Stemwood Density of Juvenile Silver Birch Trees (*Betula pendula* Roth) from Plantations on Former Farmlands

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Abstract

The purpose of this study was to determine the basic density of knot-free birch wood from young silver birch plantations to assess the quality of future roundwood timber assortments and to evaluate the effects of the individual growth traits of birch trees on basic wood density. The first test of silver birch stemwood density from plantations on former farmlands in Latvia did not reveal a substantial difference in the wood density of the birch trees compared to wood density values reported in other studies of birch wood from natural forests and plantations in the Baltic Sea region. Our study revealed a positive correlation between wood density and tree age, tree height and slenderness ratio. A negative correlation was found between wood density and ring width. These results suggest that the density of stemwood will increase as the plantations approach felling age. However, intensive management of the plantations clearly will have an effect on wood properties. As a consequence of the substantially shorter rotations and intensive silviculture of silver birch plantations, the timber industry should expect that wood extracted from the plantations in the future will have a lower density than wood harvested from natural birch stands.

Keywords: silver birch; *Betula pendula*; plantations, wood density

Introduction

Birches (*Betula* spp.) are the most widespread broadleaved tree species in most northern European countries with the highest total proportional volume in the forests of Latvia (Hynynen et al. 2009). In Latvian forests, the proportion of broadleaved species (so called pioneer species, such as birch, aspen and alder) has risen during recent decades due to the natural regeneration of private forests and an increase in the financial attractiveness of these species. Birch accounts for 30% of the total forest area and its economic significance to the national forest industry is equally as high as that of the coniferous species Norway spruce and Scots pine. High quality birch roundwood is a desirable raw material in the plywood industry, which has become one of the leading branches of the domestic wood processing industry. Small dimension birch timber is used mainly in the cellulose industry as well as for firewood.

In Latvia, two birch species with a tree-like growth form are found growing in forests as silver birch (*Betula pendula* (Roth) and downy birch (*Betula pubescens* Ehrh.). Both species are morphologically and ecologically distinct. Downy birch occurs more often on peat and wet mineral soils, while silver birch prefers well drained mineral soils. The main wood properties and the utilisation of timber are very similar for the two species; however, the productivity and stem quality traits of silver birch are superior to those of downy birch (Cameron 1996, Viherä-Aarnio and Velling 1999, Gobakken 2000, Heräjärvi 2001, Saramäki and Hytönen 2004). The most common birch species in Latvian forests is silver birch. The exact proportion of each birch species is unknown because the national forest inventory does not distinguish between the two species.

As one of the most economically important tree species, silver birch is included in the national breeding programme. A large number of forest stands have been inventoried across Latvia, and phenotypically valuable trees have been selected from a total of 37 stands. Tree seeds from these stands have been used to conduct open-pollinated progeny trials at 3 sites in Latvia (Jansons et al. 2011).

Silver birch is one of the most popular tree species for the afforestation of abandoned farmlands in Latvia because of its rapid growth rate and high productivity (Daugaviete and Krūmiņa 2001, Daugaviete et al. 2003). Investigation of afforestation methods for former farmlands in the country, including the establishment of demonstration plots (Daugaviete 1999), began in 1994. Larger scale afforestation of farmlands in Latvia was initiated in the beginning of the 21st century. The area of afforested lands per year has increased recently due to the availability of funds allocated to private forest owners by the European Union to promote the establishment of forests on former agricultural lands.

In Latvia, most of the established birch plantations are intended to produce a roundwood timber for the plywood industry. The utilisation of birch timber for plywood production is restricted by the quality standards applied to roundwood. Knottiness, stem straightness and the presence of rot and discoloration, in addition to other trunk defects, are evaluated for plywood logs using a grading system. The mechanical properties of wood are of special importance in the production of birch plywood because plywood panels are often used for construction purposes for which the mechanical resistance, stability and strength are crucial properties of building material. The density is one of the key features used to characterise the mechanical properties of wood. For example, in birch, wood density is significantly correlated with wood hardness (Dunham et al. 1999, Heräjärvi 2004).

