foliage and roots) as well as aboveground and total stand biomass (table 2). Separate equations were used for the trees with a height above and below 1.3 m, i.e. equations based on the diameter and height or height alone, respectively. To assess the temporal dynamic of these attributes in the investigated stands, we determined the system of equations that describes changes in the components' biomass over time. As the power function is thought to suit allometric relationships the best [Payandeh 1981], it is used to approximate them the most often [Zianis et al. 2005]. For this reason, this concept was adhered to and a general formula was applied to all the biomass components investigated:

$$B_i = b_{i1} \cdot a^{b_{i2}} \quad (1)$$

where: B_i – biomass [Mg/ha] of ith component (stems, branches, foliage, roots),
a – stand age [years],
b_{i1}, b_{i2} – parameters in equations for individual components.

Table 2. Biomass [Mg/ha] of individual components, aboveground part of trees (AGB) and total stand biomass with regard to age class (I – 1–4 years, II – 5–8 years, III – 9–12 years, IV – above 12 years)

Age class		Stem [Mg/ha]	Branches [Mg/ha]	Foliage [Mg/ha]	Roots [Mg/ha]	AGB [Mg/ha]	Total [Mg/ha]
I n = 46	min.	2.31	0.16	0.24	0.23	0.63	0.86
	m	2.67	0.78	1.12	1.38	4.56	5.94
	max.	8.52	1.88	2.79	4.98	12.86	17.47
	SD	2.38	0.44	0.58	0,90	3.27	4.03
II n = 30	min.	0.38	0.08	0.06	0.12	0.51	0.64
	m	14.98	2.70	1.87	3.95	19.56	23.51
	max.	41.09	6.66	3.47	8.90	51.23	60.12
	SD	9.78	1.58	0.84	2.10	12.02	13.94
III n = 22	min.	6.07	1.12	0.44	1.42	7.63	9.06
	m	39.44	6.79	2.38	8.18	48.61	56.79
	max.	79.22	13.84	4.11	16.54	97.18	113.72
	SD	17.92	3.04	0.75	3.53	21.58	25.02
IV n = 16	min.	14.54	2.36	1.06	2.82	17.96	20.77
	m	51.59	8.76	2.70	10.39	63.04	73.43
	max.	76.03	12.82	3.93	15.05	92.44	107.49
	SD	16.34	2.77	0.69	3.27	19.58	22.70

min. – minimum, m – mean, max. – maximum, SD – standard deviation, n – number of plots, AGB – aboveground biomass

The goodness-of-fit of the individual equations was assessed based on Akaike's Information Criterion (AIC), coefficient of determination (R^2) and residual standard error (RSE). To address the logical concept of additivity of the biomass equations on the plot level, the seemingly unrelated regression (SUR) was applied to determine parameters in the following model of total stand biomass:

$$B_{total} = B_{stem} + B_{branches} + B_{foliage} + B_{roots} = b_1 \cdot a^{b_2} + b_3 \cdot a^{b_4} + b_5 \cdot a^{b_6} + b_7 \cdot a^{b_8} \quad (2)$$

where: B_{total} – total stand biomass [Mg/ha],
a – stand age [years],
$b_1, \ldots, b_8$ – complex model parameters.

The parameters of all the components and the total stand biomass model were estimated using the systemfit package [Henningsen, Hamann 2006] of R software [Ihaka, Gentlemen 1996].

Results and discussion

Table 3 presents the parameters of the models (equation (1)) which enabled a calculation of the biomass of individual biomass pools using the stand age as a predictor. The applied power function estimated the component biomass quite well except in the case of foliage ($R^2 < 50\%$).

