Carbon Content in Juvenile and Mature Wood of Scots Pine (*Pinus sylvestris* L.)

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Bembenek, M., Giefing, D.F., Jelonek, T., Karaszewski, Z., Kruszyk, R., Tomczak, A., Woszczyk, M. and Mederski, P.S. 2015. Carbon Content in Juvenile and Mature Wood of Scots Pine (*Pinus sylvestris* L.). *Baltic Forestry* 21(2): 279–284.

Abstract

Carbon content in Scots pine wood depends on growth and development conditions and also varies across different sections of the trunk. Identifying this variability enables to establish the phases of tree growth, in which carbon accumulation is the most intensive. The aim of this study was to determine the carbon content of juvenile and mature wood from 103-year-old Scots pine. Tests were performed on samples from 12 model trees selected using the Draudt method. Discs were removed from the model trees at breast height, from which samples were taken for chemical analysis. Totally 48 samples represented annual growth rings 4 and 5 counted from the core (juvenile wood) and growth rings 4 and 5 from the trunk circumference (mature wood). The percentage of carbon contained in the dry matter was measured using a Vario Max CNS (Elementar) analyser. The average carbon content level in the tested wood samples was 47.54 ± 0.47 % dry mass (DM). In juvenile wood, it accounted for 48.15 ± 1.15 % DM compared to 46.94 ± 0.33 % in mature wood. The highest correlation of C content (mean) was dependent on crown volume and amounted to -0.6306.

Key words: Carbon; juvenile wood; mature wood; Scots pine (*Pinus sylvestris* L.)

Introduction

In the central part of the trunk of Scots pine (*Pinus sylvestris* L.), the annual growth rings are clearly wider than new growth closer to the outer circumference. The proportion of latewood surrounding the pith is low, whereas it is relatively high around the outer circumference. The selected sections also differ in terms of chemical composition and in microscopic structure, and therefore in the properties of the wood itself (Akgul and Tozluoglu 2009, Gryc et al. 2011, Pazdrowski 2004, Plomion et al. 2001, Schweingruber 2007, Yeh et al. 2006, Zobel and Sprague 1998). The central part of the trunk cross-section is formed of juvenile wood surrounded by mature wood. Juvenile wood consists of several annual rings depending on the species and the test methods employed to quantify it (Abdel-Gadir and Krahmer 1993, Alteyrac et al. 2006, Csoka et al. 2005). Scots pine juvenile wood consists of approximately 20 annual growth rings (Fries and Ericsson 2006, Mutz et al. 2004). According to Kučera (1994) and Tomczak et al. (2007), the formation of juvenile wood is strongly influenced by proximity to leaves, and the proportion of juvenile wood depends on how far down the crown reaches.

The role of juvenile tissue in the tree trunk has not been fully explored. Juvenile wood is characterised by lower density and it may be assumed that it is a biocomponent of the trunk acting as filler. This filler enables the tree to reach a substantial size and strength despite its relatively low density. Because the percentage of juvenile wood in the cross-section of the trunk increases in proportion to the distance from the base, it should also play a role in the formation of the biomechanical functions of the trunk (Jelonek et al. 2012). Proof of this can be seen in changes in its structure, such as the decreasing width of annual growth rings, increases in the proportion of latewood, and changes in biometric tracheid characteristics (Tomczak et al. 2007, 2008, Zobel and Sprague 1998).

The fact that the density of juvenile wood is lower than that of mature wood is an indication of its mechanical role. The total unit shrinkage per volume, as well as radial and tangential shrinkage of juvenile wood, is lower than in mature wood. Furthermore, in comparison to mature wood, juvenile wood is characterised by a higher degree of variability (heterogeneity), particularly in relation to shrinkage (Tomczak et al. 2011, Tomczak and Jelonek 2012). Additionally wood density is generally treated as a property, which tends to change not only amongst the same species from diverse geographic locations, but it can also vary, when trees from different provenances grow on the same area (Szaban et al. 2014).

The analysis of the mechanical properties of juvenile and mature wood taken from trees grown in post-agricultural soil and forest soil conditions indicate that juvenile wood is more prone to shrink and less stiff in static bending than mature wood. Additionally, test results have shown significantly lower values of the analysed properties in pine trees grown on former farmland (Jelonek et al. 2010, Tomczak and Jelonek 2013). In comparison to mature wood, juvenile wood is characterised by lower density (regardless of annual ring width), on average shorter tracheids, a lower proportion of latewood, and a higher proportion of lignin (Zobel and Sprague 1998).