In the future, a substantial amount of the birch roundwood delivered to the timber industry in Latvia will be extracted from fast growing plantations on former farmland. Therefore, predicting the timber quality of plantation trees is of great interest. Trees grown in plantations have substantially higher growth rates and shorter rotations than natural stands (Niemistö 1996, Karlsson et al. 1997). Due to intensive management and the use of genetically improved planting stock, the rotation of newly established birch plantations in Latvia is expected to be 40-50 years, which is considerably shorter than the 70-year cutting age traditionally used in natural birch forests. This shortened rotation has a positive impact on the economic indicators of tree plantation projects (Korjus et al. 2011, Tullus et al. 2012). However, the wood quality of trees with increased radial growth rates is of concern (Alteyrac et al. 2005, Gardiner et al. 2011, Genet et al. 2013).

The age of the first birch timber plantations established in the country currently exceeds ten years, allowing for an initial assessment of the growth potential and wood properties of the trees. The purpose of this study was to determine the basic density of knot-free birch wood from young silver birch plantations to predict the quality of future roundwood assortments and assess the effects of individual tree growth traits on basic wood density. Additionally, we evaluated a model designed to predict average stemwood density and used density data from cross-section discs to calibrate the model's performance.

Materials and Methods

Wood samples for determining the basic density were collected in 7 silver birch stands planted on former agricultural fields located between latitudes 56 and 58 N in Latvia (Figure 1 and Table 1). Latvia has a temperate seasonal climate with an average annual precipitation of 667 mm. The months with the greatest amount of precipitation are July and August, each of which has an average rainfall of 78 mm. The period of lowest precipitation is in February and March, each of which has an average rainfall of 33 mm (Latvian Environm... 2013).

All of the experimental sites were established on well drained mineral soils, and the variation in site index values among the stands was relatively small. The selected stands had not been thinned prior to sampling.

Wild saplings of silver birch collected from naturally overgrown areas near the plantation sites were used in the establishment of the plantations at sites 6 and 7, and one-year-old container seedlings grown from the seeds collected in forest stands were used to establish the remaining plantations. Seed origin for sites 1 and 2 is Balvi district Žīguri (Eastern Latvia) and Madonas district Kalsnava (central-eastern part of Latvia) for site 4. Sites 3 and 5 were planted with seedlings grown from seeds collected in forest stands in Aizpute district (Western Latvia). The exact geographic location of the seed sources is unknown.

Stand characteristics at the plantation sites were based on the measurements collected in four circular sample plots (radius 12.62 m, area 500 m^2) randomly placed within each experimental site prior to felling the sample trees. Diameter at breast height over the bark ($D_{1.3}$) was measured to the nearest 0.1 cm for all trees.