Table 3. Parameters (b_{i1} and b_{i2}) of equation (1) and goodness-of-fit measures for biomass of individual components

Biomass components	b_{i1}	b_{i2}	AIC	R^2	RSE
Stem	0.93890	1.53793	871.0253	0.7560	10.8474
Branches	0.20866	1.43398	466.3502	0.7429	1.8386
Foliage	0.67226	0.53456	239.8033	0.4627	0.6807
Roots	0.40890	1.24100	512.3864	0.7083	2.2499

b_{i1}, b_{i2} – parameters in equation (1) variants for individual component, AIC – Akaike's Information Criterion, R^2 – coefficient of determination, RSE – residual standard error

The total stand biomass model for young silver birch stands on post-agricultural lands, developed using the SUR approach, can be expressed in its final form derived from the equation (2):

$$B_{total} = 1.10204 \cdot a^{1.47366} + 0.25639 \cdot a^{1.35085} + 0.75334 \cdot a^{0.4864} + 0.5099 \cdot a^{1.15122} \quad (3)$$

where: a – stand age (years), and consecutive parts of the formula correspond to biomass of stems, branches, foliage and roots, respectively.

All the parameters of this model were significant. The coefficient of determination (R^2) equalled 0.6085, which means that almost 61% of the biomass variance could be explained by the diversity of the stand age. Moreover, it suggests that there are other important factors (e.g. soil conditions, climate, water availability) that are responsible for the remaining part of the biomass variability.

In general the findings concerning the production and allocation of biomass in young silver birch stands on post-agricultural lands are consistent with data presented for similar study objects in Sweden [Johansson 1999, 2007], Finland [Hytönen et al. 1995] and Estonia [Uri et al. 2007a, b, 2012; Aosaar, Uri 2008; Varik et al. 2009] as well as for other species [Vanninen et al. 1996; Helmisaari et al. 2002; Peichl, Arain 2006, 2007; Walle et al. 2007; Aosaar, Uri 2008; Varik et al. 2009; Genet et al. 2010; Kuznetsova et al. 2011]. The biomass of all the analysed components increased in the silver birch stands investigated along with stand age (fig. 1). The most rapid growth was observed for the stem biomass and, as a result, for aboveground and total biomass. The foliage constituted the smallest fraction of the total biomass of the analysed stands, while the biomass allocated to the roots and to the branches constituted rather similar fractions (fig. 2).

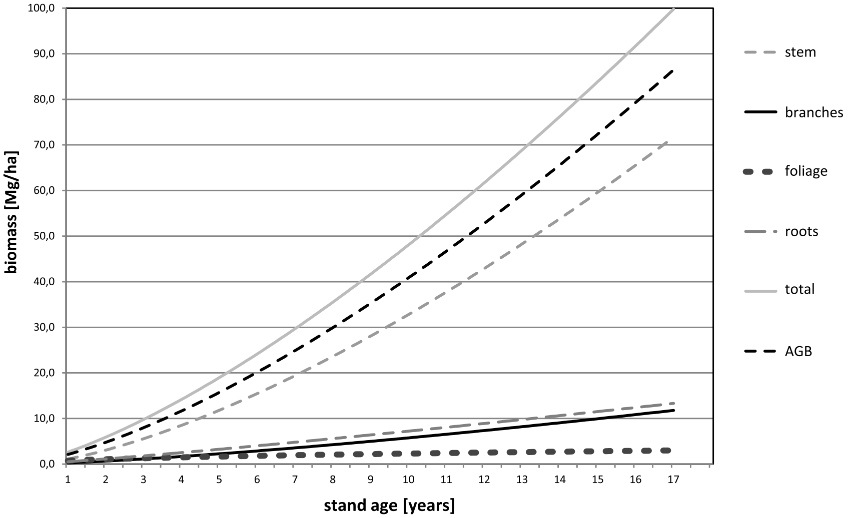

Fig. 1. Age-related changes in biomass of various pools in young silver birch stands on post-agricultural lands in central Poland