As the results of the study by Wróblewska and Sława-Neyman (1995) reveal, the spacing of tree planting significantly affects the chemical content of the wood. The wood of pine trees initially grown at closer spacings showed higher levels of cellulose and lignin.

In general, many factors affect tree growth and development, and as a consequence geographical location, habitat, biosocial position, and silvicultural treatment are visible in wood cell structure and tissue properties (Arnold and Mauseth 1999, Jelonek et al. 2008, Riesco Muñoz et al. 2008, Tomczak and Pazdrowski 2004, Wiemann and Williamson 2002). At higher temperatures and increased carbon dioxide concentration, wood undergoes strong radial growth, leading to changes in structure and properties (Telewski et al. 1999). According to some researchers, this is evidence of the effects of climate change on tree growth and development and therefore on the quality and properties of the wood (Kilpeläinen et al. 2005, Peltola et al. 2002).

Phenotype variability is a natural phenomenon, which is viewed as the classic interaction between genotype and environmental conditions. According to Lamlom and Savidge (2003), one feature of phenotype is the carbon content in wood. This is thought to be the expression of the tree's reaction to changes in climate, the result of the influence of the micro-environment on biomechanical tree processes.

Considering the differences between the described physical properties of juvenile and mature wood and the influence of the aforementioned factors on the chemical constitution of wood, our hypothesis was that carbon content levels may differ between Scots pine juvenile wood and mature wood. For such differentiation the heartwood and sapwood presence was not taken into consideration. Therefore, the aim of this study was in principle to determine the carbon content in juvenile and mature Scots pine wood. This aim was initially understood as fundamental studies rather than practical issue of carbon differences in different wood sectors of a tree trunk.

Materials and Methods

Study Site

The study was carried out in Northwestern Poland (N 53°74'85" E 16°54'99"), an area overseen by the Szczecinek Regional Directorate of the State Forests (compartment 36b). In physical-geographical terms, the research stand was located in the catchment area of the upper Parsęta in the central Western Pomeranian Lakeland macroregion (on the border of the Drawskie Lakeland and Bytów Lakeland mesoregions). Coniferous forests occupy 21.1 % of the catchment area (74.0 km^2).

The soil cover of the research stand was classified as spodic udipsamments (Soil Survey Staff 2010) and formed from mid-grain sand deposits. The pH values obtained in the experiment suggest that ion exchange and aluminium buffers were present in the soil. On the basis of phytosociological tests, the tree stand under analysis was defined as fresh coniferous forest (FCF), dominated by *Leucobryo-Pinetum*. The tree stand of 1.35 ha across the FCF habitat was planted in 1905 on former farmland. The main species was Scots pine (*Pinus sylvestris* L.), which was enriched with multi-species (oak, birch, and juniper) sub-planting. The stand of advanced age was selected for the study to make sure that substantial amount of mature wood was built to be taken for experiment. One, particular site was taken into consideration, for which detailed description, history of land use and soil classification were provided. Therefore, it should be considered as narrow research, specific for the site and soil conditions described as above.

Measurements and Selection of Trees

Tree felling (strip partial felling) was planned in compartment 36b (plot 01) covering an area of 0.68 ha, which constituted the entire test plot. At the designated test site, the breast-height diameter of all the trees was measured and recorded to the nearest 1 cm, with an error of 0.1 cm. Tree height and crown length were measured using a Vertex Laser (0.1 m precision); two to six trees representing every degree of diameter were selected for height measurement (depending on the number of trees available of a particular diameter).

On the basis of the data collected, the parameters of the model trees were calculated using the Draudt dendrometric method (h; $d_{1,3}$). Then, 12 model trees were selected from the sample area, of which the crown diameter (d_k), the height of the first live branch, and the overall height were measured. The length of the crown (l_k) was calculated as the difference between the tree height and the height of the first live branch. The breast-height diameter (*bhd*) of the selected model trees measured 26 to 46 cm, (36 ± 6 cm), and the height (h) was between 21.3 and 28.3 m (26.4 ± 2.2 m). The crown length (l_k) measured 4.9 to 11.7 m, (9.6 ± 1.9 m), and the crown diameter (d_k) ranged from 2.8 to 5.5 m (4.0 ± 0.9 m) (Table 1). The crown volume was calculated by crown length and crown diameter.

North was marked on the trunk before the trees were felled in December 2008 and January 2009.