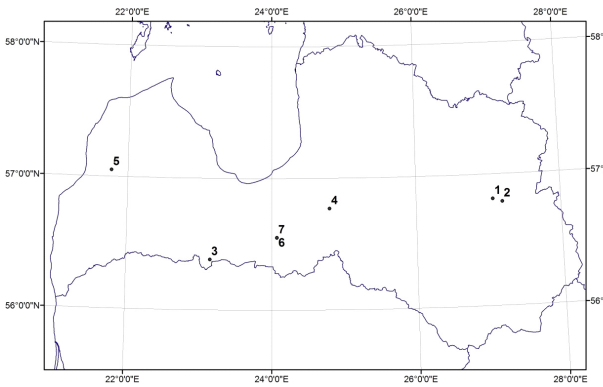

Figure 1. Location of the study sites

Table 1. Stand characteristics at the experimental sites

Site	Location		Planting year	No. of stems (ha^{-1})	Mean $D_{1.3}$ (cm)	Mean height (m)	Basal area (m^2ha^{-1})	Stand volume (m^3ha^{-1})	No. of trees sampled
	Latitude (N)	Longitude (E)							
1	56°48'49"	27°03'43"	2000	2388	8.0	11.4	12.0	73.0	10
2	56°47'24"	27°11'30"	2000	2280	8.8	12.0	13.9	73.6	14
3	56°23'00"	23°09'07"	2000	1638	9.4	11.2	11.9	68.8	20
4	56°46'14"	24°48'04"	1999	1120	11.5	13.6	11.7	78.1	10
5	57°03'02"	21°46'05"	2000	1913	10.3	11.8	16.0	98.8	3
6	56°33'01"	24°04'15"	1997	1458	12.3	15.4	17.4	128.3	10
7	56°33'04"	24°04'14"	1997	2894	9.0	15.1	18.6	135.0	20

Tree height was measured to the nearest 0.1 m for fifteen trees per sample plot, and the data were used to construct height curves. Stand attributes were calculated using common methods of forest inventory.

The sample trees selected for the study were felled during the dormancy period in 2010 and 2011. The number of sample trees taken from each plantation differed in accordance with the agreement made with the landowner. For each stand, dominant trees without any visible stem and branching defects were selected for felling to represent the future crop trees of that stand. After felling, the sample trees were divided into 1 m sections and cross-section discs were retrieved at stump height, at a height of 1.3 m, and at the end of each section. The sampling of wood for the density analysis was performed at 1 m distance along the entire stem using a 12 mm increment borer. The vertical location of samples along the stem was expressed as a relative height, ranging from 0 (stump height) to 1 (top). The cores were retrieved perpendicular to the stem axis to obtain a wood segment that extended from the bark to the pith. The cross-section discs and increment cores were packed in polyethylene bags and transported to the laboratory for analysis.

The cross-section discs were sanded and scanned at 1,200 dpi resolution. The basal area of the discs and tree-ring width were measured along two perpendicular diameters with the programme WinDENDRO Reg 2009b. Average tree-ring width (RW) was calculated as the arithmetic mean of the ring width (mm) measurements from the cross-sectional disc at 1.3 m in height. Because the age of wild saplings used for the establishment of plantations in sites 6 and 7 was different, the biological age of each tree was determined as the number of tree rings at stump height.

Basic wood density was determined using the water-displacement method as the ratio of oven dry weight to green volume in accordance with the methodology described by Ilic et al. (2000) removing the bark prior to measuring. In our study, the term 'wood density' is used to denote the average basic wood density of the stem, calculated as a basal area-weighted mean using measurements at 1 m intervals.

The stem volume equation developed by Liepa (1996) was used to calculate the volume of each sample tree. The slenderness ratio (SR) of the trees was calculated by dividing tree height (m) by $D_{1.3}$ (cm).

Table 2. Characteristics of the sample trees

Characteristics	Mean	Min.	Max.	Standard deviation
Height (m)	15.26	11.6	20.3	2.318
$D_{1.3}$ (cm)	12.21	9.2	16.9	1.573
Biological age (years)	-	11	15	-
Stem volume (dm^3)	87.99	39.68	187.41	29.436
Ring width (mm)	5.79	4.02	8.57	0.92
Slenderness ratio	1.26	0.84	1.66	0.172
Wood density (kg m^{-3})	454.76	407.74	522.80	26.046

To predict average wood density using the sample discs taken at different heights, the following equation was used (Repola 2006):

$$BD_{ik} = b_0 + b_1 h_k + b_2 \frac{d_k}{t_k} + b_3 hr_{ik} + b_4 hr_{ik}^2 + b_5 hr_{ik}^3 + u_{0k} + u_{1k} hr_{ik} + u_{2k} hr_{ik}^2 + e_{ik} \quad (1)$$

where BD_{ik} = basic density of stem position i tree k (kg m^{-3}); d_k = tree diameter at breast height (mm); t_k = tree age (years); hr_{ik} = relative height of position i tree k; $b_0 \ldots b_5$ = parameters of the fixed effects; u_{0k}, u_{1k} and u_{2k} = parameters of the random effect in tree k; e_{ik} = random parameter of stem position i tree k.