AGB – aboveground biomass

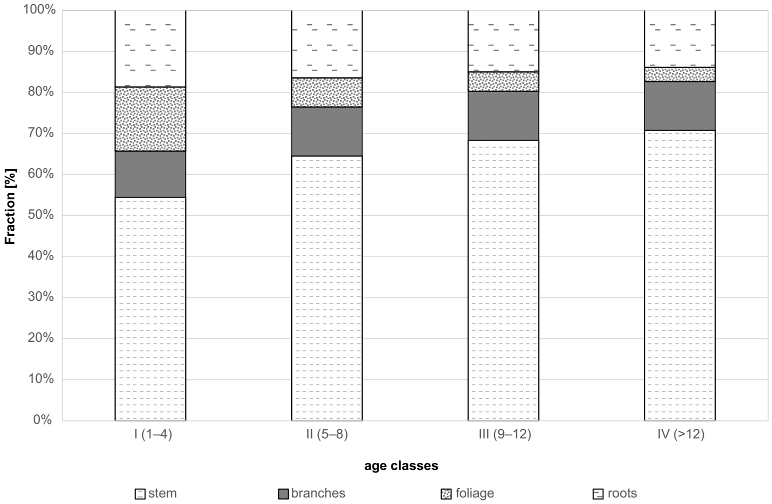

Fig. 2. Age-related changes in fraction of various pools in total stand biomass in young silver birch stands on post-agricultural lands in central Poland

The productivity of young silver birch afforestation observed in central Poland is similar to the amount of biomass found in other parts of Central and Eastern Europe. In 8-year-old natural silver birch stands growing on abandoned agricultural land in Estonia, Uri et al. [2007a] reported the aboveground biomass equal to 31.2 Mg/ha, which is very close to this study's observations, which amounted to 29.93 Mg/ha. In other studies performed in silver birch stands of that age and located in various places in Estonia, Uri et al. [2007b] showed a slightly lower biomass than found in this study. The stem biomass was reported to be from 3.79 to 15.65, the branches from 1.34 to 4.22, the leaves from 0.81 to 3.91, and the total aboveground biomass from 6.02 to 22.78 Mg/ha, while in this study the respective average values were 23.61, 4.25, 2.07 and 29.93 Mg/ha. Uri et al. [2012] investigated the allocation of aboveground biomass in a chronosequence (6, 14, 13, 18 years) of silver birch stands growing on fertile sites in Estonia. The aboveground biomass equalled 25.7, 39.9, 67.6 and 81.3 Mg/ha, respectively. These values are higher than observed in the stands analysed in Poland (table 2). The stem biomass reported by Uri et al. [2012] ranged from 18.2, to 72.3 Mg/ha, which is also relatively high compared to the amounts found in this study. The research presented in this paper, however, was performed on rather poor soils. In turn, according to Johansson [1999] the aboveground biomass of silver birch stands on post-agricultural areas in Sweden, amounted to 5.7–55.7 Mg/ha at 7–11 years of age, while the plots in this research contained from 0.51 to 97.18 Mg/ha at 5–12 years of age.

The dynamics of biomass do not only concern the absolute amount of biomass accumulated in various parts of trees, but also applies to its relative allocation, because the fractions of the various components within the total biomass also change over time (fig. 2). The age-dependence of biomass allocation has been reported for various species [Peichl, Arain 2006, 2007; Aosaar, Uri 2008; Varik et al. 2009; Genet et al. 2010; Kuznetsova et al. 2011]. In the silver birch stands investigated in central Poland, the share of stem biomass within the total stand biomass was the highest among the analysed components and increased with stand age. The fraction of roots and foliage decreased, while the amount of branch biomass remained rather constant. These findings are quite consistent with other studies regarding young silver birch afforestation from other countries. Johansson [1999] observed that stem biomass constituted 61–90% of the aboveground biomass in stands at 8–32 years of age. Uri et al. [2007b] found the production of stems accounted for 62.4% of the total biomass in 8-year-old stands. In 14-year-old birch afforestation in Estonia, Varik et al. [2009] observed 78% of aboveground biomass allocated to the stems. The significant change in the contribution of stem biomass to the aboveground or total tree biomass occurring with tree age was observed by Peichl and Arain [2006] in a white pine chronosequence in southern Ontario, Canada. These findings suggest the need to use age-sensitive biomass expansion factors in order to achieve precise estimates of total aboveground biomass from stem volume data. Biomass allocation to the roots decreases slightly over the time, which results from the shift in the "growth policy" of a plant which no longer needs to invest in spreading out and an effective root system [Bijak et al. 2013]. Johansson [2007] observed a similar pattern of biomass allocation to that found in this study, however, he also found that the total biomass of 12-year-old silver birch stands and its fractioning was greatly affected by initial spacing. Similar findings were presented by Claesson et al. [2001]. Among other factors that influence biomass production and allocation, various authors name site fertility [Peichl, Arain 2007; Uri et al. 2012], soil conditions [Johansson 1999, 2007] and nutrient content [Kuznetsova et al. 2011].