Table 1. Model Tree Characteristics

No. of tree	[1]bhd [cm]	[2]h [m]	Crown [m]	
			Length [l_k]	Diameter [d_k]
1	26	21.3	6.3	2.8
2	31	26.1	11.1	3.7
3	32	22.5	10.5	2.9
4	35	26.8	12.8	3.1
5	36	27.2	9.2	3.3
6	37	27.8	8.8	4.4
7	38	27.5	7.5	4.2
8	39	27.1	5.1	4.1
9	40	28.2	8.2	5.2
10	42	27.7	6.7	4.4
11	45	28.3	2.3	5.5
12	46	25.8	2.8	4.9
mean	37	26.4	7.6	4.0

[1]Breast height diameter; [2] height of a tree

Materials

Discs were cut from all the sample trees at breast height ($h_{1.28m}$ to $h_{1.32m}$), from which wood samples were taken for chemical analysis. The sample constituted annual growth rings 4 and 5 counted from the core (juvenile wood) and annual rings 4 and 5 from the outer circumference of the tree (mature wood). From each cross-section, two series of samples were taken: one along the north radius, and the second along the south radius (Figure 1). A total of 48 representative samples were collected in this way.

Methods

To perform the carbon content analysis, the wood samples were first dried at 65 ºC, and then ground in an electric mill, Mortar Grinder PULVERISETTE 2 produced by FRITSCH.

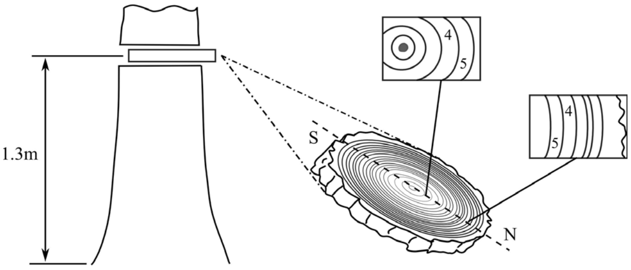

Figure 1. Wood samples selection from inner (juvenile wood) and outer (mature wood) areas: 4th and 5th annual rings, counting from pith and from outer trunk cross section respectively

The ground organic material (wood particle size: 10-20 µm) was analysed in a Vario Max CNS (Elementar) to determine the carbon content in dry wood as a percentage. The analytical sample weight was approximately 50 mg. Each sample was analysed in duplicate, and the results were averaged. The difference in the contents of C in two consecutive measurements of the same sample was no greater than 5 %. For reference purposes, sulfadiazin, SQC001S Sigma-Aldrich (sewage sludge), and CP1 AgroMAT™ (compost), were used.

The amount of carbon, expressed as a percentage, was submitted for statistical analysis using Statistica 10 software. The carbon values in the juvenile and mature wood did not exhibit a normal distribution (as revealed by the Shapiro-Wilks test). The Mann-Whitney test was applied to determine statistically significant differences. Furthermore, a range of analyses were performed based on regression and correlation coefficient (r) equations to ascertain the dependence of carbon content on selected biometric tree features.

Results

The average carbon content in the tested wood samples was 47.54 (SD 1.03) dry mass (DM). In the juvenile wood, the carbon level was recorded at 48.15 (SD 1.08) DM, whereas in the mature wood, it accounted for 46.94 (SD 0.48) DM (2.58 % more in juvenile wood) (Table 2).

Table 2. Carbon (C) Content in Juvenile and Mature Wood

Tree number	C, % of dry mass	
	Juvenile wood	Mature wood
Overall	48.15	46.94
1	50.68	46.43
2	47.15	46.59
3	48.19	47.27
4	48.55	46.72
5	47.93	47.16
6	48.32	46.71
7	47.61	46.93
8	48.52	47.38
9	47.13	46.88
10	47.70	47.40
11	46.85	47.13
12	49.19	46.64

Differences in carbon content (C) in the juvenile wood and mature wood were statistically significant (*p* = 0.000008). The correlation of C content with selected biometric tree features was calculated for the crown and breast-height diameters. The only significant correlation for carbon content (mean) was dependent on the volume of the crown and measured -0.6306

Table 3. Correlation Coefficient (*r*) of C with Selected Biometric Tree Features

C-content in relation to:					
breast height diameter (C in juvenile wood)	breast height diameter (C in mature wood)	breast height diameter (C mean)	crown volume (C in juvenile wood)	crown volume (C in mature wood)	crown volume (C mean)
-0.4302	0.3880	-0.3412	-0.5542	-0.0616	**-0.6306**