Based on the methodology described by Repola (2006), the model was calibrated using wood density data from the sample discs taken at 1.3 m height and a relative height of 70 %. Model performance was evaluated using the root mean square error (RMSE) and mean percentage error (E %):

$$RMSE = \sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{n}} \quad (2)$$

$$E_{\%} = \frac{100}{n} \sum \frac{|y_i - \hat{y}_i|}{\hat{y}_i} \quad (3)$$

where y_i is the observed value, $\hat{y}_i$ is the predicted value and n is the number of observations.

All statistical analyses were performed using SYSTAT 13. Relationships between average stem basic density and other tree characteristics (Table 2) were determined using Spearman's correlations. A forward stepwise multiple regression procedure was used to determine which characteristics explained the greatest amount of variation, and variables were retained in the model using a significance level of $p < 0.05$. To verify the assumption (for least-squares regression) that the residuals followed the Gaussian distribution (Motulsky and Christopoulos 2004), normality of the residuals was assessed using the Shapiro-Wilk test.

Results

Relationship of stem variables to density

The correlation analysis revealed significant relationships between wood density and a number of the tree characteristics (Table 3). Wood density was positively correlated with tree age, SR and tree height, but no significant correlation was observed between stem volume and $D_{1.3}$. Trees with a higher radial growth rate tended to have lower wood density, as demonstrated by the negative correlation between density and RW.

Based on the methods used in the stepwise multiple regression analysis, only two significant variables were retained in the predictive model for stemwood density of birch trees: RW and age (Table 4). The regression model accounted for 38% of the total variation in wood density.

Predicting average stemwood density

The predictive model for average wood density, which was developed by Repola and tested on birch stem density data in our experiment, can be calibrated to any individual birch stem using density data from one or more cross-sectional discs. Despite significant variation in all stem density data, Repola's model was a very good fit for our empirical data. The model predicted average wood density with a level of error below 2.0% (Table 5). In our analysis, using density data from two discs did not improve the performance of the model; moreover, the $E_{\%}$ was slightly bigger when the model was calibrated with data from two discs.

Discussion

The age of harvested trees in this study ranged from 11 to 15 years (Table 2). According to Bonham and Barnett (2001), a silver birch stem from the pith to the 10^{th}-15^{th} ring is composed of juvenile wood. Therefore, the timber analysed in this study consisted mainly of juvenile wood. Although juvenile wood typically has a lower density (Saranpää 2003), the average observed stemwood density of the birch in our study was 454.76 kg m^{-3}, which is consistent with the range in stemwood density reported in other studies from the Baltic Sea region (429-512 kg m^{-3}) (Hakkila 1979, Bhat 1980, Stener and Hedenberg 2003, Heräjärvi 2004, Möttönen and Luostarinen 2006, Repola 2006).

Table 5. Observed and predicted values for average wood density of birch stems (mean ± standard deviation) and the prediction errors

Method	Density	RMSE	$E_{\%}$
$WD_{measured}$	454.76 ± 26.046		
$WD_{model(1.3m)}$	449.22 ± 28.664	11.42	-1.1
$WD_{model(1.3m\ and\ 70\%)}$	445.22 ± 27.790	11.90	-2.0

$WD_{measured}$ = average wood density calculated as the basal area-weighted mean using 1 m interval measurements; $WD_{model(1.3m)}$ = average wood density calculated with equation (1), calibrated with density data from a stem disc at 1.3 m in height; $WD_{model(1.3m\ and\ 70\%)}$ = average wood density calculated with equation (1), calibrated with density data from stem discs at 1.3 m in height and 70% of stem height

Table 3. Spearman's correlation coefficients for wood density and tree characteristics

Variable	Spearman's correlation coefficients by variable					
	Ring width (RW)	Density	Height	$D_{1.3}$	Stem volume	Slenderness ratio (SR)
Density	-0.474**					
Height	-0.342**	0.462**				
$D_{1.3}$	0.441**	0.040	0.536**			
Stem volume	0.208*	0.173	0.773**	0.941**		
Slenderness ratio (SR)	-0.781**	0.482**	0.644**	-0.276*	0.038	
Age	-0.586**	0.612**	0.806**	0.311**	0.525**	0.596**

* Correlation significant at the 0.05 level ** Correlation significant at the 0.01 level.