Conclusions

During the first 15 years after their establishment on abandoned farmland, naturally regenerated silver birch stands in central Poland could produce on average approximately 75 tons of dry aboveground biomass per hectare. The major (50–70%) part of this biomass was stored in the tree stems and this share increased with age. The fractions of foliage and roots decreased over time, while the share of branches remained constant. The significant age-dependency of allometric relationships suggested the necessity of using age-sensitive biomass expansion factors to estimate the biomass from stem volume data.

References

Alves L.F., Vieira S.A., Vieira M.A., Scaranello P.B., Camargo F.A.M., Santos C.A., Joly L.A. [2010]: Forest structure and live aboveground biomass variation along an elevational gradient of tropical Atlantic moist forest (Brazil). Forest Ecology and Management 260: 679–691

Aosaar J., Uri V. [2008]: Biomass production of grey alder, hybrid alder and silver birch stands on abandoned agricultural land. Forestry Studies 48: 53–66. DOI: 10.2478/v10132-011-0055-0

Bernadzki E., Kowalski M. [1983]: Brzoza na gruntach porolnych (Silver birch on post-agricultural lands). Sylwan 127 [12]: 33–42

Bijak Sz., Zasada M. [2007]. Oszacowanie biomasy korzeni w drzewostanach sosnowych Borów Lubuskich (Assessment of the belowground biomass in Scots pine stands of Bory Lubuskie). Sylwan 151 [12]: 21–29

Bijak Sz., Zasada M., Bronisz A., Bronisz K., Czajkowski M., Ludwisiak Ł., Tomusiak R., Wojtan R. [2013]: Estimating coarse roots biomass in young silver birch stands on post-agricultural lands in central Poland. Silva Fennica 47 [2] article id 963

Bronisz K., Bronisz A., Zasada M., Bijak Sz., Wojtan R., Tomusiak R., Dudek A., Michalak K., Wróblewski L. [2009]: Biomasa aparatu asymilacyjnego w drzewostanach sosnowych zachodniej Polski (Biomass of assimilation apparatus in Scots pine stands of western Poland). Sylwan 153 [11]: 758–767

Carroll M., Milakovsky B., Finkral A., Evans A., Ashton M.S. [2012]: Managing carbon sequestration and storage in temperate and boreal forests. In: Ashton M.S., Tyrrell M.L., Spalding D., Gentry B. (eds.). Managing forest carbon in a changing climate. Springer, Dordrecht, Heidelberg, London, New York: 205–226. DOI:10.1007/978-94-007-2232-3_5

Claesson S., Sahlén K., Lundmark T. [2001]: Functions for biomass estimation of young Pinus sylvestris, Picea abies and Betula spp. from stands in northern Sweden with high stand densities. Scandinavian Journal of Forest Research 16: 138–146

Genet H., Bréda N., Dufrêne E. [2010]: Age-related variation in carbon allocation at tree and stand scales in beech (*Fagus sylvatica* L.) and sessile oak (*Quercus petraea* (Matt.) Liebl.) using a chronosequence approach. Tree Physiology 30 [2]: 177–192. DOI:10.1093/treephys/tpp105

Helmisaari H.-S., Makkonen K., Kellomäki S., Valtonen E., Mälkönen E. [2002]: Below- and aboveground biomass, production and nitrogen use in Scots pine stands in eastern Finland. Forest Ecology and Management 165: 317–326

Henningsen A., Hamann J. [2006]: Systemfit: A package to estimate simultaneous equation systems in R.