Statistically significant $r > 0.576$ at $p = 0.05$

Discussion and Conclusions

The mean carbon content in the tested dried wood samples was 47.54 %, which was close to the mean value of carbon in wood tissue (Pereira et al. 2003). However, the wood exhibited quantitative differences in the carbon content, which can be observed not only between tree species, but also within the same species. There were various influencing factors, such as growth and environmental conditions, as well as tree age and tree structure (Fukatsu et al. 2008, Laiho and Laine 1997). There was also large difference in C content in juvenile wood (SD 1.08) in comparison with mature wood (SD 0.48). One of the reasons for that could be that at the earlier stage of tree development first annual rings are of very different width in comparison with annual rings in outer tree cross section. However, this statement needs further detailed research.

A difference of 2.58% in carbon content was detected between the juvenile and mature wood, where the level was higher in the juvenile wood. This difference was probably due to the amount of earlywood in the annual rings. Studies by Lamlon and Savidge (2003) showed that carbon content in earlywood was higher than in latewood, and there was a higher percentage contained in the earlywood of juvenile wood (Zobel and Sprague 1998).

The macrostructure of juvenile wood reveals the influence of growth and environmental conditions defined by a tree's social position in the stand. Trees with a well-developed crown usually dominate the stand in the very early phases of development. The width of their annual growth rings is generally higher in comparison to trees, whose crowns are in a less favourable position. As far as pines are concerned, greater width of annual growth (thicker trees) results in a proportionally higher amount of earlywood with lower C content. There was no correlation between C content and morphological tree characteristics, although a strong correlation has been identified with crown characteristics, which is the part of the tree directly related to assimilation. According to Lemke (1966), larger tree crowns are less efficient at assimilation than small crowns. The proportional relation is reversed between the C content in wood and the crown size, which may be linked to Lemke's hypothesis (1966). At the same time, it may also be assumed that this connection is also dependent on other factors. Amongst other factors, crown efficiency is significantly affected by the tree's physiological age. According to Assmann (1968), trees with a breast-height diameter of 20 to 25 cm and a height of 12 to 20 m showed the highest level of efficiency, whereas Eckmüllner and Sterba (2000) claimed that crown efficiency mostly depends on needle mass. Additionally, Jelonek et al. (2008) showed that crown efficiency is related to the age and biosocial position of the tree in the stand.

As pine age increases, the proportion of juvenile wood decreases in the volume of the whole stem; the older the tree is, the lower the proportion of juvenile wood in relation to mature wood (Pazdrowski et al. 2005, Tomczak et al. 2005). In terms of unit volume, therefore, older pine trees have lower carbon content in the wood when compared to younger trees. The same stocking per unit surface in younger stands of pine trees will consequently assimilate more carbon in comparison to older trees. This is especially important, when mature forests are at high risk of disturbance and have low productivity. The harvesting of these stands and regeneration will offer, in the long term, higher carbon sinks (Nabuurs et al. 2013). Therefore, it can be concluded for forest management practice, that in younger pine stands, greater carbon assimilation *per* timber volume unit occurs compared to mature stands, as younger pine trees have a higher percentage of juvenile wood, which has higher carbon content than mature wood.

A very important factor shaping conditions of growth and development is the origin of the soil and how it is exploited. Its significance is supported by studies carried out by Jelonek et al. (2010), which indicated differences in timber from post-agricultural stands. Considering the structural diversity of the soil in relation to mature wood may be a significant element in the assessment of timber value. In a comparison of the volume of the juvenile wood to the volume of the whole stem grown in former farmland soil and forest soil, Tomczak et al. (2009) observed that the ratio was higher in the 2nd, 4th, 5th, and older age classes in trees from forest soils.

Eventually it can be concluded, that the carbon content (C) in juvenile wood was higher compared to mature wood of Scots pine, aged 103 and grown on former farmland of given characteristics. These differences were statistically significant. The mean C content in pine wood correlated negatively with crown volume: the bigger the tree crown volume, the lower C content in the wood. The correlation between mean C content and crown volume was statistically significant. There was no correlation between C mean content and DBH both for juvenile and mature wood.

Acknowledgments

This research was supported by the Polish Ministry of Science and Higher Education in the years 2008-2012 as research project No. N305 337334.

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Received 03 August 2014
Accepted 08 October 2015