Table 4. Stepwise multiple linear regression analysis of tree characteristics and tree density. The unstandardized coefficient, standard error and *p* value are reported for each significant predictor.

Predictor	Coefficient estimates	Standard Error	Tolerance	*p*	R^2
Constant	0.382	0.037		0.000	0.384
RW, mm	-0.007	0.003	0.735	0.010	
Age, years	0.008	0.002	0.735	0.000	

Our results showed that birch stemwood density increased in older trees, which is consistent with results reported in previous research (Hakkila 1979, Bhat 1980). The wood properties of plantation birch trees were studied in Finland, and it was found that the basic density of timber from plantations was significantly lower than that of the timber from naturally regenerated stands (Möttönen and Luostarinen 2006). Another study revealed significant differences in the wood anatomy of planted and naturally occurring silver birch. The fibre and vessels were thicker in the naturally growing trees than in the planted trees (Luostarinen and Möttönen 2010). It should be noted that there were substantial differences in the age of the harvested trees in the studies mentioned above, with the naturally growing trees being 70-80 years old, compared to 33 years for the planted birch. The authors, Möttönen and Luostarinen, recognise that the difference in wood properties between the natural forest and the plantations can be explained to a certain extent by the age of the trees (Möttönen and Luostarinen 2006). The relationship between wood density and tree age suggests that the stemwood density of the planted silver birch in our study will continue to increase until the plantations reach felling age.

Contradictory statements are found in the literature about the effect of birch growth rates on the mechanical properties of the wood. In general, the effect of growth rate on the mechanical properties of diffuse porous trees such as birch is considered to be small (Fukazawa 1984, Zhang 1995, Saranpää 2003). Studies by Dunham et al. (1999) showed that the wood strength of fast growing silver birch trees was only approximately 10% lower than that of slower growing trees. Heräjärvi stated that the basic density of downy birch wood material is dependent on the growth rate, but no such relationship has been observed for silver birch (Heräjärvi 2004). In contrast to the results of the studies mentioned above, Bhat (1980) reported a negative correlation between wood density and RW, suggesting that silver birch trees with higher radial growth rates have a lower wood density. A similar negative correlation was found in our study.

To understand the influence of growth rate on wood density, it is important to determine the differences between juvenile and mature wood because the presence of juvenile wood is one of the main causes of variation in wood properties (Saranpää 2003). The contradictory results from different studies about the effect of growth rate on wood density demonstrate the need for more detailed studies of birch wood properties. Although juvenile wood properties are less distinct from mature wood properties in diffuse-porous hardwood tree species compared to softwood tree species (Maeglin 1987, Bao et al. 2001), the relatively low stem density of the faster growing trees in our study can be linked to observed juvenile wood properties from past studies.

Our study found a positive relationship between wood density and tree height and SR (Table 3). A higher SR indicates a potential decrease in tree stability and an increased risk of damage to the trunk from physical-mechanical stimuli, e.g., wind, snow, ice and rainfalls. The formation of reaction wood (tension wood, in the case of hardwoods) is a physiological response of woody plants to mechanical stress that allows the trees to remain in balance with their physical environment (Telewski 2006). The anatomy of tension wood differs from that of normal wood. In tension wood, the fibres fail to form a proper secondary wall and instead form a highly cellulosic wall layer (Wiedenhoeft 2010). Young trees are especially subject to the formation of tension wood, and during a tree's formative years, a considerable proportion of tension wood can form in the juvenile zone (Maeglin 1987). The denser wood of the taller trees with higher SR in this study can be explained by the higher proportion of tension wood in the stem, which would have formed to enhance stem stability.