Hodgman T., Munger J., Hall J.S., Ashton M.S. [2012]: Managing afforestation and reforestation for carbon sequestration: considerations for land managers and policy makers. In: Ashton M.S., Tyrrell M.L., Spalding D., Gentry B. (eds.). Managing forest carbon in a changing climate. Springer, Dordrecht, Heidelberg, London, New York: 227–256. DOI:10.1007/978-94-007-2232-3_5

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 [1]: 103–119

Hytönen J., Saarsalmi A., Rossi P. [1995]. Biomass production and nutrient uptake of short--rotation plantations. Silva Fennica 29 [2]: 117–139

Ihaka R., Gentlemen R. [1996]: R: a language for data analysis and graphics. Journal of Computational and Graphical Statistics 5 [3]: 299–314

Jagodziński A.M., Jarosiewicz G., Karolewski P., Oleksyn J. [2012]: Zawartość węgla w biomasie pospolitych gatunków krzewów podszycia leśnego (Carbon concentration in the biomass of common species of understory shrubs). Sylwan 156 [9]: 650–662

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 [1]: 41–52. DOI:10.1093/forestry/cpl049

Johansson T. [1999]: Biomass equations for determining fractions of pendula and pubescens birches growing on abandoned farmland and some practical implications. Biomass and Bioenergy 16: 223–238

Karlsson A., Albrektson A., Forsgren A., Svensson L. [1998]: An analysis of successful natural regeneration of downy and silver birch on abandoned farmland in Sweden. Silva Fennica 32 [3]: 229–240

Kuznetsova T., Lukjanova A., Mandre M., Lõhmus K. [2011]: Aboveground biomass and nutrient accumulation dynamics in young black alder, silver birch and Scots pine plantations on reclaimed oil shale mining areas in Estonia. Forest Ecology and Management 262 [2]: 56–64. DOI:10.1016/j.foreco.2010.09.030

Lorenz K., Lal R. [2010]: Carbon sequestration in forest ecosystems. Springer, Dordrecht, Heidelberg, London, New York: 288

Mälkönen E. [1977]: Annual primary production and nutrient cycle in birch stand. Communicationes Instituti Forestalis Fenniae 91 [5]: 35

Ochał W., Grabczyński S., Orzeł S., Wertz B., Socha J. [2013]: Alokacja nadziemnej biomasy u sosen zajmujących różne pozycje biosocjalne w drzewostanie (Aboveground biomass allocation in Scots pines of different biosocial positions in the stand). Sylwan 157 [10]: 737–746

Orzeł S., Forgiel M., Ochał W., Socha J. [2006]: Nadziemna biomasa i roczna produkcja drzewostanów sosnowych Puszczy Niepołomickiej (Aboveground biomass and annual production in stands of the Niepołomicka Forest). Sylwan 150 [5]: 16–32

Payandeh B. [1981]: Choosing regression models for biomass prediction equations. Forestry Chronicles 57: 229–232

Peichl M., Arain M.A. [2006]: Above- and belowground ecosystem biomass and carbon pools in an age-sequence of temperate pine plantation forests. Agricultural and Forestry Meteorology 140: 51–63

Peichl M., Arain M.A. [2007]: Allometry and partitioning of above- and belowground tree biomass in an age-sequence of white pine forests. Forest Ecology and Management 253: 68–80

Repola J. [2008]: Biomass equations for birch in Finland. Silva Fennica 42: 605–624

Ribeiro S.C., Fehrmann L., Soares C.P.B., Jacovine L.A.G., Kleinn C., de Oliveira Gaspar R. [2011]: Above- and belowground biomass in a Brazilian Cerrado. Forest Ecology and Management 262: 491–499