Generalisations about the positive relationship between tree height and SR to wood density should be made cautiously because the trees analysed in this study were juvenile trees, and relationships between growth traits and wood properties may be different in the mature trees. However, the relationship between wood density and tree height observed in this study is beneficial for tree breeders because tree height is the primary trait used in most tree breeding programmes (Pliura et al. 2007). Based on our results, the use of height as a selection trait in a juvenile age silver birch progeny trials is not expected to have a negative effect on wood density in the selected population.

The regression analysis showed that a relatively small part of the variation in wood density was explained by the tree variables used in this study (Table 4). From the literature, we know that it is difficult to predict wood density using stand and tree characteristics, even if the management history is known (Saranpää 2003). Silviculture, geographic location and environment are all sources of variation in wood density (Guilley et al. 1999, Briffa et al. 2002, Guller 2007). Additionally, genetic variability is high in silver birch, and may affect wood density (Stener and Hedenberg 2003, Baliuckienė and Baliuckas 2006). Planting stock used for the establishment of the plantations in our study included natural saplings and container seedlings grown from seeds collected in forest stands. The high genetic variability of the trees at the experimental sites is clearly responsible for a large part of the variation in wood density that was not explained by other variables in the regression model.

Mathematic modelling is often used in predicting wood density in commercially important tree species in certain regions (Rozenberg et al. 2001, Bouriaud et al. 2004, Guilley et al. 2004, Gardiner et al. 2011). However, models that predict silver birch wood density are scarce and have mainly been published in Finland because of the national economic importance of silver birch. Although our study used only wood obtained from plantations, the Repola's model performed well in predicting the average wood density of the sampled stems. This result suggests that the model can be used to predict the stemwood density of birches in our country, characterise wood quality, and generate density data for the estimation of stem biomass.

Conclusions

The first study of stemwood density in silver birch trees from plantations on former farmlands in Latvia did not find wood density values that were substantially different from the wood density values reported in other research. We found a positive correlation between wood density and tree age, tree height and slenderness ratio, but a negative correlation was found between wood density and RW. These results suggest that the wood density of stems will increase as the plantations move towards felling age. However, intensive management of the plantations clearly will have an effect on wood properties. As a consequence of the substantially shorter rotations and intensive silviculture of silver birch plantations, the timber industry should expect that wood extracted from the plantations in the future will have a lower density than the wood currently harvested from natural birch stands.

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ПЛОТНОСТЬ СТВОЛОВОЙ ДРЕВЕСИНЫ БЕРЕЗЫ ПОВИСЛОЙ (*BETULA PENDULA* ROTH) В МОЛОДНЯКАХ НА БЫВШИХ СЕЛЬСКОХОЗЯЙСТВЕННЫХ ЗЕМЛЯХ

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Резюме

Целью данного исследования было оценить плотность древесины березы без сучьев в молодых насаждениях березы повислой, вызванная необходимстю определения качества будущых ассортиментов круглого леса, а также определить влияние отдельных покозателей роста березы на плотность древесины. Проводимые нами исследования стволовой древесины березы повислой с плантаций на бывших сельскохозяйственных землях не выявили существенной разницы в отношении плотности древесины по сравнению с данными других исследований. В нашем исследовании определена положительная корреляция между плотностью древесины и возрастом деревьев, высотой деревьев и коэффициентом соотношения высоты/ диаметра. Отрицательная корреляция выявлена между плотностью древесины и шириной годичных колец деревьев. На основе этих результатов можно предположить, что плотность стволовой древесины березы повислой увеличится по мере достижения возраста главной рубки. Однако интенсивная хозяйственная деятельность в берёзовых лесных плантациях неизбежно повлияет на свойства древесины в будущем. В последствие значительно укороченного оборота рубки и интенсификации лесного хозяйство на березовых плантациях, со временем плотность древесины деревьев, растущих в плантациях очевидно будет меньше по сравнению с плотностью древесины, заготавливаемой в настоящее время в березовых насаждениях естественного происхождения.

Ключевые слова: береза повислая, *Betula pendula*, плотность древесины, лесные плантации.