Skovsgaard J.P., Nord-Larsen T. [2012]: Biomass, basic density and biomass expansion factor functions for European beech (*Fagus sylvatica* L.) in Denmark. European Journal of Forest Research 131: 1035–1053

Strub M., Cieszewski Ch. J., Bijak Sz., Bronisz K., Bronisz A., Tomusiak R., Wojtan R., Zasada M. [2014]: Equations for aboveground biomass of Betula pendula growing on former farmland in central Poland. Forest Science [in review]

Suchanek A., Socha J., Chwistek K. [2012]: Biomasa i roczna produkcja drzewostanów Ojcowskiego Parku Narodowego (Biomass and annual production of forest stands in the Ojcowski National Park). Sylwan 156 [6]: 451–462

Uri V., Lõhmus 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. European Journal of Forest Research 126 [4]: 495–506. DOI:10.1007/s10342-007-0171-9

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 and Bioenergy 31: 195–204

Uri V., Varik M., Aosaar J., Kanal A., Kukumägi M., Lõhmus K. [2012]: Biomass production and carbon sequestration in a fertile silver birch (*Betula pendula* Roth) forest chronosequence. Forest Ecology and Management 267: 117–126. DOI:10.1016/j.foreco.2011.11.033

Vanninen P., Ylitalo H., Sievänen R., Mäkelä A. [1996]: Effects of age and site quality on the distribution of biomass in Scots pine (*Pinus sylvestris* L.). Trees 10: 231–238

Varik M., Aosaar J., Ostonen I., Lõhmus K., Uri V. [2013]: Carbon and nitrogen accumulation in belowground tree biomass in a chronosequence of silver birch stands. Forest Ecology and Management 302: 62–70. DOI:10.1016/j.foreco.2013.03.033

Varik M., Aosaar J., Uri V. [2009]: Biomass production in silver birch stands in Oxalis site type. Forestry Studies 51: 5–16. DOI: 10.2478/v10132-011-0073-y

Walle I.V., Camp N.V., Casteele L.V., Verheyen K., Lemeur R. [2007]: Short-rotation forestry of birch, maple, poplar and willow in Flanders (Belgium) I – Biomass production after 4 years of tree growth. Biomass and Bioenergy 31: 267–275

Wojtan R., Tomusiak R., Zasada M., Dudek A., Michalak K., Bijak Sz., Bronisz K. [2011]: Współczynniki przeliczeniowe suchej biomasy drzew i ich części dla sosny pospolitej (*Pinus sylvestris* L.) w zachodniej Polsce (Trees and their components biomass expansion factors for Scots pine (*Pinus sylvestris* L.) of western Poland). Sylwan 155 [4]: 236–243

Zasada M., Bronisz K., Bijak Sz., Dudek A., Bruchwald A., Wojtan R., Tomusiak R., Bronisz A., Wróblewski L., Michalak K. [2009]: Effect of the cutting age and thinning intensity on biomass and carbon sequestration–the Gubin Forest District case study. Folia Forestalia Polonica seria Forestalia 51: 138–144

Zasada M., Bronisz K., Bijak Sz., Wojtan R., Tomusiak R., Dudek A., Michalak K., Wróblewski L. [2008]: Wzory empiryczne do określania suchej biomasy nadziemnej części drzew i ich komponentów (Empirical formulae for determination of the dry biomass of aboveground parts of the tree). Sylwan 152 [3]: 27–39

Zianis D., Muukkonen P., Mäkipää R., Mencuccini M. [2005]: Biomass and stem volume equations for tree species in Europe. Silva Fennica Monographs. Finnish Society of Forest Science, Finnish Forest Research Institute

Acknowledgements

This research was supported by the Polish National Science Centre within grant N N305 400238, entitled “Ecological consequences of the silver birch (*Betula pendula* Roth.) secondary succession on abandoned farmlands in central Poland”.